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LITHO-FACIES OF INSHORE ESTUARINE AND TIDAL-INLET DEPOSITS

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SUMMARY

Three litho-facies may be distinguished in inshore estuarine and tidal-inlet deposits. In general these litho-facies are related to the intensity of the current action over the bottom. The current action shows rapid variations in time due to alternating spring and neap tides and/or wind influences and to shifts of the channel axis. As a result fining and coarsening upward sequences of the sediment types are found. The frequency of occurrence of the litho-facies varied with depth in the estuary studied, but not in the tidal inlets.

INTRODUCTION

Extensive engineering works are under construction in the estuaries and sea arms in the SW part of The Netherlands. Two large excavation pits were made in the middle of the Haringvliet estuary in which large sluices were built. Numerous borings providing continuous cores were made in this estuary and adjacent tidal inlets. This offered an excellent opportunity to study inshore estuarine and tidal-inlet sedimentary features for scientific and technical purposes.

The scientific aim of this study was:

a. to distinguish different litho-facies on basis of their sedimentary structures and to relate them to hydrodynamic conditions;

b. to determine the vertical and horizontal relations between these litho-facies.

The investigated area is shown on fig. 1. It consists of different tidal channels, separated by shoals mostly emerging at low water. The tidal range varies from 3,40 m in the SW to 1,65 m in the NW of the area. Maximum tidal-current velocity lies between 1,5 m/sec till 2 m/sec incidentally.

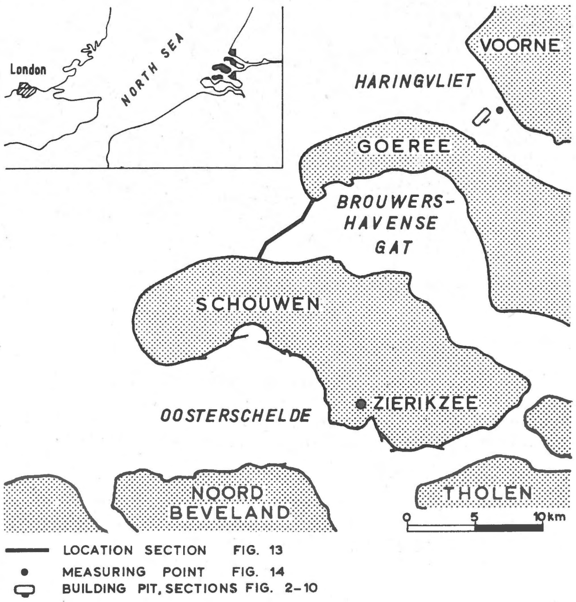

Fig. 1
Investigated Area.

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LITHO-FACIES

General

Inshore-tidal deposits are found in estuaries, tidal inlets and tidal flats. They can also been encountered in lagoons subjected to tidal currents but protected from severe wave attack by barrier ridges and islands, shoals, etc. All such areas show a pronounced and everchanging bottom relief creating distinct variations in sedimentary strata in horizontal and vertical direction.

In this study only the tidal channel and the subtidal part of the shoal deposits, formed below L.W. are treated. The topstratum tidal-flat and marsh deposits in the investigated are are not different from those described by van Straaten (1954) and Reineck (1967).

Three different litho-facies may be distinguished in the tidal-channel and shoal deposits. The differences between these facies are in a general way related to the intensity of the water movement over the bottom.

Litho-facies I
Deposits formed under high-current action.

Litho-facies II
Deposits formed under medium-current action.

Litho-facies III
Deposits formed under low-current action.

Litho-facies I: Deposits formed under high-current action

This facies is characterised by coarse-grained sand (d_{50} from 200 to 500 μ; mean about 275 μ) containing clay pebbles, shell debris, peat lumps and detritus and shows mega cross-bedded structures. The set thickness is in the order of 0,1 m and more.

The cross-stratification includes:

- (semi) tabular sets
- troughs sets
- fill structures.

From the *(semi) tabular sets* normally only the lower parts of the foresets, the concave or tangential toesets and the bottom sets are preserved. The lower set boundaries are straight or slightly scooping. The observed maximum set height amounts to about 2 m. Ebb and flood foresettting occurs often in superposition but within the same level ebb and flood

