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TIDAL DEPOSITS AND THEIR SEDIMENTARY STRUCTURES

(Seven examples from Western Europe)

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ABSTRACT

Seven examples of tidal sedimentation ranging between modern and Devonian age are illustrated and briefly discussed. They cover known (modern intertidal and subtidal) and mostly undetermined ancient tidal subenvironments, and have been taken from:

1. The estuarine reach of a tidal river, subtidal, Holocene, Barendrecht excavation, The Netherlands.
2. An estuarine channel, subtidal, Holocene, Haringvliet excavation, The Netherlands.
3. A Lower Pleistocene (Tiglian), possibly subtidal estuarine succession, Hattem (Veluwe), The Netherlands.
4. A dune-bearing estuarine sand-bank, intertidal, modern Western Scheldt, The Netherlands.
5. The Lower Cretaceous (Lower Greensand) Woburn sands ± 50 km NW of London, England, being probably deposited in an open marine tidal environment.
6. The Oligocene (Tongrian) Kerkom- and Neerrepen sands SE of Brussels, Belgium, representing an as yet uncertain type of tidal subenvironment.
7. An Upper Devonian tidal succession belonging to the transgressive complex (Cork beds) overlying the Old Red, W. of Cork, Eire.

The following features were considered to be diagnostic for these (and other?) tidal deposits (a) vectorial bimodality of the cross-stratification, (b) common joint occurrence at different proportions of largescale and smallscale structured units in super- of juxtaposition. (c) Usually poorly developed sequential regularity with occasional occurrence of fining-upward sequences. (d) Unidirectional cross-stratified sets displaying several kinds of features resulting from the intermittent and bidirectional character of the currents (discontinuity planes). (e) Fairly common occurrence of flaser- and/or lenticular bedding respectively consanguineous mud-sand interlaminations in smallscale-structured units. (f) Slight to intense bioturbation in several types of sandy and/or muddy units.

At the present state of knowledge a reliable determination of the tidal *sub*-environment (e.g. inshore, offshore, intertidal, subtidal) seems to be virtually impossible for ancient clastic deposits, except for a few cases. Establishment of detailed paleocurrent patterns may help in distinguishing open-sea tidal deposits from inshore ones.

INTRODUCTION

General

The past few decades sedimentologists have contributed considerably to the knowledge of recent tidal deposits and they have tried with variable success to demonstrate the tidal nature of a number of ancient successions in Western Europe (van Straaten, 1954a; Hülsemann, 1955; Gullentops, 1957; Niehoff, 1958; Allen and Narayan, 1964; Reading and Walker, 1966; Wunderlich, 1970; de Raaf, 1970; Kuijpers, 1970; de Vries Klein, 1970a; Kuijpers, 1971). During their own study of pre-Holocene deposits the present authors became convinced that there are sufficient criteria pointing to tidal deposition in general but experienced that it is at the present state of knowledge in most cases impossible to tell the type of tidal *sub-environment*. It is felt that this is principally due to the fact that in the studies of modern tidal environments attention was mainly focussed on the intertidal zone because of its better accessibility.

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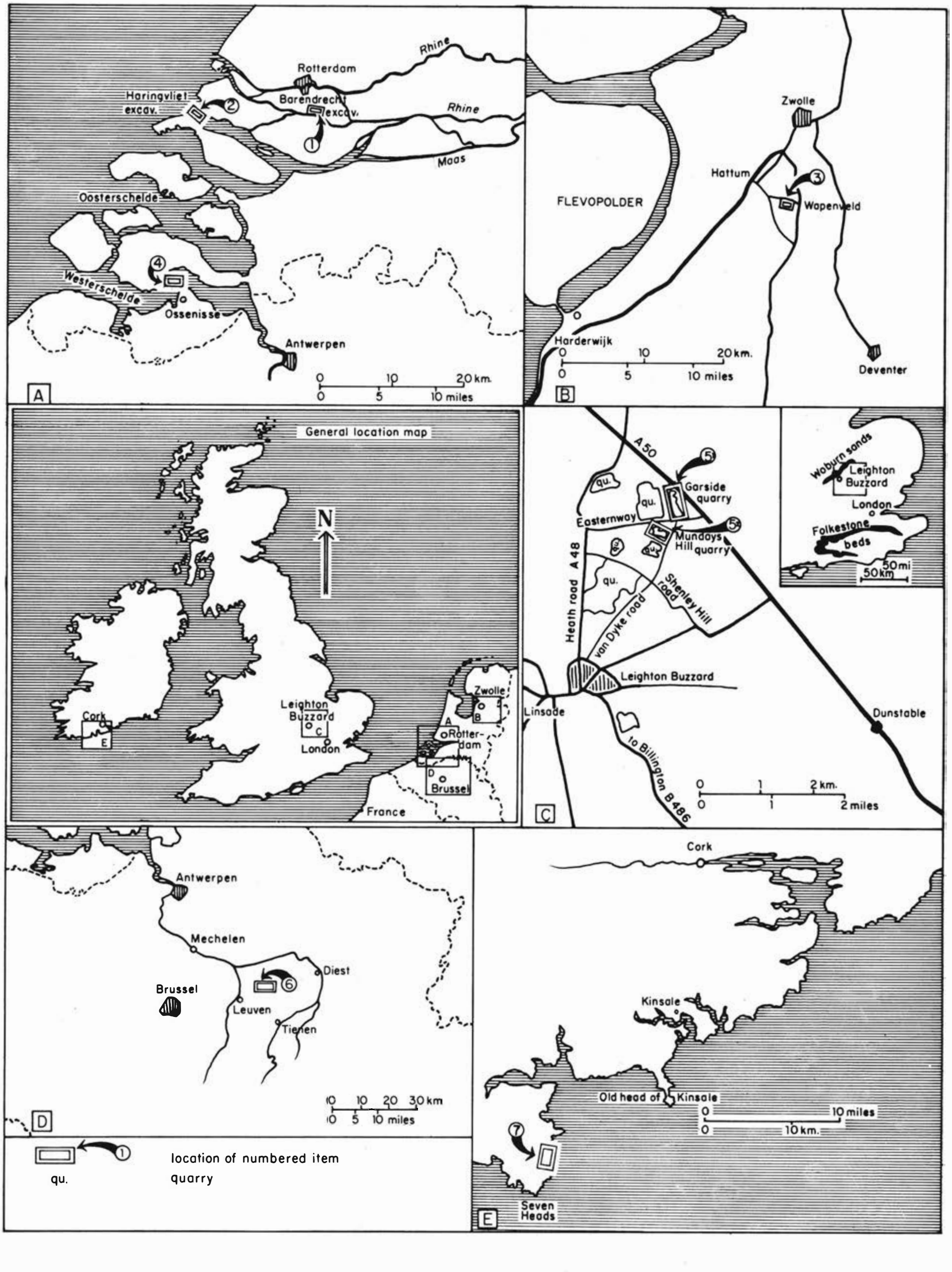
Rhine
Rotterdam
Haringvliet excav.
Barendrecht excav.
Rhine
Maas
Oosterschelde
Westerschelde
Ossenisse
Antwerpen
0 10 20 km.
0 5 10 miles
A
Zwolle
Hattum
FLEVOPOLDER
Wapenveld
Harderwijk
0 10 20 km.
0 5 10 miles
Deventer
B
General location map
N
Cork
E
Leighton Buzzard
C
London
Zwolle
B
A
Rotterdam
D
Brussel
France
A50
qu.
Garside quarry
qu.
Easternway
Mundays Hill quarry
Heath road A48
qu.
Shenley Hill road
van Dyke road
Leighton Buzzard
Linsade
to Billington B486
Dunstable
0 1 2 km.
0 1 2 miles
C
Woburn sands
Leighton Buzzard
London
Folkestone beds
50mi
50km
Antwerpen
Mechelen
Diest
Brussel
Leuven
Tienen
0 10 20 30 km
0 5 10 miles
D
location of numbered item
qu.
quarry
Cork
Kinsale
Old head of Kinsale
0 10 miles
0 10 km.
Seven Heads
E

In this respect reference can be made to the studies of Häntzschel, 1936; van Straaten, 1951, 1953, 1954b, 1964; Hülsemann, 1955; Reineck and his school (1958-1970, see bibliography); de Vries Klein, 1963, 1970b; Evans, 1965.

As to the studies in modern sub-tidal environments, these are largely dealing with morphological, geophysical, hydrographical and textural-compositional features (van Veen, 1936; Stride, 1963; Houbolt, 1968; James and Stanley, 1968; Terwindt, 1970a, 1970b) and do not provide much information about the sedimentary upbuilding. An exception forms Reineck's (1963) investigation of the southeastern bight of the North Sea (Deutsche Bucht), which provides a wealth of information on composition, texture and sedimentary structures, their association and distribution, not only for the intertidal but also for the subtidal zone. As regards The Netherlands, valuable insight is gained into inshore subtidal deposits from studies of the Haringvliet (Oomkens and Terwindt, 1960; Terwindt, 1971) and Barendrecht excavations (the present article).

Seven examples

In the course of their general research programme concerning sediments from the continental, transitional and marine environments the authors have come across several examples of tidal deposits, from which seven are selected here for a rather cursory treatment. These seven examples range in age between modern and Devonian, and in consolidation between loose and completely lithified. *They are briefly introduced in separate sections numbered 1-7 and dealt with in seven correspondingly numbered figures with extensive captions.* For location see map. The photographs are slightly retouched in order to enhance contrast.

1. BARENDRECHT EXCAVATION (fluvial subtidal)

In 1966, with the assistance of Messrs. van Beek and Koster (Utrecht) a large (± 380 x 80 m), roughly NW-SE trending excavation was studied on the northern embankment of the Oude Maas (Old Meuse), south of Rotterdam. The southern long edge of the excavation ran parallel to the present local river course at a few tens of metres distance. The vertical succession from a depth of 10 m below NAP[2)] upward showed a distinct fining-upward character, which deviates, however, distinctly from the normal type found more landinward in the fluvial deposits of the Dutch deltaic plain. Indeed a comparison with present day hydrographically equivalent sections of the nearby Lower Rhine (Terwidt et al., 1963) suggests that estuarine conditions (i.e. bidirectional water and sediment movement) may very well have existed in former days in the Old Meuse near Barendrecht. To what extent this tidal influence was active around 1200 A.D., the most probable period of deposition as determined by archeological finds, is unknown, but its effect is clearly reflected in the directional bimodality characterising the upper part of the Barendrecht section.

