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Diagnostic sedimentary structures of the fluvial-tidal transition zone – Evidence from deposits of the Rhine and Meuse

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Abstract

In mesotidal settings the transition of a coastal plain estuary to the river is marked by the change of a multiple ebb and flood channel configuration to a single channel system. At high river discharge fluvial processes operate, whereas in periods of low discharge the flow is complicated by a tidal component and a landward intrusion of the salt wedge. These hydraulic and morphological characteristics make the transitional zone different from the 'pure' fluvial and estuarine environment. Inspection of published and unpublished data from a number of outcrops of Recent and Tertiary deposits of the Rhine reveals that also in a sedimentary sense a transitional zone can be recognized. In order to separate this zone from the upstream fluvial and downstream estuarine environment a sedimentological definition of the fluvial-tidal zone is proposed being the part of river that lies between the landward limit of observable effects of tidal-induced flow deceleration on fluvial cross-bedding at low river discharge and the most seaward occurrence of a textural or structural fluvial signature related to the high river stage.

Many structures of the fluvial-tidal zone suggest conditions of rapid deposition. This may reflect the high mobility of channels that characterise the fluvial-tidal zone, or deposition in a bay-head delta setting. The diagnostic features of the fluvial-tidal transition zone, as manifested in the studied outcrops, are described and illustrated in detail. They primarily refer to large-scale dune cross bedding and decimetre- scale successions (cycles) in vertical sense:

Dune cross bedding: Foresets tend to be more or less regularly spaced or bundled. These bundles are often delineated by slightly erosive discontinuities, arranged in a daily variance mode due to remote tidal effects. The discontinuities are draped by silt and peat detritus rather than by clays, as is the case in the estuarine environment. In the pebble size grade, peat also predominates over clay. The dune foresets often pass downward into thick bottomsets, produced by suspension load on the gently inclined toe of the dune, leading to a knicked ('shovel') appearance of this assemblage. In contrast with the fluvial and tidal counterparts, bottomsets in the transitional zone show a disorder in direction of cross-laminations. Foresets are frequently used by ripples moving up high on them ('setclimbers'). These ripples usually are not of the backflow type as found in fluvial deposits. Directions of ripple movement parallel to foreset-strike are also found. Incidentally, setclimbing is developed to such a degree that entire crossbedded sets are made up of multi directional small scale cross lamination.

Decimetre-scale successions: In the case of tidal deposits decimeter-scale rhythmic successions are generated either by seasonal changes or spring-neap tidal cyclicity. Fluvial cyclic successions can be found in fills of abandoned channels and represent high and low discharge alternations. In contrast to this, diagnostic decimeter-scale successions of the transitional environment consist of alternating units reflecting fluvial dominance at high river discharge versus dominance of tidal currents at low discharge.

Although none of the sedimentary features of the fluvial-tidal zone is unique for this environment, they allow a rather safe signature of this environment when several are found together.

Introduction

During the past decades the tidal facies sensu stricto has been described in many papers, textbooks and conference volumes (e.g. De Raaf & Boersma, 1971, Ginsburg, 1975; Reineck & Singh, 1980; De Boer et al, 1988; Smith et al, 1991; Flemming & Bartholoma, 1995). The facies characteristics of fluvial systems also have been published in large numbers and to a high degree of detail. The reader is referred to the many sedimentologic textbooks in general, and more particularly to proceedings of conferences on fluvial sedimentology (e.g. Miall, 1996; Collinson & Lewin, 1983; Ethridge et al, 1987; Marzo & Puigdefabregas, 1993; Fielding, 1993; Smith & Rogers, 1999). By contrast, not very much is published on the fluvial-tidal transition zone. This is remarkable because this zone differs hydraulically to such a degree from the upstream fluvial and downstream estuarine zone, that one would expect it to be distinguishable as a separate sedimentary environment.

One of the main characteristics of the transitional zone is the fluctuation in time of fluvial and tidal influence related to river flood waves. In this zone fluvial and tide dominated deposits thus may be expected to alternate in the vertical succession. The influx of fresh water is a key condition of the estuarine environment. Deposits from the fluvial-tidal zone may contain the only sedimentary indications of the existence of such an influx into a tidal basin. Deposits of the central or outer part of an estuary lack this signature. This also means that on outcrop scale, flood and ebb direction can only be determined in deposits of the transitional environment. Therefore, the recognition of the fluvial-tidal zone is of crucial importance to the sedimentary reconstruction of ancient estuarine environments. With transgression and regression, the facies of transitional sediments will move up and down the lower river reach. This makes it even more interesting to distinguish them, as they mark the farthest upstream extent of a transgression. Recognising these deposits may therefore permit a more precise determination of the maximum flooding surface in sequence stratigraphy. (Shanley et al., 1992). Another reason why the fluvial-tidal transition zone is so important is its great length in many low-gradient rivers, reaching tens or even hundreds of kilometers. As a result, substantial volumes of deposits may, in fact, be fluvial-tidal in character (Dalrymple and Choi, 2006). The failure to recognize subtle tidal influences in fluvial deposits might lead to erroneous paleogeographic reconstructions.