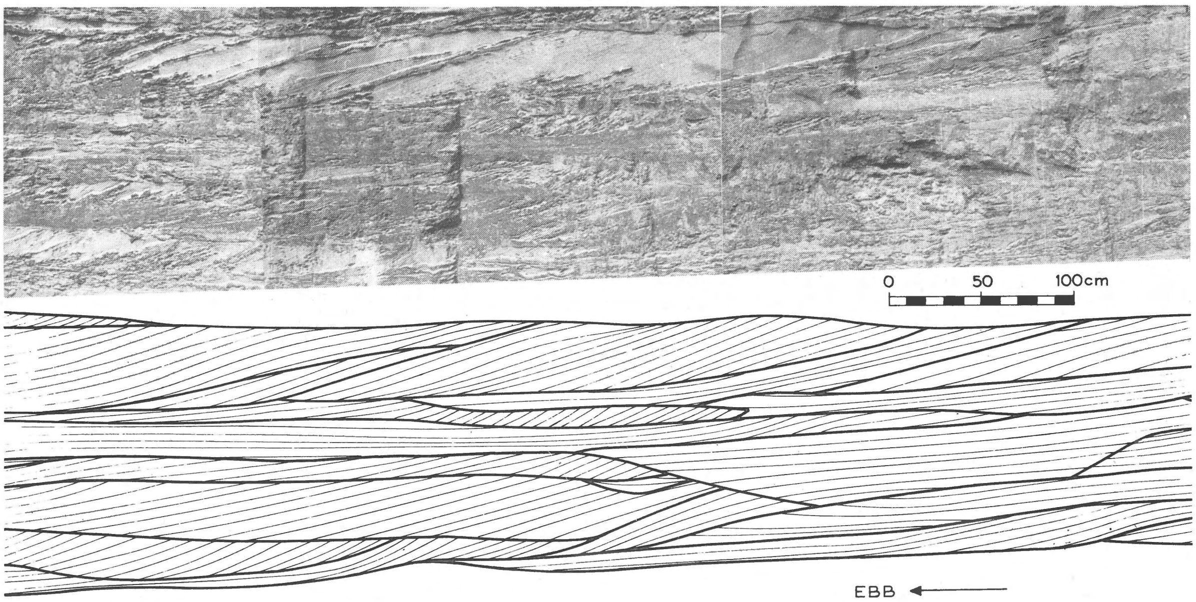


Fig. 2
Cross-bedding in estuarine deposits, showing only ebb foresetting and no structural indication of the flood currents. Section almost parallel to the current direction.

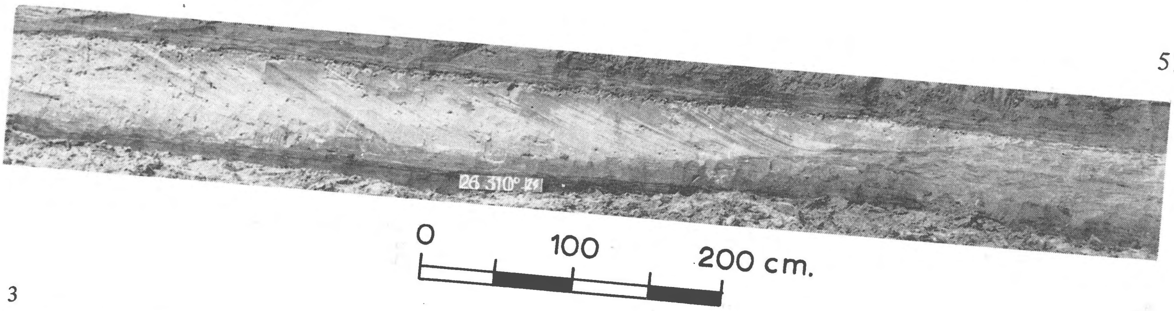
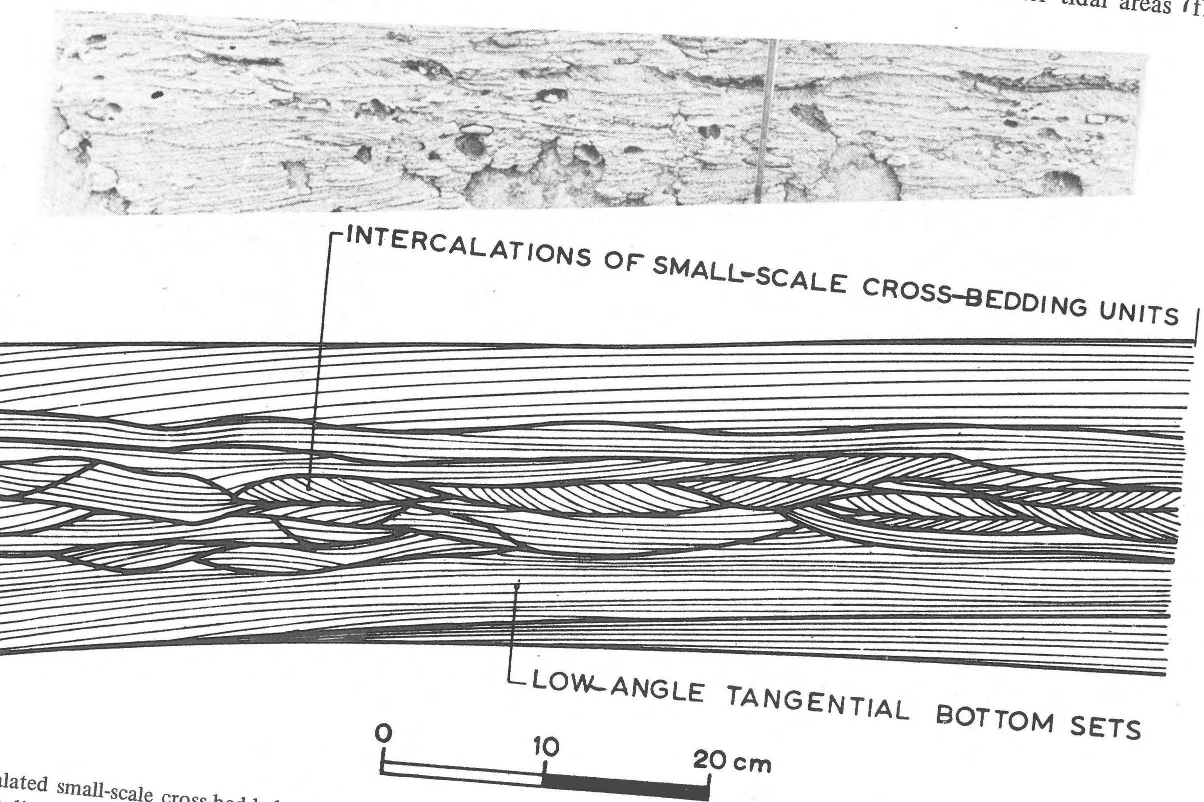