2. HARINGVLIET EXCAVATION (estuarine subtidal)

During construction of the closing dam in the Haringvliet estuary (for position see location map) a large excavation reaching to a depth of about 15 m below NAP permitted the study of an estuarine succession in great detail. Oomkens and Terwindt (1960) described several lithologically and structurally different units and related them to conditions of flow. Student reports on behalf of the Sedimentological Department Utrecht University were made by Verdenius (1963) and Lier (1967). Terwindt (1971) studied the estuarine deposits in the SW Netherlands on a regional scale, using borings and current data from the Haringvliet and nearby tidal inlets so as to gain insight into the relationship between lithology, depth and, where possible, hydrographic characteristics. This author distinguished three estuarine lithofacies characterized by:

I. Largescale cross-stratification of trough, tabular or fill character.
II. Flaser bedding, smallscale cross-laminated and some horizontally laminated sand.
III. Lenticular bedding, sand-clay alternations.

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2) NAP = Dutch ordnance level = approximate present mean sea level.

The division adopted by us is twofold: A large-scale-structured group (henceforth called **LS-group**) corresponding to Terwindt's facies I and a smallscale-structured, generally heterolithic, group (henceforth called **SS-group**) embracing both lithofacies II and III.

The sedimentary succession in the Haringvliet excavation showed marked lateral changes of facies in the wall running parallel to the long axis of the pit. In fact the LS-lithofacies group was much stronger developed toward the northeastern and southwestern ends of the pit than in its centre. This should be attributed to the influence exerted by nearby ebb and flood channels, which for many tens of years (Oomkens and Terwindt) appeared to have been situated just north and south of a broad submerged shoal on which the excavation was located. Consequently the great development of heterolithic sediments found in the centre of the pit is presumably related to the relatively more current-protected environment of the mentioned shoal. Apart from the structures dealt with in our example (fig. 2) other structures are encountered, which, however, have no diagnostical value (e.g. the presence of fill structures).

Terwindt (1971) arrived at the important conclusion that no sequential order on a larger scale (embracing tens of metres) exists in the tidal deposits of the inlets south of the Haringvliet. Regarding the Haringvliet estuary, however, this author states that his facies III shows a gradual increase and facies II a decrease with decreasing depth, the frequency of facies I remaining the same at all depths.

3. HATTEM MUNICIPAL SAND PIT
(possibly estuarine subtidal)

In the Noord-Veluwe region (The Netherlands) bordered to the east by the valley of the river IJssel Pleistocene deposits are exposed in several large sand pits. The strata are dipping eastward, generally at 30-50°. The succession is, however, split up into several tectonic imbrications, which are thrust to the west and attain several tens to a hundred metres in thickness. The thrustplanes dip accordingly toward the IJssel valley. Lateral push by an ice lobe, which moved up the IJssel valley from the North (de Jong, 1952; 1955; 1967) during the Riss glaciation, is presumably responsable for the structure in question. Similar, but east-thrusted imbricate sheets are found to the east of the present IJssel valley but have not yet been investigated sedimentologically.

The deposits found in these imbricated units range in age from Lower Pleistocene to Middle Pleistocene (inclusive) according to the stratigraphical subdivision of van der Heide and Zagwijn (1967).

In the quarry presently investigated the entire succession is outcropping and comprises the Tiglian-Harderwijk-Enschede and Urk (I and II) Formations. Except for the Tiglian Formation from which the present tidal example is taken all Formations are clearly of fluviatile origin. The tidal Tiglian Formation is characterized by a recurrent alternation of LS- and SS-lithofacies groups. In both groups the tidal action manifests itself by a vectorial bimodality, in which the landward direction (eastward) is the subordinate one. The mud content in the succession is strikingly high, which is in sharp contrast with the overlying fluviatile beds. The outcrop in question throws a new light upon the position of the shoreline in Tiglian time. Sedimentological investigations of the municipal quarry were carried out in 1969-1970 with the assistance of Messrs. Beekman and van der Bilt (Utrecht). Stratigraphic subdivisions were kindly provided by Mr. J.G. Zandstra, Netherlands Geological Survey, Haarlem. Investigations on a more regional scale are still in progress (1971).

4. OSSENISSE SHOAL, WESTERN SCHELDT,
(estuarine intertidal)

In the summer of 1969 an investigation programme of one month duration was carried out on the shoals (sand banks) of Ossenisse (south of Hansweert) by the Department of Sedimentology, University of Utrecht, with the assistance of Rijkswaterstaat and the Royal Dutch Navy. The investigations comprised the recording of changes in surface topography (dune configuration, etc.), the study of internal structures sampled by lacker peels, the rate of sand movement, etc. in relation to the neaptide-springtide cycle. These data were collected at nine different places on the shoal. Simultaneously continuous current measurements were made from two platforms during the inundation periods of the shoal. The results are still being worked out and will be published by Terwindt and Boersma. A preliminary note was issued by Boersma (1969).

Dune morphology and behaviour was found to be highly variable from place to place and often unpredictable from the external shape.

On completing the present article an important contribution by de Vries Klein (1970b) dealing with, in many respects, comparable sediments came to hand. As regards the thirteen sedimentary features observed by this author on sand bars (his table 8, p. 1124) more than half cannot be considered in our opinion as criteria of intertidal sand bars, as they are equally characteristic of subtidal deposits. Amongst the real intertidal criteria left (e.g. late-stage sheet run-off and water-level reduction phenomena) fossil preservation may occur, as Wunderlich (1966, 1970) admirably demonstrated, but, as far as we know is exceedingly rare.

5. LOWER CRETACEOUS WOBURN SANDS, LOWER GREENSAND (Open-sea tidal)

The Lower Greensand, which contains first rank tidal deposits, is very well exposed in two regions in southern England, respectively south and north of London (c.f. inset to location map). In the southern belt of outcrops the Lower Greensand is amongst others represented by the Folkestone Beds. In the northern belt beds of equivalent age occur in the neighbourhood of the town of Leighton Buzzard and are named "Woburn sands". Especially in the latter region a dense network of quarries exists, which seems to offer a good opportunity for a three-dimensional reconstruction of the environment of deposition. As argued in the caption of Fig. 5 a partly very LS- and a predominantly SS- (heterolithic) facies association can be distinguished at Leighton Buzzard.

In the first-mentioned association giant foresetting (height up to 5 m) is of common occurrence. Upslope and downslope transport of sediment took place along these giant slopes as manifested amongst others by largescale foresetting of moderate height, ascending or descending the depositional slopes and by observed downwards or upwards wedging out of giant foreset bundles. The investigations so far suggest that one is dealing here with an ancient tidal open-sea environment (with spiral flow effects, etc.) comparable to the present North Sea as found by Houbolt (1968) and Terwindt (1970b).

One of the authors (Boersma) has started an investigation in these deposits at a more regional scale to provide additional evidence in support of last-mentioned assumption.

As regards the Lower Greensand (Folkestone beds) of the southern belt as far as we know only Allen and Narayan (1964) reported on some structural aspects.

6. OLIGOCENE AND LOWER PLIOCENE OF CENTRAL BELGIUM, LEUVEN-TIENEN AREA (tidal of different types)

Here many quarries, some of them very large but unfortunately rather at a distance from each other, enable us to study several types of shallow-marine sands. Of these, the Kerkom, Neerrepen and Diestian sands were studied in some detail for their sedimentary structural and sequential characteristics. This study was carried out in the summer of 1970 with the assistance of a number of students from Utrecht. Necessarily the study had a limited scope. Comprehensive investigations are known from Gullentops (1963) and other Belgian scientists (e.g. Gulinck, 1963), who mainly studied granulometry, composition and to a lesser degree structures.

In the often very coarse (up to crs. sd.) Kerkom sands directional bimodality is ubiquitous in all investigated quarries. This precludes a fluviatile genesis. Moreover, true fluviatile fining-upward cycles were not found. The balance between the opposing currents was variable and gave sometimes rise to a strong predominance of one direction. As far as the, as yet, incomplete current measurements permit a statement, it would appear that northerly and southerly directions prevail, indicative of an inshore environment. However, also easterly directions occur though at a subordinate rate and only in a few quarries. As to the implication of the latter data (longshore or strongly curving inlet configuration) it is hoped that future research will clarify the matter.

In the overwhelmingly horizontally laminated, fine-grained Neerrepen sands it came rather as a surprise that tidal currents, though weak, were also locally active, as is manifested by bimodality in predominantly small-scaled structures.

As regards the Diestian sands (Lower Pliocene) an open-sea tidal origin was already brought to the fore by Gullentops (1957).

Further research work regarding the Tertiary formations in Belgium is planned.

7. UPPER DEVONIAN CORK BEDS OF SOUTHERN IRELAND
(tidal of different types)

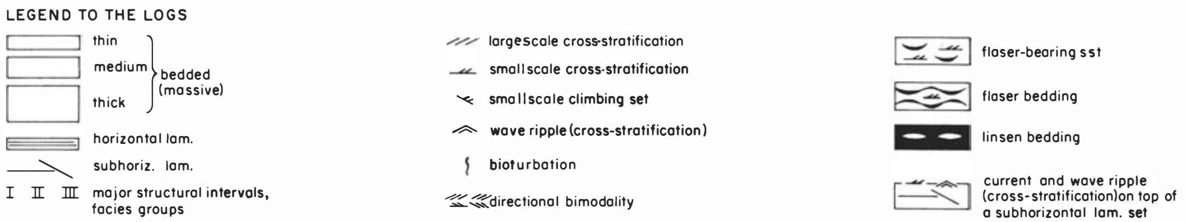
Along the south coast of Ireland, W. of Cork, an Upper Devonian transgressive series overlying the Old Red forms extensive outcrops. In this series transitional in facies between continental and marine, investigations are being carried out (1969-1971) the results of which will be laid down in PhD theses by van Gelder, Kuijpers, and Leflef (see de Raaf, 1970). In the investigations the emphasis is laid on sedimentary structural and sequential characteristics in vertical and lateral distribution. These studies lean heavily upon the work by Naylor (1964, 1969, Naylor et al., 1969), who unraveled the major tectonic, stratigraphic and gross facies features of the area.

The example of tidal sedimentation given in the present publication has been taken from the topmost part of the exposed Devonian rocks just north of the Seven Heads Bay syncline, east coast of Seven Heads peninsula. Kuijpers (1971) described the succession exposed to the south of this syncline.

The tidal deposits discussed in fig. 7 are made up by a LS- and a heterolithic SS-facies organized in a more or less distinct fining-upward sequence. By far the major part (some ten metres) of the sequence here comprises LS-facies. The SS-facies embraces not more than a few metres thickness.

Further down in the succession the LS-facies and the SS-facies are getting more in balance with each other and concomitantly the fining upward character is clearer developed. This part of the succession amounts to a thickness of about 50 m. Still further down in the stratigraphical column (northward along the coast) the SS-facies becomes predominant, and the fining-upward tendency gradually makes place for an irregular alternation of LS- and SS-facies. The whole succession described above probably belongs to Naylor's Hole-open Formation as distinguished by him on the Old Head of Kinsale-peninsula to the east of the Seven Heads. Very recently de Vries Klein (1970) described Precambrian tide-dominated deposits, which resemble extraordinarily those of the Devonian section with largescale herring-bone structures described in this article. His facies I seems to correspond fairly well to our grosso modo LS-facies association and his facies II to our SS-facies but for the ubiquitous mudcracks he mentioned, which seem to be absent at Seven Heads Bay. We did not find clear evidence for late-stage sheet-runoff neither for a high tidal-flat nature of our SS-intervals and are in doubt whether the organization into a fining-upward sequence has a bathymetric significance and points to a regression in the Irish example. The vertical changing over from a LS-interval into a SS one corresponding to a decrease of energy may also develop under subtidal conditions.