Fig. 3
Filling of flood mega-ripplé trough (lithofacies I) in contact with small-scale rippled sand (lithofacies II).

foresetting was never observed. This is a very peculiar fact because it indicates a very pronounced predominance of the currents in one direction over opposite directions. The most extreme observation in this respect was a section of 15 m in length and 3 m in heights which showed only ebb foresetting without any sign of bimodal features suggesting interfering flood-current action. Truncations within the foresets occur but are relatively rare. (fig. 2). However it must be assumed that the movement of the ripples stopped developing during the counter-current phase of the tide. The slack-water period(s) is sometimes marked by a thin silt layer spreading over the foresets of the ripple. It also appeared that retardation of the ripple movement may give rise to trough filling, fig. 3. The observation, described above, cannot be regarded as diagnostic for tidal deposits, because bidirectional foresetting was reported from other tidal areas (f.i.



...lated small-scale cross-bedded sets between bottom sets of enframing large-scale ripples. (Section almost parallel to the ... direction).

R e i n e c k, 1963).

Between two units of low-angle tangential bottom sets the counter currents may manifest themselves in intercalated small-scale cross-bedded units. The foresetting in these units shows however also opposite directions (fig. 4). We are not dealing here with back-flow ripples (B o e r s m a et al., 1968) but with composite sets. Perhaps the intercalated small-scale units represent a intermediate period of weakening bimodal currents.

Troughs cross-stratification, produced by linguoid current ripples is illustrated in fig. 5. Spoon-shaped cross-stratified units are called trough sets by the present author if the length axis of the troughs is roughly parallel to the direction of the ripple propagation because this is an indication that the troughs are syngenetic with the ripples. Furthermore there should be vortex action in the ripple trough with connected avalanching sediment movement over the lee side of the ripple causing the coarsest sediments to be found at the base of the foresets. Often the bedding seems to be concordant with the trough profile. If the trough axis makes an angle with the main direction of sediment movement the spoon-shaped units are regarded as *fill structures* of pre-existing depressions. Vortex activity is less likely in the depressions. The sediments are dumped in these depressions, showing low-angle cross-bedding with the coarsest material in the upslope parts of the units. The bedding abuts mostly discordantly against the bottom of the depression (fig. 5). All kinds of transitions between trough sets and fills do occur. It is often difficult to make a clear distinction between them.

In the trough as well as in the fill cros-stratification there are very few indications of counter-current effects. Superimposed ebb and flood foresetting is also rare. Small-scale cross-stratified sets and flaser bedding may be found between the mega cross-bedded structures (fig. 5). The maximum height of trough sets and fill structures observed is 0,5 m.

Litho-facies I represents periods of important bed-load transport in the form of large-scale current ripples. Adaptation of the bottom morphology to the changing direction of the currents may give rise to (lateral) filling of existing depressions. The base levels of the troughs of the travelling ripples change in height with time and space as is inferred from flume as well as field observations. During an erosion phase the mean value of the base levels is lowered. After the

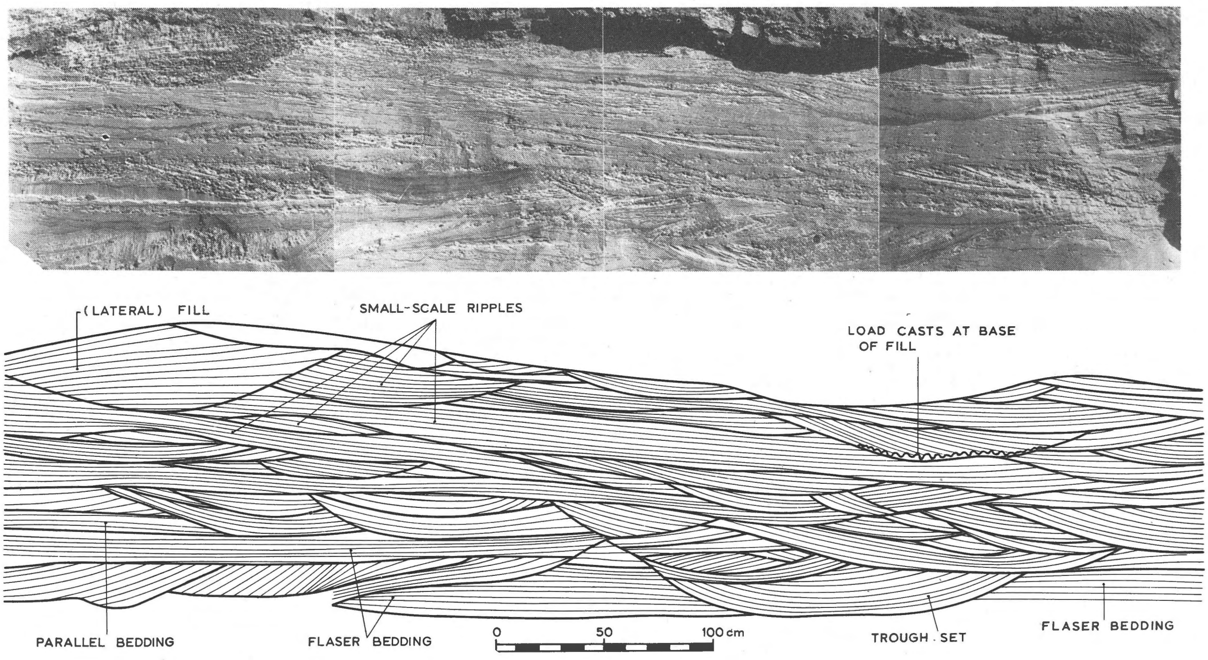


Fig. 5
Trough cross-stratification and fill structures (Section perpendicular to the current direction).

erosion phase has passed sedimentation may take place and the bottom is gradually heightened. So the lower parts of the large-scale ripples may be preserved.

Litho-facies II: Deposits formed under medium-current action

This facies is characterised by medium- to fine-grained sands (d_{50} between 150-240 μ, mean about 180 μ) with or without clay drapes and by horizontal and cross-bedded structures. Set thicknesses vary from 0,01 to 0,1 m. Slight bioturbation may occur.

The observed structures are:
- horizontal sand lamination
- small-scale cross-stratified sets
- flaser bedding
- load casts.

Horizontal sand lamination may originate from selective settling of sand from suspension in turbulent water. This mode of formation is evidenced by the fact that individual sand laminae may be followed over distances up to 2 m.

Selective settling is only possible if the turbulence of the water is so intensive that fine sand, silt and clay if deposited, are easily and quickly resuspended before they become entrapped by overspreading coarser sand. The observation that the sand lamination contains only very small amounts of silt and clay cannot be attributed to the absence of these materials in the suspension because sampled suspension in the studied area reveal that the concentration of sand and mud is of the same order of magnitude. Although there are no definite proofs at this moment the possibility may be mentioned that the horizontal sand lamination results from settling out of heavily loaded suspensions caused by severe wave action on submerged shoals and to a certain extent probably displaced by tidal currents. This suggestion may be substantiated by the fact that the lower boundary of the sand lamination is usually very sharp, sometime erosive. It represents a break in the existing sedimentation conditions. Furthermore there is no regularity in the position of the sand lamination. It may be intercalated in litho-facies I and III even. On the top a more gentle transition to other structural units is found as indicated below.

Small-scale trough and tabular sets show a very delicate cross-lamination (fig. 6). Ebb and flood foreset directions are frequently found alternating

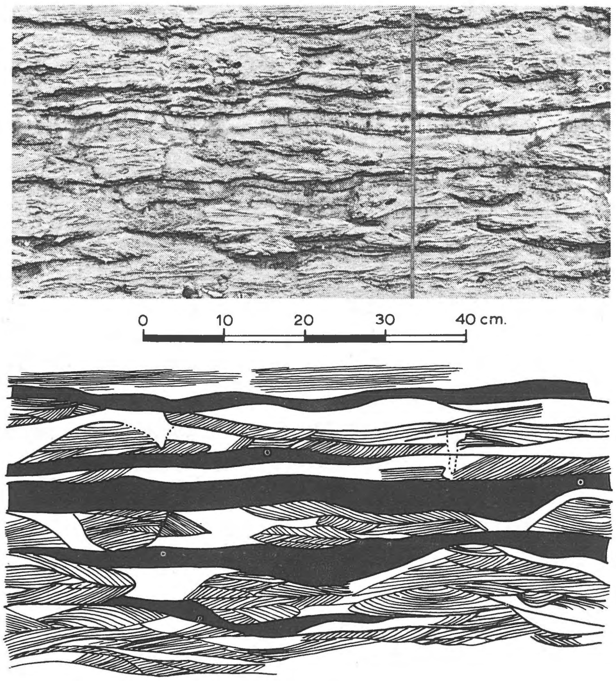


Fig. 6
Small trough and tabular sets (Section almost parallel to the current direction).

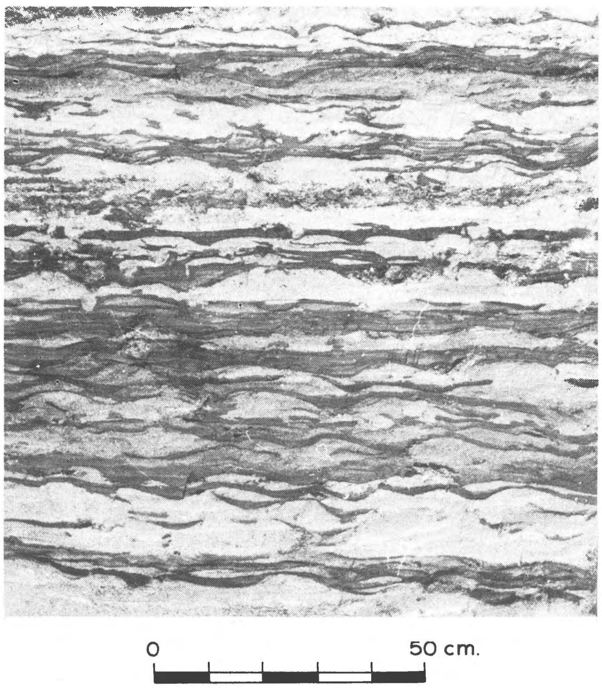


Fig. 7
Flaser bedding.

above each other and within the same level. Sometimes one foreset direction strongly dominates.