DESCRIPTIONAL PART



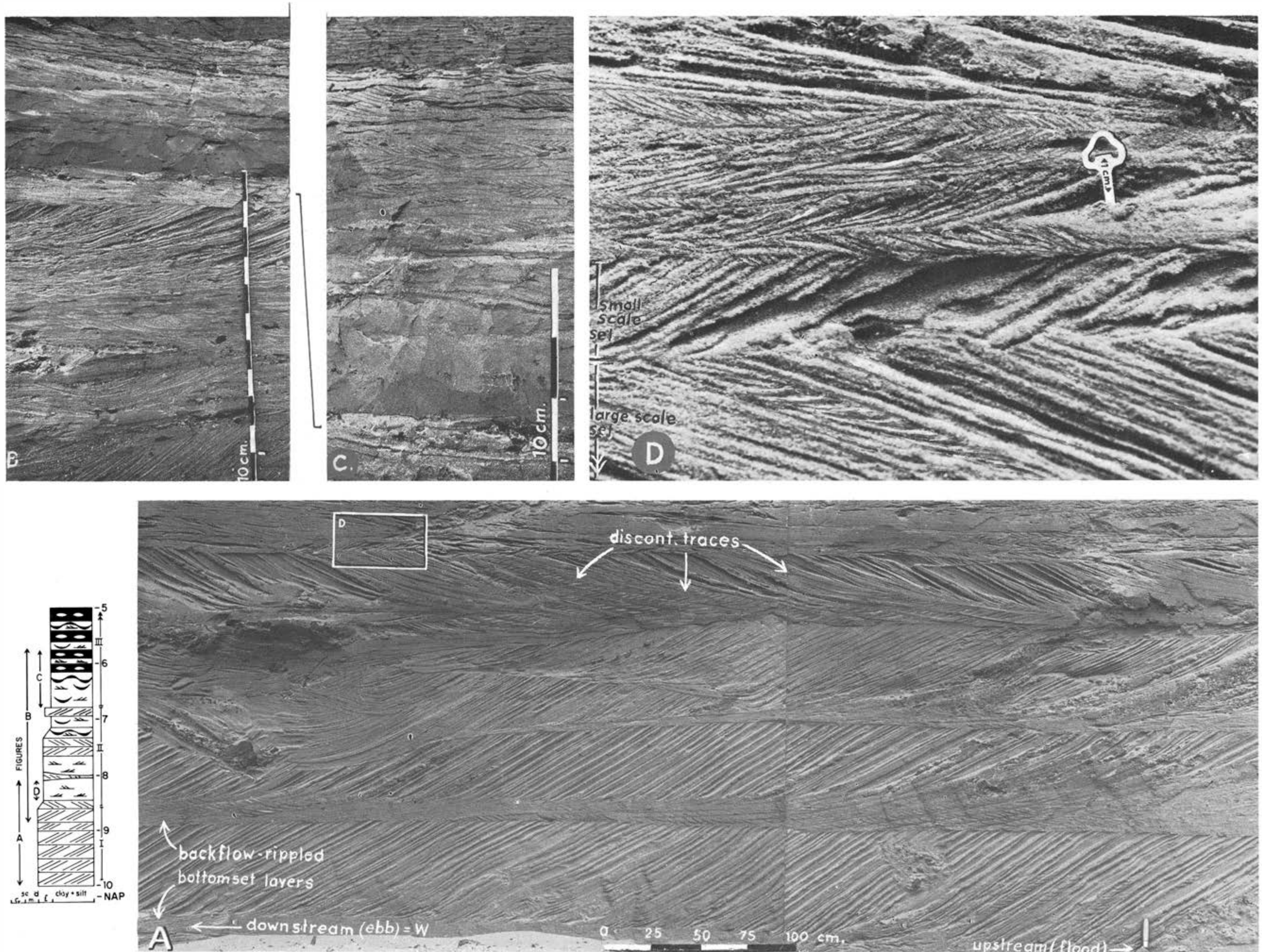

B
10 cm.
C.
10 cm.
small scale set
large scale set
1 cm
D
discont. traces
backflow-rippled bottomset layers
A
down stream (ebb) = W
0 25 50 75 100 cm.
upstream (flood)
FIGURES
NAP
clay + silt

Fig. 1A-D

Examples of transitional (inner estuarine – fluvialtidal) deposits. Barendrecht excavation. The succession is fining-upward (see log), three intervals (I-III) can be delineated on the basis of gross grainsize and scale, type and directional characteristics of the sedimentary structures.

The lower interval, I (see fig. A), consists of long, planar sets (up the 20 m set length) showing largescale unimodal seaward (W) – directed cross-stratification. A thick bottomset layer underlies the foreset layer of each set. Close examination shows that the bottomset layers largely consist of smallscale backflow-ripple type. Here and there these countercurrent ripple structures appear to climb high up on the foresets (see lowermost largescale set fig. A and fig. D). Clay pebbles may replace the medium-coarse sand of the mega-foresets. The filling-up of erosional holes results in local deviations from the unidirectional pattern and concentration of clay fragments.

The middle interval, II (fig. D and upper part of A), is characterized by an association of large- and smallscale sets with local but nonconsequent directional bimodality. Herringbone structures, where found, are due to superposition of oppositely-directed sets of a similar or different scale. Average grainsize here is finer than in interval I and to a higher extent coupled with mud admixture, especially in the smallscale cross-stratified units.

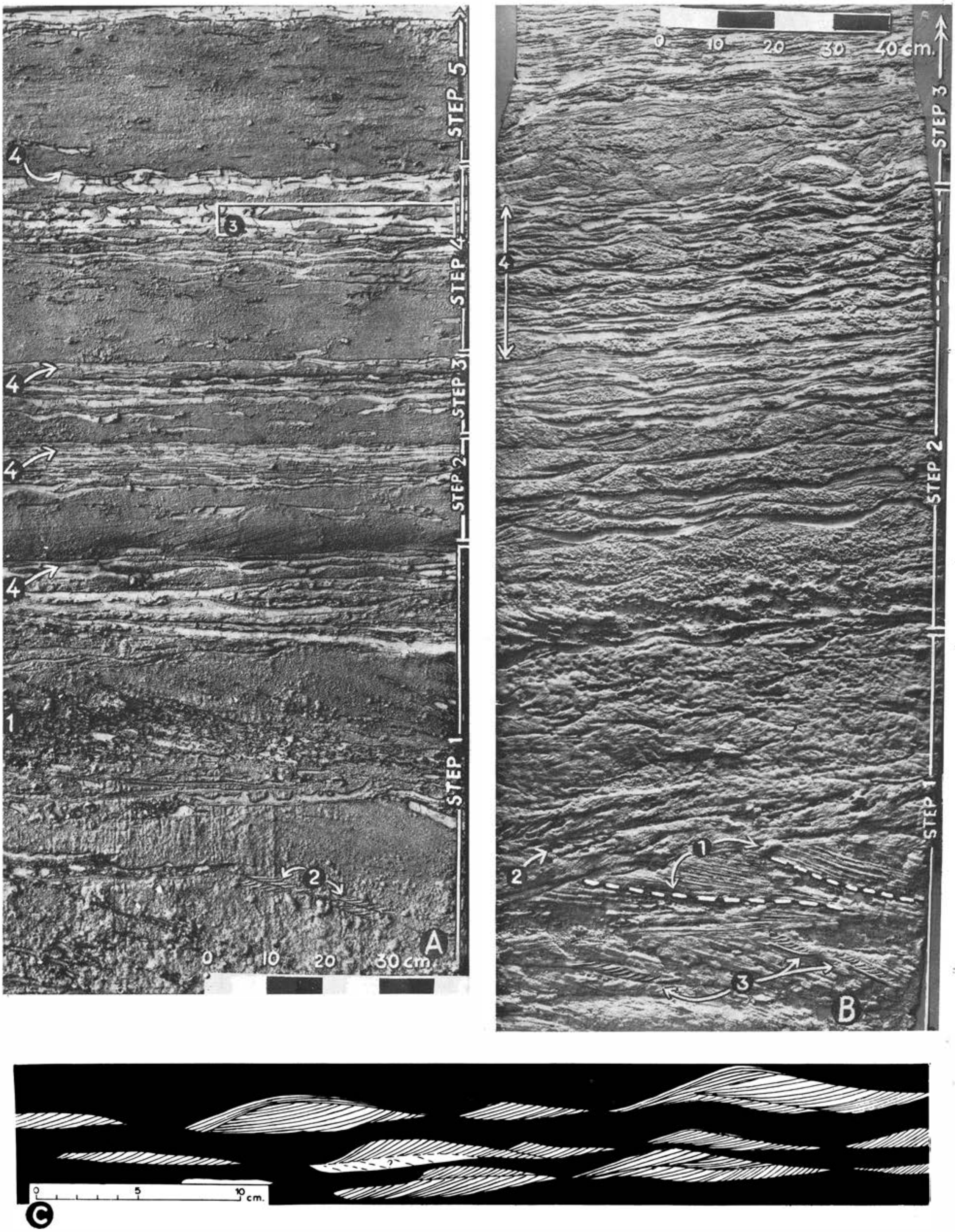
Noteworthy is the discontinuous nature of foresetting in the lowermost landward-directed largescale set (see fig. A); starting from "reactivation" planes (C o l l i n s o n, 1970) only small bundles of foresets are formed successively. Smallscale sets found in this interval are of the planar type with moderate to long setlengths (up to 40 cm).

The upper SS-interval, III (fig. B and C), mainly consists of alternating units of flaser and linsen types (nomenclature R e i n e c k and W u n d e r l i c h, 1968). However, a predominance of flaser structure (irregular mud drapes interspersed in smallscale cross-stratified sands) was observed in the lower portion, which passes upward into linsen structure (sand lenticles in mud).

The sedimentary structural upbuilding of the lower interval bears strong resemblance to that of upper-pointbar deposits from purely fluvial reaches (cf B o e r s m a, 1968). Apparently the tidal flood current if active at all in Barendrecht at the time of upbuilding were of insufficient strength and duration to produce structural features important enough to escape subsequent ebb erosion. The situation was quite different in the middle, transitional interval. Here, at average lower intensities of flow (note size of structures, smaller grainsizes), the effects of flood currents are clearly discernable and almost as important as those of the seawards running currents.

The upper SS, interval was apparently deposited under still lower intensities of flow, becoming minimal towards the top as is witnessed by the upward-increasing mud content. Although directional characteristics were here rather difficult to quantify, the observations suggested that a rigorous directional bimodality governs this part of the section.