The *flaser bedding* (fig. 7) results mostly from the presence of mud flims in ripple troughs. It represents then a remnant of a mud layer, which is deposited over the ripple presumably during slack water, but eroded from the ripple crest after the turn of the tide (Reineck & Wunderlich, 1968). However ripple crests covered by clay drapes are also common in this type of bedding.

Where continuous clay layers occur within this litho-facies, loadcasting is often encountered.

Frequently, although not always, it was observed that the structures of litho-facies II show the following sequence: at the base horizontal sand lamination followed by trough and tabular sets without flasers but repeatedly truncated, overlain by trough and tabular set with flasers and well developped rippleform sets. This succession represents a gradual decrease in bottom-current velocity.

The maximum thickness of a litho-facies II complex in the investigated area was 20 m.

Litho-facies III: Deposits formed under low-current action

This facies is characterised by fine sand (d_{50} between 75-180 μ mean about 130 μ) and clay layers. The sand layers show horizontally laminated and small-scale cross-bedded structures. Set thicknesses are of the order of 0,01-0,001 m. Occasionally bioturbation occurs.

The main structures are

- lenticular bedding (Reineck, 1967)
- sand-clay alternations (Reineck & Wunderlich, 1969).

The *lenticular* bedding consists of sand lenses of irregular form embedded in mud layers (as described by Reineck, 1967). They may represent isolated small-scale ripples which have travelled over a clay bed and which have been covered up by clay subsequently. It is difficult to make the set type visible. The boundary between sand and clay layers is very sharp. The thickness of the sand lenses and clay layers lies normally between 0,5 and 3 cm.

The sand-clay alternations (fig. 8) consists of horizontally parallel bedded sand and clay layers of 0,1-1 cm thickness. Here too the boundary between sand and clay layers is usually very sharp. Loadcasting

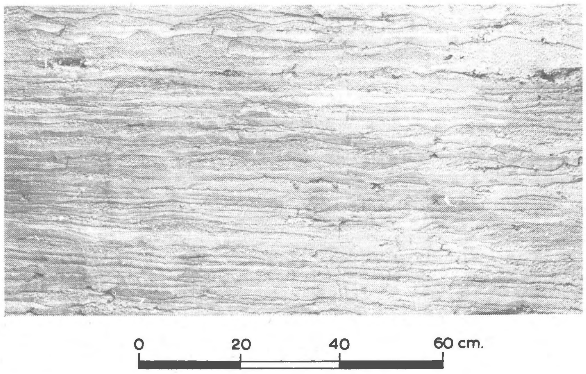


Fig. 8
Sand-clay alternations.

affects some of the clay intercalations. Many questions concerning the mechanism of formation of both bedding types arise. Some of them will be treated in a subsequent publication.

The maximum observed thickness of a litho-facies III complex was 17 m.

The three mentioned litho-facies, occurring in one section are illustrated in fig. 9. A succession of facies I to facies III represents a decrease in sand-transport capacity (decrease in grain size and magnitude of the sedimentary structures) and an increase in the sedimentation of clay.

FREQUENCY OF OCCURRENCE OF LITHO-FACIES IN RELATION TO DEPTH

About 200 continuously cored borings, made in the Haringvliet estuary, the Brouwershavense Gat and

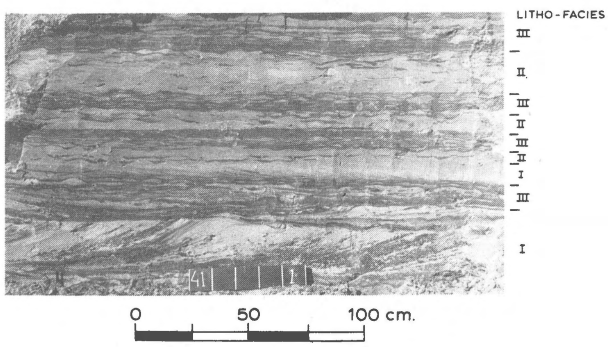


Fig. 9
Litho-facies occurring in a vertical section.

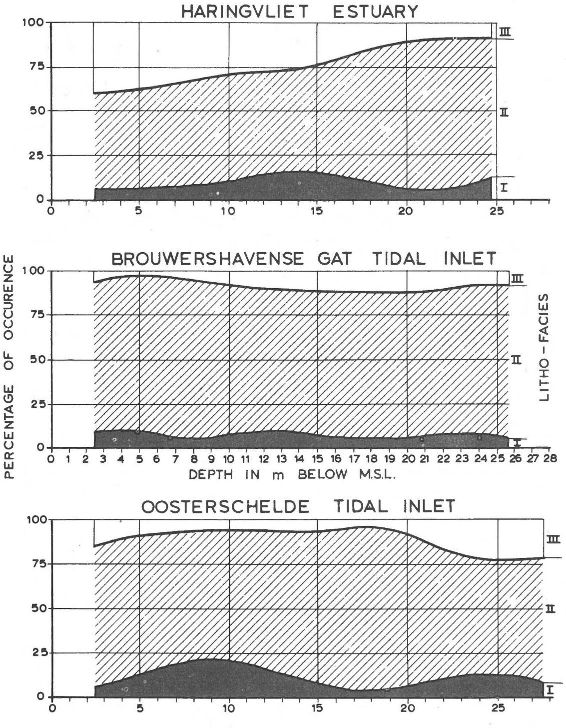


Fig. 10
Percentage of occurrence of litho-facies in relation to depth in the Haringvliet estuary and the Brouwershavense Gat and Oosterschelde tidal inlet.

Oosterschelde tidal inlets were analysed for the three mentioned litho-facies. This analysis was mainly based on texture and therefore could not be very accurate. In particular sandy layers belonging to facies I can give rise to confusion and may be mistaken for sands of facies II. Checks with lacquer peels, however, indicate that notwithstanding such inaccuracies the data are suitable for general considerations, Only that part of the borings was analysed, the core material of which was doubtlessly deposited in the estuary and tidal inlets in very recent times, say after 1800 as evidenced by former hydrographic maps.

From the obtained data the relative frequency of each litho-facies as a fuction of depth was determined. Five point-moving averages were applied in order to exclude meaningless local variations. It follows from fig. 10 that in the Brouwershavense Gat and Oosterschelde tidal inlets the relative frequencies showed no relation with depth: It also appeared that the frequency of facies II is very predominant, indicating that the sedimentation in these areas usually takes place under bottom-current action of moderate intensity.

In the Haringvliet estuary, however, facies III shows a gradual increase and facies II a decrease with decreasing depth. The frequency of facies I remains the same at all depths considered. Therefore in this particular estuary a gradually fining upward tendency may be established.

SEQUENTIAL ANALYSIS

In a former publication (Oomkens and Terwindt, 1960) it was suggested that the sediments in the investigated area showed a distinct fining-upward sequence, which was ascribed to a general decrease in the current intensity near the bottom with decreasing water depth. Such ideal fining-upward sequence expressed in the described litho-facies, would show a succession of facies I to facies III.

Sedimentary strata were considered to belong to a sequence if the strata showed a gradual change in magnitude of the sedimentary structures, grainsize, and number of clay layers in a vertical sense.

Sequences were classified uncomplete if either litho-facies I or litho-facies III was missing.

Abrupt changes in the succession, not showing sequential features were named random intercalations.

The above-mentioned borings were analysed for fining- and coarsening-upward sequences and random intercalations mainly on basis of the textural properties.

Table 1 gives the relative frequency of occurrence.

The table shows that there is little difference in the frequency distribution of fining- and coarsening-upward sequence of litho-facies in the different areas. So from the present data it is impossible to conclude that inshore estuarine and tidal-inlet deposits are characterised by fining-upward sequences of litho-facies. Coarsening-upward sequences have almost the same probability of occurrence. It was commonly observed that fining- and coarsening-upward sequences alternate above each other. Figure 11 gives an illustrative example.

Great lateral variations in litho-facies do also occur (fig. 12). It is normally very difficult to trace a