The metre scale alongside the log refers to depth below NAP. The measuring tape in fig. B is divided in tens of centimetres; the key in fig. D bears a 1 cm reference mark.


STEP 5
STEP 4
STEP 3
STEP 2
STEP 1
0 10 20 30 cm.
A
0 10 20 30 40 cm.
B
0 5 10 cm.
C

HARINGVLIET

Fig. 2A, B.

Photographs of lacker peels examplifying the estuarine sediments exposed in the Haringvliet excavation. Peels made at a depth of 12-15 m below NAP. Two lithofacies groups are distinguished:

The LS-lithofacies group is dominated by largescale cross-stratified sets of the planar but more usually of the trough type. Diagnostic (tidal) features of these sets are:

a. Directional bimodality between individual sets or co-sets.
b. Prevalence of short setlengths either due to erosional truncation or to "dying" out of foresetting by gradual decrease of the foreset-angle.
c. Traces or stretches betraying discontinuities, which interrupt but do not destroy the unidirectional foresetting in one set (see B at 1).
d. High mud content either in the form of mud drapes or pebbles and flakes (see A at 1, B at 2).
e. High concentrations (also pockets) of shell fragments.
f. Smallscale oppositely-directed ripple structures may be interspersed between and climb high up the slope of largescale foresets, but are of a different (non-interfingering) character than those encountered in fluvial deposits (see A at 2, B at 3).

The SS-lithofacies group is characterized by an interlamination of mud and sand at a variable rate giving rise to its heterolithic nature. Between the hardly mud-flasered sand and the hardly sand-lineated muds being the two end members of the series, many transitional types occur (see classification of flaser and linsen bedding of Reineck and Wunderlich, 1968). The interlaminations may have a more or less straight, streaky character, but lenticularity and wavy bedding strongly prevails. Directional bimodality in this lithofacies group is a common feature especially between differently-structured (minor) intervals. Within one interval, however, a unimodality may exist (see B4); in case of bimodality its degree may be quite variable and changing laterally. As such, unimodal and bimodal intervals may be encountered in any order of superposition. The type of modality of a heterolithic unit may be identical to or contrasting with that of the adjacent largescale-structured unit.

Wave-generated cross-stratification was not observed in the present examples of subtidal deposition. However its recognition is often very difficult, since the reversing tidal currents responsible for the ripple structures in some heterolithic intervals are of so short a periodical character as to simulate (wave-) orbital oscillations. Smallscale sets with pseudo-wave features found in A at 3, are enlarged in fig. C. Burrows may occur.

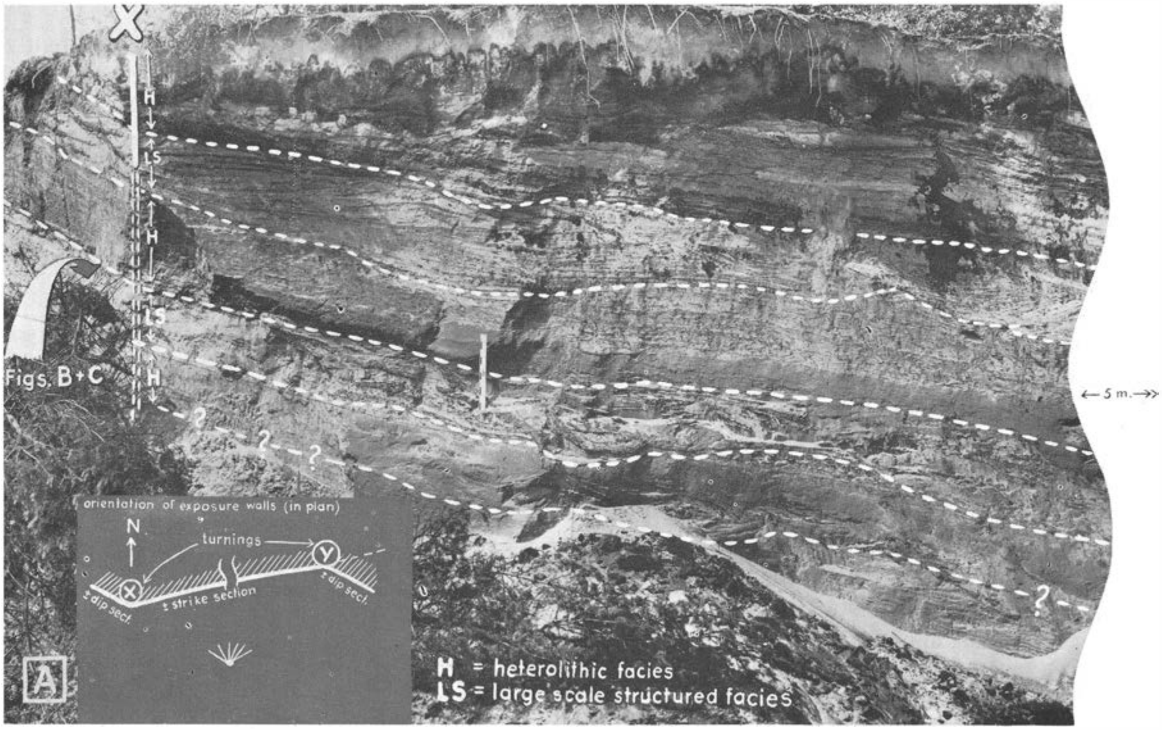
Presence or absence of sequential order

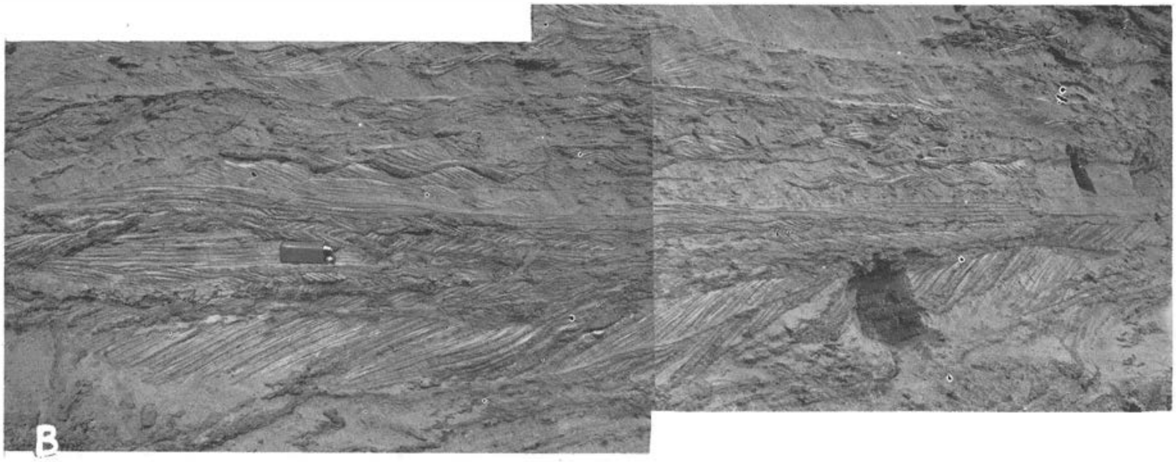
At a scale covering only a few metres of thickness or less a fining-upward tendency was observed in several instances.

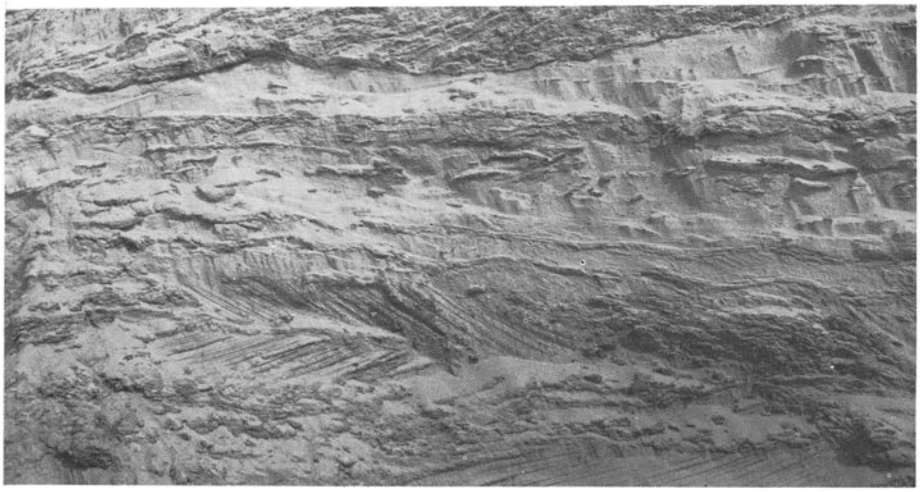
This fining-upward shows up in the following ways:

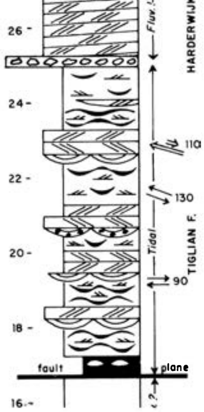
a. A decrease in number and thickness of the individual sets participating in the successive LS-units.
b. A decrease of clay (pebble) admixture and shell fragments in the LS-cross-stratified units.
c. An upward increase in the clay content in the heterolithic units.

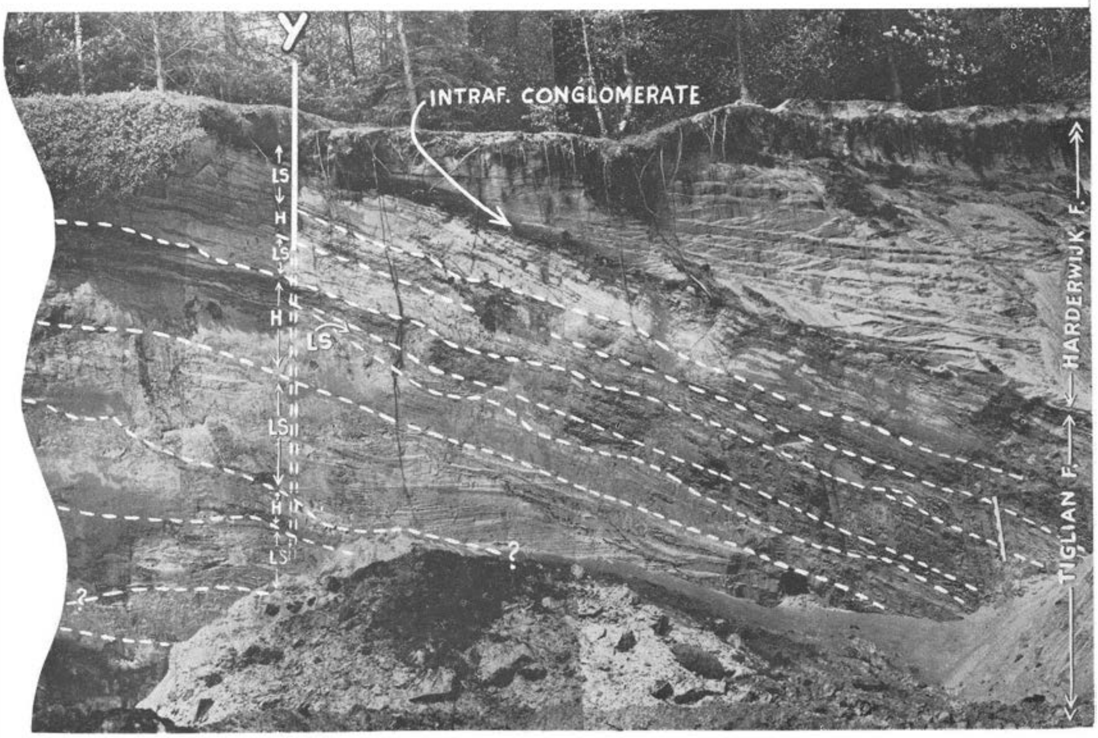
Often the fining-upward takes place in a more (B) or less (A) distinct stepwise manner. The changing over from a heterolithic unit to its overlying largescale cross-stratified unit, or from a clay-rich type of heterolithicum to a clay-poor one is generally abrupt (see A at 4) as is demonstrated by an erosive, straight or scouring, lower boundary. The jump in grainsize may be conspicuous, but more often is not.


X
H
LS
H
LS
H
Figs. B+C
?
orientation of exposure walls (in plan)
N
turnings
± dip sect.
± strike section
± dip sect.
A
H = heterolithic facies
LS = large scale structured facies
←5 m.→


B




m.
26
24
22
20
18
16
fault
plane
Fluv.
Tidal
110
130
90
HARDERWIJK F.
TIGLIAN F.



HATTEM

Fig. 3A-C.

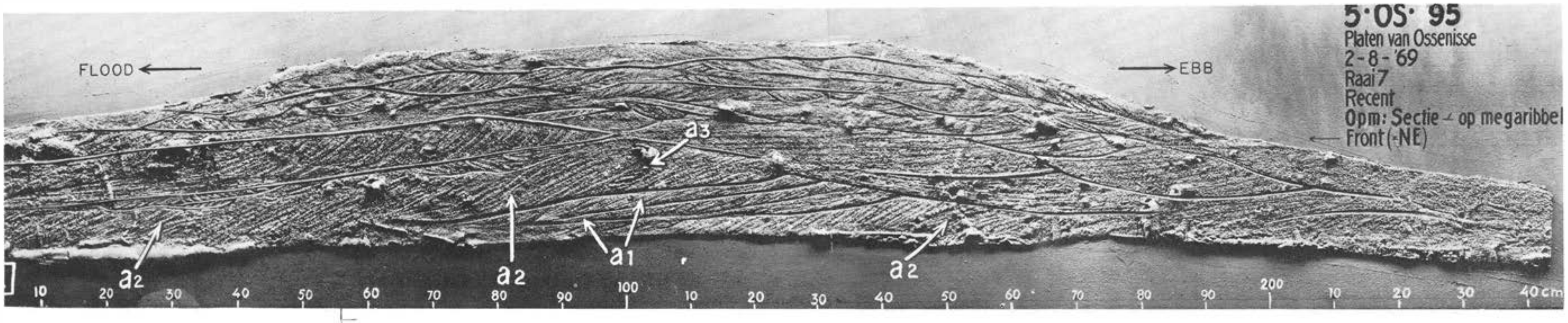
General view (A) and detailed pictures (B, C) of lower Pleistocene ("Tiglian") tidal deposits lying at the base of an essentially fluviatile Pleistocene succession (see log). The latter's pure white sands are organised in tabular, largescale sets of cross-stratification. These sets are inclined with respect to the conglomeratic boundary between the tidal and fluviatile formations. Note the exposed walls change orientation with respect to tectonic as well as sedimentary directions; turnings x and y (see inset of A). The tidal deposits (thickness ± 8.50 m) are composed of the same two types of lithofacies groups as distinguished in the Haringvliet (item 2) and Lower Greensand (item 5): a LS-group and a heterolithic SS-group. The parts in the succession taken up by these groups are delineated in photograph A. The group seems to occur in couples (bipartite cycles) each starting off with the erosively-based largescale group.

The LS-groups are dominated by trough and semi-tabular cross-stratified sets mostly of short length at least in part generated by dune migration. Clay is a major constituent of the sets and occurs either as clay-flakes and -pebbles or as drapes on the foresets. In addition, minor beds showing SS- sand-clay interlaminations (heterolithicum) may separate the large sets.

in the lowermost (± 17.20-18 m) and the uppermost (± 23.30-25 m) intervals where semitabular largescale sets of cross-stratification are intercalated (see photographs B and C taken from the lowermost interval).

Directional bimodality is manifest throughout the present Tiglian tidal succession. Westward directions prevail over eastward directions particularly in the LS-intervals. This westward direction tallies well with the general direction found in the overlying fluviatile formations of the area and probably represents the seaward direction. This defective bimodality strongly points to a fluviatile influence in the tidal environment. In several aspects there is a strong resemblance to estuarine deposits found in the northern, channel-fill, part of the Haringvliet excavation (no general view presented here). For instance in both cases we see in vertical sections a recurrence of laterally extensive channelling levels with festoon-like lower boundary. It seems therefore likely that the Tiglian deposits are laid down in an inlet of the sea through which there was also considerable seaward outflow. Whether this outflow was due to a strong fluviatile influence or to ebb-channel character in an estuary or to both could not be ascertained at this stage of investigation. The Hattem deposits have characteristics in common with both the Haringvliet and the Barendrecht sediments but seem to be more tide-dominated and seaward deposited than the latter.

Scale: Ruler in A measures 1 metre; in fig. C for scale see lighter.


5·OS· 95
Platen van Ossenisse
2-8-'69
Raai 7
Recent
Opm: Sectie ⊥ op megaribbel
Front (-NE)
FLOOD
EBB
a1
a2
a3
10 20 30 40 50 60 70 80 90 100 10 20 30 40 50 60 70 80 90 200 10 20 30 40 cm

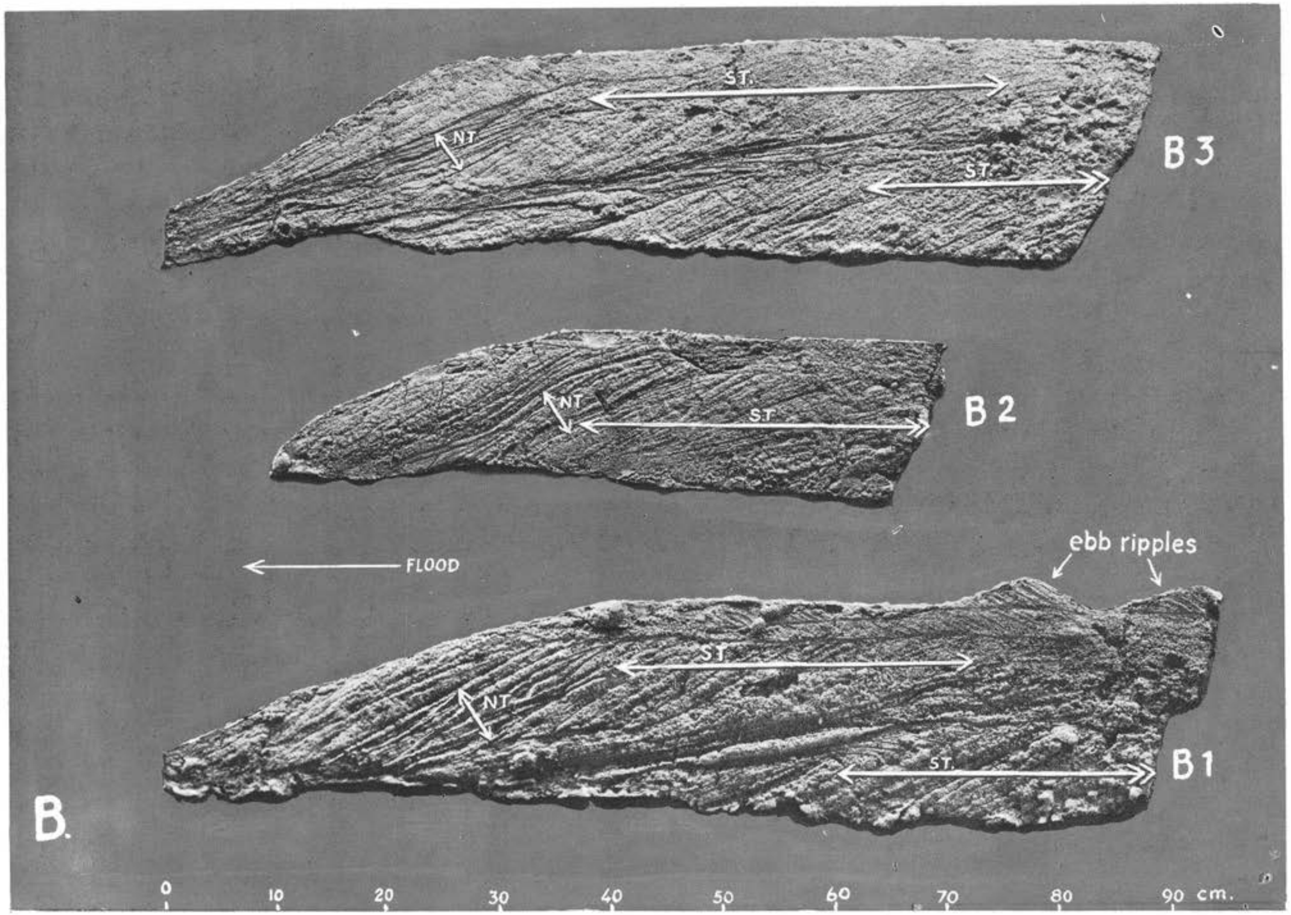

B.
B 3
B 2
B 1
ST.
NT.
FLOOD
ebb ripples
0 10 20 30 40 50 60 70 80 90 cm.

Fig. 4A, B

Examples of the internal structure of tidal dunes found on top of an estuarine inter-channel bar largely emergent during ebb (Ossenisse shoals, Western Scheldt, The Netherlands).

Upper boundaries of demonstrated lacker peels coincide with local relief, boundaries are arbitrarily set by limitations of the peeling technique. Fig. A shows a more or less symmetrical dune containing two structural intervals: A lower, essentially LS-cross-stratified interval and an upper SS one. The latter covers the dune.