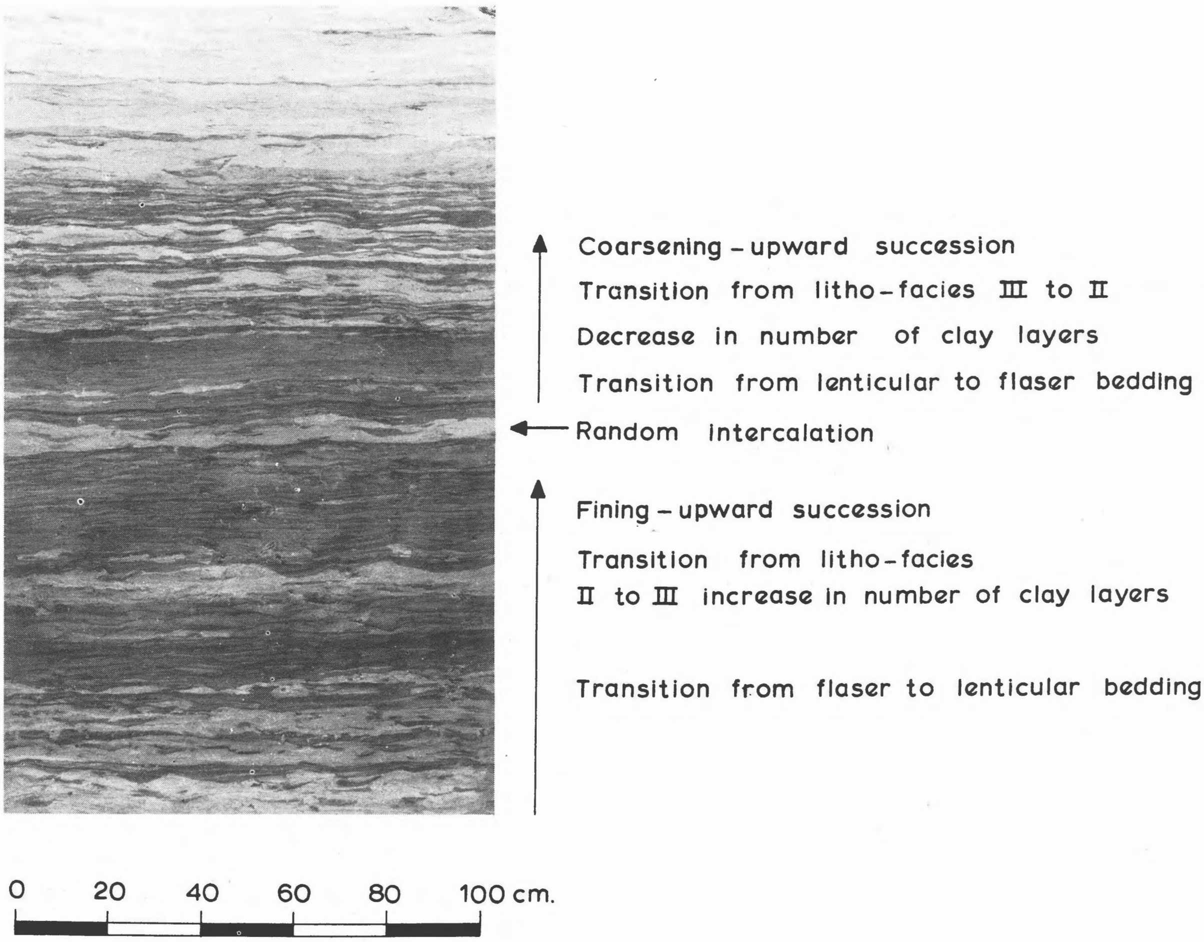


Fig. 11
Alternating fining- and coarsening-upward sequences.

TABLE 1
Relative frequencies of sequences.

		Haringvliet estuary	Brouwers-havense Gat tidal-inlet	Oosterschelde tidal-inlet
FINING UPWARD	complete	13	10	10
	uncomplete	34	43	40
COARSENING UPWARD	complete	13	9	10
	uncomplete	19	27	32
RANDOM INTERCALATIONS		21	11	8
Total number of analysed sequences and intercalations.		478	257	129

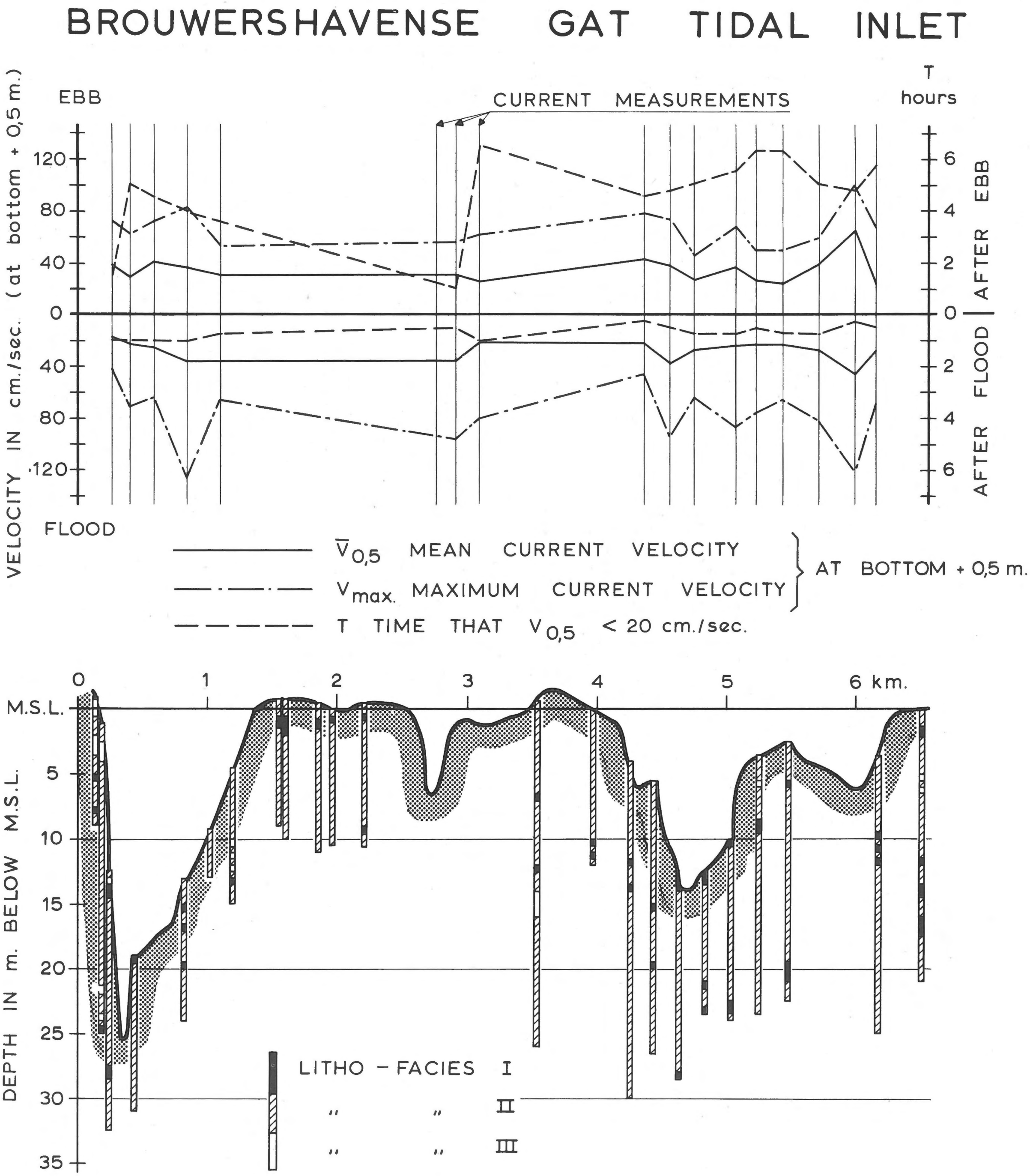


Fig. 12
Variability of litho-facies and the current velocity at bottom + 0,5 m in the Brouwershavense Gat tidal inlet.