Except for a few smallscale cross-stratified sets intercalated between two largescale sets in the middle left of the figure the lower structural interval is directionally unimodal (flood) whereas the upper interval is strongly bimodal. A most remarkable feature of the LS-cross-stratified interval is that the sets have inclined boundaries either downdipping (lefthand side of figure) or updipping (righthand side) in the direction of cross-stratification. These inclined boundaries most likely represent dune stoss-side type erosion planes generated by the ebb (lefthand side) and the flood (righthand side) currents. Thus during ebb the front of the leftward pointing flood ripple is erosively attacked and modified into a more gently inclined surface, over which during the successive flood tide the dune builds out again by means of largescale cross-stratification. Ebb erosive power may be so high as to reduce the thickness of the largescale cross-stratified (flood) sets to those, normal for structures from the smallscale domain (cf. a1). In other instances, however, the ebb apparently fails to produce any other effect than a kind of break in the otherwise continuous largescale foresetting. This feature shows up by a very slight trace of erosional unconformity and/or a change in the foreset angle (cf. a2). Sometimes at the trace of unconformity a single set of reversely-directed smallscale cross-stratification is found (cf. a3).

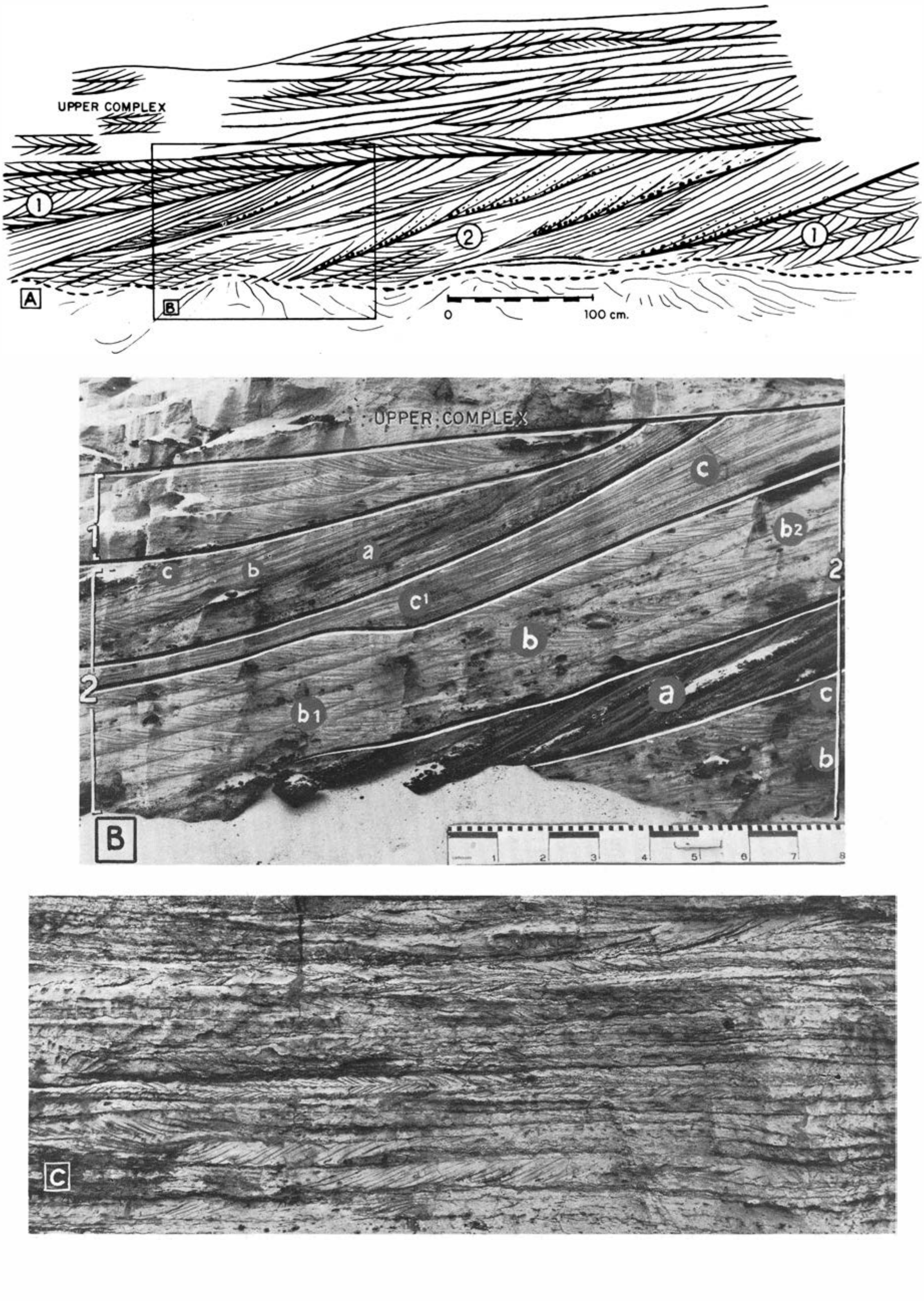
The structural bi-partite upbuilding of the dune suggests that the latter underwent two stages of deposition, different in many respects. The upper interval was laid down by alternating ebb and flood currents of about equal, though relatively small strength. By counting the superimposed "generations" of oppositely directed sets one may conclude that a minimum of four ebb-flood semidiurnal cycles were responsible for the formation of this interval.

During deposition of the underlying LS-interval the dune was apparently subject to much higher energy conditions whereby the flood currents outweighed those of ebb in depositional effect. It was obviously during flood that the dune was subject to movement. The subsequent ebb at most scalped the flood dune's top, possibly leading to some modification (reversal?) of its external asymmetry.

The above interpretations are in good accordance with the visual recording of events, which took place at the present locality during the period preceding and following the sampling. It was learnt then that the dunes were "active" only during a few days around spring-tide, while they were virtually immobile but for their covering smallscale ripples, for the larger period in the middle of which lies the neap-tide. In fact the lacker peel was processed some three days after optimal spring-tide (range nr. 7; August 2, 1969). By comparing this lapse of time with the minimum "age" of four times twelve hours (two days) deduced for the upper structural interval one may conclude that the dunes halted within one day after the given spring-tide.

Figures B1-3 represent vertical sections through one and the same dune front at a few metres from each other made just after the neap-tide period (July 27; spring-tide, July 30; location, observation platform North). From visual recording it is known that the dunes had been practically immobile for several preceding days and just started to move forward at very low speeds, which were slightly different for adjoining stretches of the front.

Hesitating lee-side accretion during the neap-tide stage of the dune is represented in the lacker peels by a bundle of wavering foresets (cf. NT). Newly set-in movement makes itself visible in the form of a more rigidly cross-stratified stretch occurring at the extreme lefthand end of the peels. An extrapolation of these observations makes it plausible that the long, regularly cross-stratified stretches (cf. ST) of the sets further to the right were generated in preceding spring-tide periods.


UPPER COMPLEX
1
2
1
A
B
0
100 cm.
UPPER COMPLEX
c
1
c
b
a
c1
b2
2
b
2
b1
a
c
b
B
C

LEIGHTON BUZZARD – WOBURN AREA

Fig. 5A-C.

Two examples are given of tidal-sea deposits belonging to the Lower Greensand (Woburn beds) of southern Engeland. The illustrations (A-C) only concern parts of two of the many quarries of the area. The Woburn beds display here two lithofacies groups:

I. LS-lithofacies group.

II. Predominantly heterolithic, SS-lithofacies group.

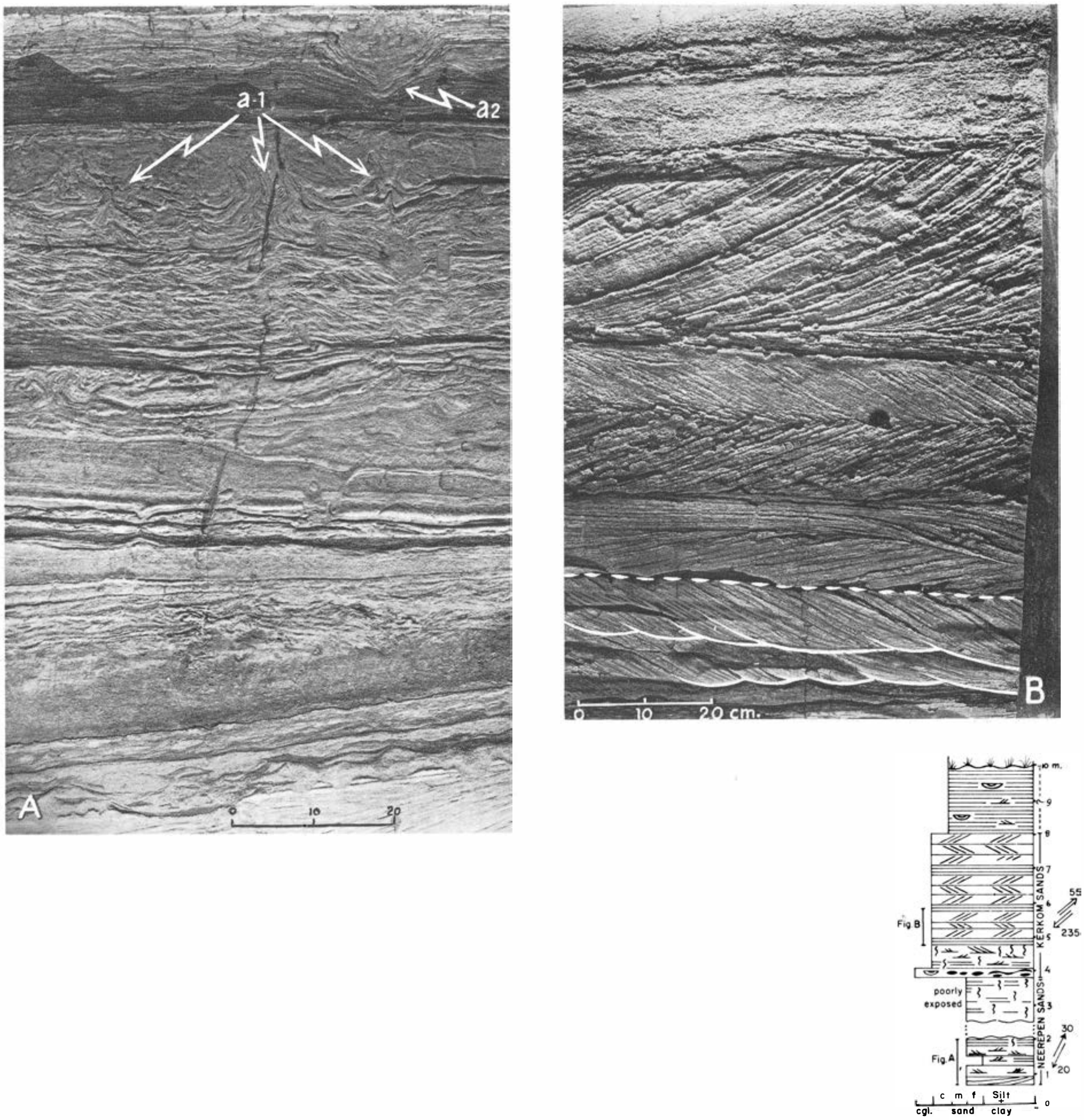
Within each group several subfacies can be distinguished. The examples dealt with below represent but a random selection from a host of tidal phenomena.