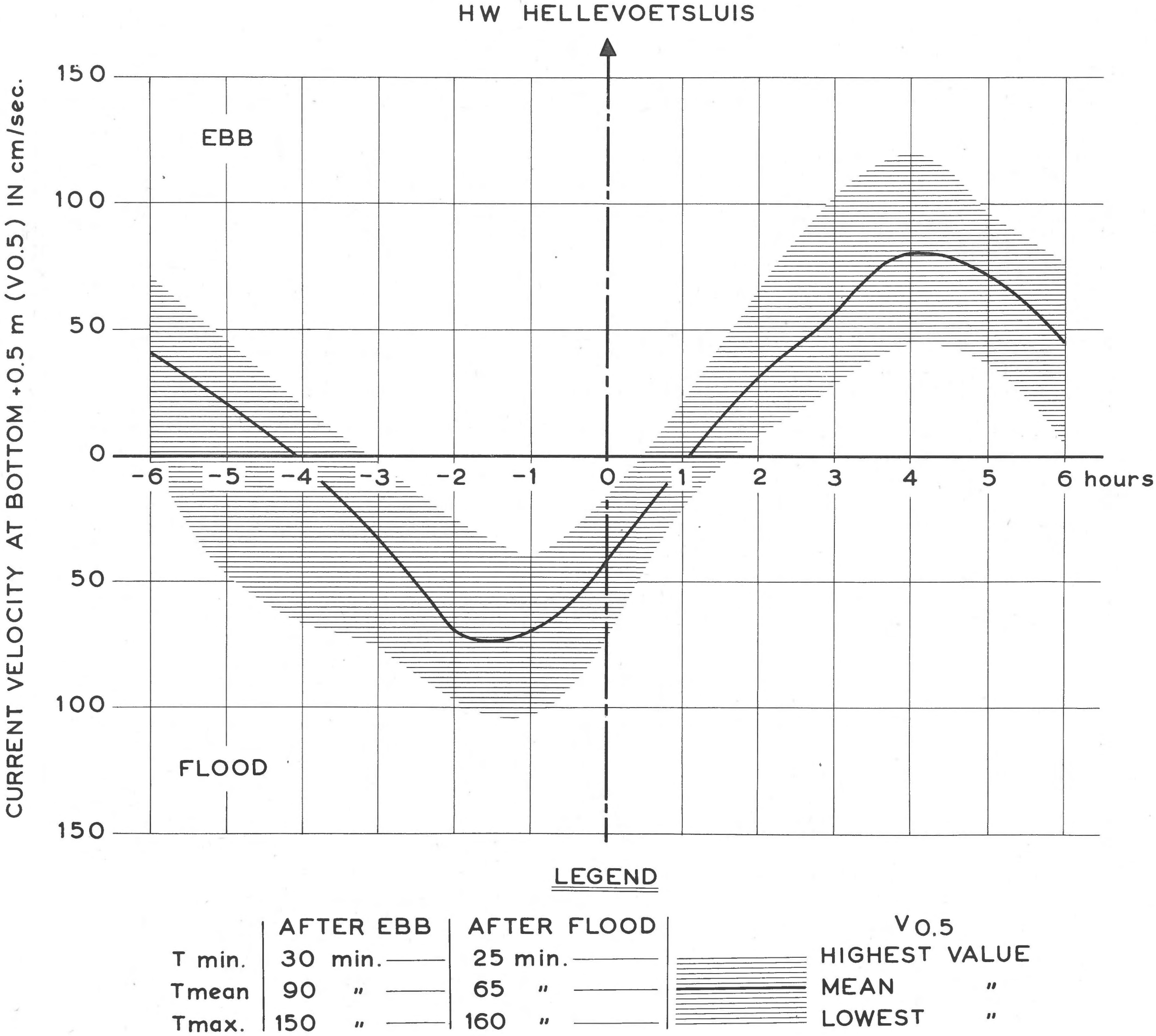


Fig. 13
Variation of mean and bottom + 0,5 m current velocities, measured in one location in the Haringvliet estuary.

continuous layer over distances of more than tenth of meters.

A possible explanation of the rapid change of litho-facies in vertical and lateral sense may be the variability of the strength of the bottom currents in place and time due to differences in HW and LW levels by spring and neaptide and/or wind influences on the tidal volumes and to shifts of the channel axis. To illustrate this variability the maximum and mean current velocity, taken at 0,5 m above the bottom ($V_{0,5}$) over the ebb and flood period, gathered from simultaneous measurements across one of the tidal inlets are given in fig. 12. Also the time that $V_{0,5}$ drops below 20 cm/sec. is included. It is thought that during this time sedimentation of silt and clay take place as evidenced by flume experiments of Einstein and Krone (1961). It was also found that $V_{0,5}$ was a reliable mean value of the current velocities in the lower quarter or third part of the vertical where the highest suspended sediment concentrations occur. It can be seen from fig. 12 that important variation in the mentioned parameters occur in lateral direction. The time variation of the mentioned parameters is illustrated in fig. 13. This figure is based on 36 current-velocity measurements over a full tidal cycle in one measurement point in the Haringvliet estuary in a period of one year. The measurements were taken at varying tidal amplitudes and river discharges. Similar figures were obtained from the tidal inlets.

It should be noted that due to these important and rapid variations of the hydraulic conditions near the bottom the author could not establish a relation between the described litho-facies and an exact, well defined hydraulic parameter. The main reason is the uncertainty whether incidental measured velocities near the bottom are indicative for the hydrodynamic conditions during the formation of the litho-facies.

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