I. Fig. A (Garside's quarry, Heath and Reach) shows an upper complex consisting of bimodal planar, largescale cross-stratified sets. It rests by means of an horizontal boundary plane on a complex, which as a whole shows cross-bedding at an even larger scale. Nearer inspection revealed that the latter complex is of a very intricate structure, in which two types of major structural units can be distinguished:
   1. Wedge-shaped bodies (see fig. A extreme right and left of drawing) entirely consisting of largescale tabular sets of cross-stratification, which show directional bimodality.
   2. A large body characterized by a superposition of metre-scale foresetbundles (see central part of figure in between the bodies (1)). The structural differentiation occurring within each foreset bundle belonging to (2) is remarkable, because close examination shows a subdivision of the bundle in three discrete intervals, a, b, and c (see fig. 3) marked by:
      a. Very largescale foresetting in coarse, pebbly sand resting on an inclined base (= local depositional slope). This interval has often a dark rusty colour apparently due to the precipitation of ferrous material.
      b. Largescale foresetting ascending the slope in planar sets (b1) and generally merging up-dip into slope-parallel waver-type lamination (b2).
      c. Slope-parallel lamination of the "giant" foresetting type showing grain-size differentiation and an even stratification. Downslope, the present interval concordantly buries the "frozen" mega-ripple top of the (b)-interval by bending over the latter's relief in the middle left of fig. B (at c1).

II. Fig. C (Munday's Hill Quarry, Heath and Reach) represents a predominantly heterolithic SS-facies association, characterized by beds showing smallscale cross-stratified sand-mud interlaminations (flaser and linsen) with random intercalations of largescale cross-stratified sets.
   Directional bimodality is conspicuous and is characteristic not only for the smallscale but also for the largerscale structures, as well as for combinations of both types of structures.

The facies rich in heterolithic SS-beds shown in fig. C is attributed to a rather low-energy tidal environment without appreciable relief.

The facies association represented in fig. A on the other hand, indicates a prevalence of high-energy conditions. The lower complex would have been deposited in an environment with a pronounced submarine relief in contrast with the upper complex, which is assumed to represent an environment practically devoid of relief. The horizontal discontinuity plane separating both complexes points to a radical change in submarine morphology.



a-1
a2
A
0 10 20
B
0 10 20 cm.
10 m.
KERKOM SANDS
NEEREPEN SANDS
Fig. B
Fig. A
poorly exposed
55
235
30
20
c m f
Silt
cgl. sand clay

OLIGOCENE BELGIUM

Fig. 6A, B.

Examples from tide-governed Lower Oligocene (Tongrian) succession, east of Leuven (Belgium).

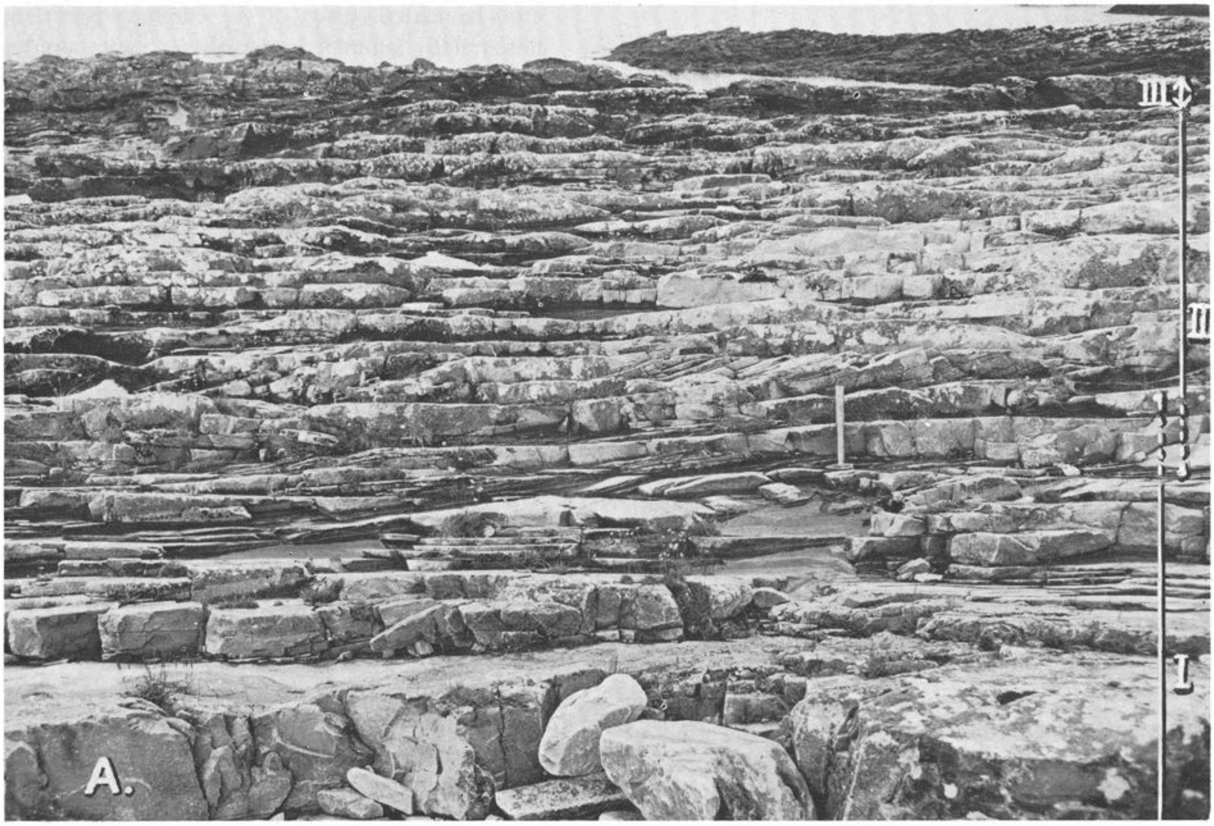
Three lithofacies groups can be distinguished (see log):

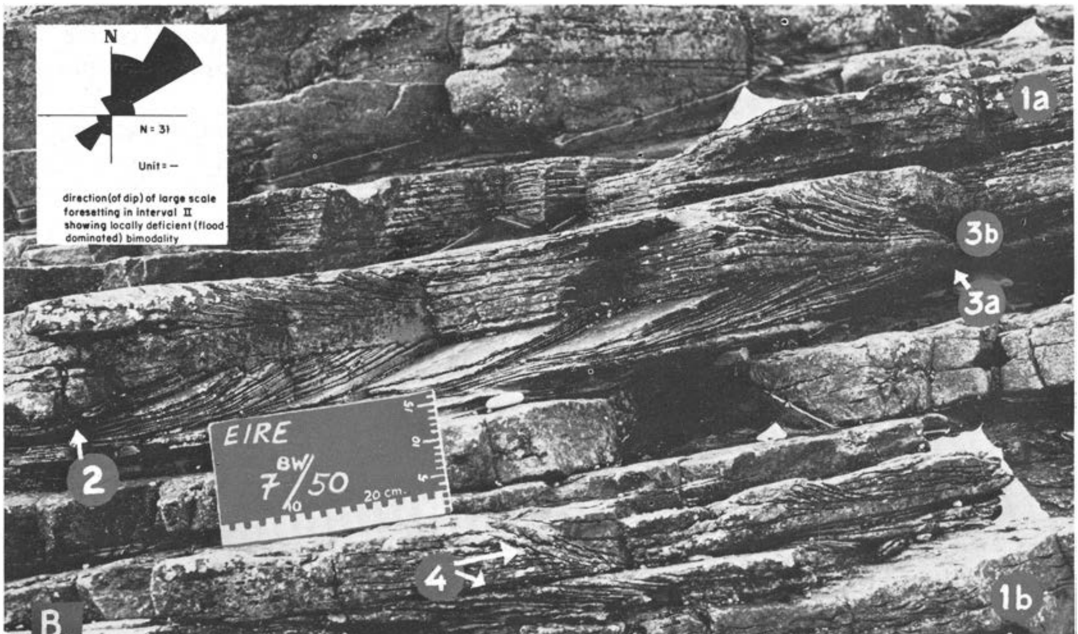
1. A *lower* group, fine sandy and silty, greenish coloured (glauconite), mainly characterized by smallscale cross- and horizontal lamination. The cross-laminated sets are often of the climbing type (see photograph A). The present lithofacies is known as the "Neerrepen Sands" and is marked by directional bimodality in the Academic Hospital quarry. In other outcrops of the present lithofacies (e.g. Kesselberg) horizontal to subhorizontal lamination prevails strongly over cross-lamination, although isolated wave-ripple and current-ripple horizons occur. In both cases largescale cross-stratified structures are an exceptional feature.
   Contorted bedding is a prominent feature in the present quarry and of two types. The first, the diapiric-convolution type, is probably the effect of water escape from oversaturated sandy layers (at a1). The second type is presumably mainly due to organisms escaping from burial (e.g. at a2). On the whole several kinds of structures produced by organisms known from tidal and other shallow-marine environments (Crustacea, Annelidae, Molluscs) are abundant not only in the lower but also in the middle lithofacies group.
2. A *middle* group, known as the "Kerkom Sands", with grain sizes varying largely between coarse and medium grades. Largescale cross-stratification is the dominant feature (see photograph B). Smallscale cross-laminated (often of the climbing type) and horizontally laminated intervals are common intercalations further to the east (Vissenaken, Kerkom). In the present quarry this lithofacies group starts off with a conglomeratic bed containing clay galls and traces of scour-and-fill structures.
   Directional bimodality is ubiquitous in the middle group in LS- as well as SS-strata (see log).
3. An *upper* group, comprising two metres of remarkably evenbedded, horizontally laminated medium sand. A few, scattered, shallow-depression fills, as well as thin and short cross-laminated sets are occasionally encountered here. This lithofacies seems to be of local occurrence.

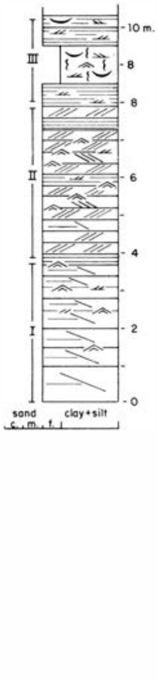
The above provides convincing evidence of strong tidal action in the Oligocene during the "Kerkomian" along the southern border of the predecessor of the North Sea. Nowhere have purely fluviatile Kerkom Sands been found in the visited quarries. As regards the lower lithofacies group comprising the Neerrepen sands tidal currents also seem to have played a part though to a less extent. The sequential characteristics of these sands point moreover to intermittent influxes of material separated by periods of slow or non-deposition as suggested by the occurrence of wave-ripple horizons covered by fine suspension material and of zones of maximum bioturbation alternating with less burrowed ones.

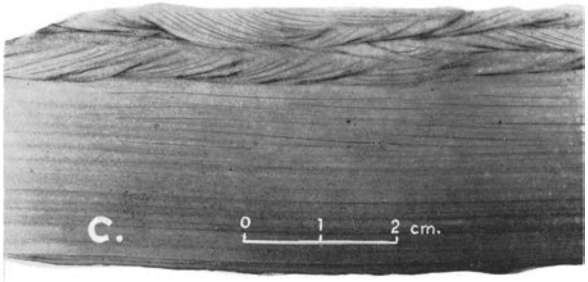
As yet the authors feel unable to decide on the exact tidal subenvironments of deposition for the present succession.

Photographs of lacker peels taken in the Academic Hospital Quarry, ± 4 km east of Leuven.


III
II
I
A.


N
N = 31
Unit = —
direction(of dip) of large scale foresetting in interval II showing locally deficient (flood-dominated) bimodality
1a
3b
3a
2
EIRE
7 BW/50
20 cm.
4
1b
B.


10 m.
8
8
6
4
2
0
III
II
I
sand
clay + silt
c. m. f.



UPPER DEVONIAN, SOUTHERN IRELAND

Fig. 7A-C.

Examples taken from tidal deposits belonging to the marine Upper Devonian of Seven Heads Bay (Cork beds, SW Ireland).

The photographs concern the upper part of the succession, which can be divided into structural cycles of the type shown in the log. Each cycle ideally consists of three major intervals (I-III) grading into each other from bottom to top.

I. The lower interval characterized by subhorizontally laminated sandstones exhibiting slight beddingplane divergencies and organised in beds of upward decreasing thickness (from metre-scale to dm-scale). Again and again it was observed that certain surfaces of individual beds bear ripplemarks or that horizontal lamination at the top of individual beds is erosively covered by a smallscale cross-laminated layer only one or a few cm-ers thick. The latter may have a clearly wave-generated or current-generated structure, but fairly often both types of structure appear to occur in direct superposition, in which cases the wave structures always form the very top. Current (parting) – lineation is absent in the present interval.

II. The middle interval is characterized by largescale cross-stratified sets often of the planar type, interbedded with (sub)horizontally laminated sets and with some co-sets showing smallscale (current) cross-lamination. Again wave ripples are found to occur here and there at the partings, which separate the sets. Current direction is bimodal, which is quite notable in the largescale cross-stratified units, but also, though less striking, to the field observer in their smallscale counterparts as is perfectly shown by radiographs (see C). The set thicknesses of the sandstone beds of interval II vary from one or more centimetres to a maximum of 35 cm.

III. The upper, heterolithic, SS-interval made up primarily of flaser and linsen beds and some silt beds, interspersed by a few thin (± 5 cm), horizontally laminated or smallscale cross-laminated sandstones.

Photograph A provides a general view from the 2 m-level (see log, interval I) upwards. Subhorizontally laminated beds in foreground display upward decreasing bed thickness and an increasing rate of bedding-plane divergency, which seems to announce the cross-stratification prevailing in interval II. The first genuine largescale cross-stratified set occurs above the 40 cm long hammer shaft. The cross-stratified interval is distinctly more evenbedded, as is well demonstrated in photograph B. Further salient features of the latter figure are:

1. The occurrence of horizontally laminated beds and smallscale cross-stratified cosets (at 1a and 1b respectively).
2. Largescale foresets merging into long and sometimes thick bottom sets, which are asymptotic to the lower set boundary (at 2).
3. The fanning up and down character of the largescale foresets (at 3a and 3b).
4. The often low angle inclined or "hesitating" character of the foresetting (at 4).

Curiously enough part or whole of the cross-stratified interval (II) may over a distance of a few tens of metres laterally merge into thin-bedded, (sub-) horizontally-laminated complexes without alteration of thickness. In the latter smallscale wave and current structures are intercalated. This structural change is effected by the gradual fading out of the megaforesets through a fanning-up of the laminae to horizontal position. On the other hand, megasets may start off with horizontal lamination, which gradually inclines more and more downstream. This mode of birth and disappearance of mega-foresetting seems to indicate that mega-foresetting preferentially developed where flow expansion was made possible by pre-existing shallow depressions. Greater difficulties arise when it is endeavoured to explain the generating conditions of the lower, subhorizontal interval. A few preliminary considerations are given here: The absence of current lineation on bedding planes of subhorizontally laminated beds seems to indicate that grain traction and helical (current parallel) eddies (A l l e n, 1968) could not develop or hardly so.

Possibly, successive, rapidly slackening currents causing sudden high rates of fall-out from suspension, which is known to suppress vortical activity, might be responsible for the formation of the "horizontal" beds of interval I. The recurrent appearance of wave and current ripples on top of these beds might indicate that:

1. These sand influxes were of a spasmodic nature, short periods of rapid deposition alternating with possibly longer periods during which tranquil but still agitated water conditions existed.
2. Deposition must have taken place at shallow depth, above wave base.

As to the tidal subenvironment(s) where this kind of deposition took place the authors as yet feel incapable of making a definite statement.

CONCLUDING REMARKS

Studies of sediments from the Transitional Zone made by the authors indicate that there is a number of characteristics that point to tidal action in modern and ancient environments. These diagnostic features, which seem to hold good with regard to intertidal as well as subtidal deposits, can be listed in descending order of importance:

1. *Directional bimodality in smallscale, largescale or mixed (small-large scale) cross-laminated set ups.* One direction prevailing strongly over the other results in a deficient bimodality.

2. *SS-units and grosso modo LS-units being commonly coupled (in super- or juxtaposition) at different proportions.* The cross-lamination prevailing in both units is often accompanied by horizontal lamination of varying and often speculative genesis. The units form generally discrete lithofacies associations of variable thickness but may also occur intimately intertwined. Their co-existence points to hydrodynamic conditions, which are highly variable in space and time, connected with subaqueous (changes in) morphology. The SS-units, which are often heterolithic (variable sand/mud ratio), were formed under relatively low-energy conditions. The LS-units represent sedimentation patterns with prevalent high-energy conditions. Especially where the latter units are thickly developed, they may contain subordinate smallscale cross-laminated, often muddy, horizons, caused by ephemeral interruptions of the high-energy regime.

In open-marine tidal sedimentation the largescale structures tend to prevail and giant foresetting is known to occur here.

3. *The intricate character of the sequential order.* Composite fining-upward complexes, characterized by a basal, often channelling, LS-unit transitionally followed by a SS-, usually muddy, unit were encountered in certain tidal environments. In the Haringvliet the fining-upward complexes range in thickness from a few dm to a few metres and remain a feature of rather secondary importance. In Barendrecht such a sequence comprises, however, a number of metres.

In ancient tidal sediments of bipartite upbuilding (LS- and SS-units) sequential regularity is not of common coccurrence. Only occasionally a fining-upward comes to the fore. Mostly the picture is blurred by sequential reversibility.

Thus, tidal deposits differ sequentially from fluviatile (fining-upward) as well as from deltaic sediments (coarsening-upward).

4. *Secondary phenomena related to the bi-directional and intermittent character of tidal currents.*

a. The frequent occurrence of discontinuity planes (in grossly unidirectional megasets), which truncate or do not truncate previously deposited bundles of foresets. These planes bear subsequent bundles, mostly characterized by a different angle of foresetting. This feature points to repeatedly interrupted progradation of the megaripple followed by reactivated sedimentation.
b. The discontinuity in question is often stressed by the occurrence of one or a few sets of oppositely directed smallscale ripples ascending the megaforeset slope or the truncation surface without showing backflow-ripple character (no interfingering between largescale and smallscale laminae).
c. Deposition of some silt or clay on the discontinuity plane or on the abovementioned ascending ripples.
d. The local fanning up and down of the mega-foresets.
e. The very frequent occurrence of megasets of a short length or if they are long, containing discontinuity planes (see a).
f. The megasets mentioned under e often have

scooping lower set boundaries.

5. *The widespread and quantitatively important development of beds of flaser and lenticular (linsen) character and of straighter types of sand-mud interlamination in the SS-units.* This feature, however, should be handled with the utmost caution, as it may also occur in sediments from a great number of modern non-tidal environments[3)] (see e.g. Reineck, 1960; Coleman and Gagliano, 1965 and Kanes, 1970). In the tidal flaser and linsen beds studied by the authors the following modes of cross-lamination were observed:

1. Bimodal current-ripple cross-lamination } sometimes with wave-reworked top
2. Unimodal current-ripple cross-lamination } sometimes with wave-reworked top
3. Wave-generated cross-lamination (Sevenheads bay, Ireland, in the succession underlying the described example).

The first type of cross-lamination points undoubtedly to tidal deposition but is difficult to recognize in the field when lenticles are small-sized. A flaser and linsen complex of unimodal directional character can only be considered as indicative of tidal action if the observed foresetting is diametrically opposite to that of certain intervals belonging to enframing non-heterolithic strata.

6. *Slight to intensive bioturbation in several types of sandy and/or muddy units, frequently suddenly disappearing without being related to a change in character of the sediments.* This is a curious but frequently occuring feature in ancient tidal deposits. Its diagnostic value so far remains uncertain.

The listed cross-sectional features shared by subtidal and intertidal deposits as a rule overshadow entirely those upon which a distinction between both types of deposits could be made. This is presumably due to the rare preservation of the original morphological surfaces and microreliefs observable during emersion and last but not least to the apparent scarcity of sequential features typical for the intertidal domain. In case marginal (salt-) marsh sediments are preserved the latter situation becomes less problematic. One is therefore generally seriously handicapped when endeavouring to discern subtidal sediments from intertidal ones in a succession of beds.

As regards the distinction between on the one side offshore to open sea and on the other inshore tidal deposits structural and sequential evidence should, where possible, be supplemented, by data about the prevailing paleocurrent patterns so as to get information concerning shore-line position, presence or absence of bimodal longshore currents, etc. The authors' studies in Ireland and Belgium show that this is not a simple affair. It is believed that painstaking future research may contribute considerably to the understanding of the manyfold aspects of tidal sedimentation and it is a "consolation" that up to the present but a very small fraction of the total amount of tidal deposits formed during the Geological Past has been discovered and studied, which leaves ample opportunity to the elucidation of a number of features, which are still enigmatic at present.

[3)] A random selection: (Coastal) lake sediments (Rhone deltaic plain); proximal fluviomarine sediments (Rhone prodelta); lagoonal sediments (Wiggers, 1955, fig. 33, 89: Almere formation Zuiderzee, The Netherlands); marsh sediments (Kanes, Colorado river delta, Texas); interdistributary bay sediments (Coleman et al. Mississippi delta); some Dutch interfluvial and fluvial sediments (the authors' experience). Rhone delta core material obtained through courtesy of Kon. Shell EP Lab. Rijswijk, The Netherlands.

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