In this paper it is aimed to pinpoint common characteristics that allow recognition of the fluvial-tidal transition as a separate facies entity in outcrops and boreholes. Our data record refers to observations, descriptions, photographs and lacquer peels of deposits of the Rhine and Meuse rivers that were exposed in large, temporary excavations. This implies that the validity of our study may be principally restricted to medium-sized rivers of the temperate climatic zone, such as the Rhine, that pass through a mesotidal coastal plain estuary into the sea. The deposits we studied range in age from Pliocene (5 Ma) for deposits of the Lower Rhine Embayment in Germany (see Ziegler, 1990, for an overall paleogeographic reconstruction) to sub-recent (500 BP) for sediments exposed in pits in the western part of the Netherlands. Although the drainage area of the Pliocene Rhine did not extend yet into the Alps (Gliese and Hager, 1978; Berendsen and Stouthamer, 2001), outcrop evidence suggests a river with about the same discharge as the present Rhine. A larger annual rainfall during the Pliocene possibly explains this. At present the lower Rhine has a year-average discharge of 2300 m^3s^{-1}. The Rhine follows a tectonic rift system were subsidence is more or less counter-balanced by sedimentation. Marine incursions alternate with more alluvial conditions. The river enters the southern North Sea in a mesotidal setting. At the studied locations we deduced from historical data, from facies transitions and from sedimentary structures that the selected deposits were formed in the fluvial-tidal zone.

A comparison between our record of sedimentary structures from the Rhine and Meuse rivers and the scarce published record is difficult. Only Gosh et al. (2005) and Plink-Björlund (2005) provide detailed sedimentological descriptions. However, their geological background information only allowed a rather crude reconstruction of the depositional environment, leaving their assignment of structures to the fluvial-tidal transition zone rather speculative. In other studies information is restricted to scattered statements and illustrations that tend to focus on large-scale architectural elements (e.g. Allen and Posamentier, 1993; Shanley et al. 1992; Thomas et al., 1987; Yoshida, 2000; Eberth, 1996; Clifton, 1994 and Willis, 2000).

The sedimentology of the fluvial-tidal transition zone cannot be understood without considering the main changes in hydraulics and morphology that are related to the intrusion of the tidal wave and the seawater into this zone. This is the subject of the next section. Then, we will propose a definition of the fluvial-tidal zone, which enables the recognition of this zone by sedimentological criteria. This is followed by a description of the studied outcrops showing the transitional deposits. Finally the diagnostic characteristics of the fluvial-tidal zone will be discussed.

The fluvial-tidal zone in the case of rivers like the Rhine

Medium sized rivers, like the Rhine, which debouch into a meso-tidal or macro-tidal sea, usually have an estuarine lower course. Here, the generally winding, meandering river widens to provide space for the development of sand-bedded flood and ebb channels separated by shoals (Van Veen, 1950). The tidal wave is deformed by the presence of these shoals. As a result the maximum flood velocity and discharge is reached when the shoals are being flooded. The maximum ebb discharge occurs at a lower water level, when the shoals become emergent (Van der Spek, 1997; Lanzoni and Seminara, 1998; Wang et al. 2002). Consequently the ebb flow is concentrated in channels, whereas the flood is free to cross the shoal morphology. As a result the ebb channels dictate the large morphological changes. They show a down-estuary migration of bends, much similar to fluvial meanders (Van den Berg et al., 1996). Thus, ebb channels are the main dynamic elements in the morphology of the estuary, and inner bend deposits may be expected to be over-represented as a sub-environment in the sedimentary record. Deposits of estuaries connected to the Rhine and Meuse River have been studied extensively in a number of large excavations in the SW Netherlands during the sixties and seventies of the 20th century (Fig. 3; Oomkens and Terwindt, 1960, Terwindt, 1971; 1988; Van den Berg, 1982; 1986). The exposures showed that inner bend deposits consist mainly of cosets of small scale and large scale cross-stratification, produced by migrating dunes generated by either the flood or the ebb flow. Fining upward sequences, typical for point bar deposits of meandering rivers are not well developed. In vertical sense the inner bend of an estuarine channel ends in a shoal, which is a rather high energetic, flood-dominated area, subject to some wave winnowing. The sediment in estuarine channels and shoals consists mainly of fine sand, which inhibits the grain segregation processes necessary to generate a fining upward trend.

Upstream, the characteristic estuarine landscape of flood and ebb channels passes into an often strongly meandering single channel system. Salinity is low, but there is still a tidal influence. However, the rising tide is no longer able to scour separate flood channels. Another characteristic of this zone is the high amount of suspended material. In tide-dominated estuaries this so-called turbidity maximum generally occurs at, or somewhat landward of the head of the salt intrusion, where salinities are about 0.1 - 0.5‰ (Dyer, 1995). The location of the turbidity maximum is not stable, as it depends on the magnitude of river discharge and the tidal phase. It travels over some distance back and forth with ebb and flood tide respectively. At low river discharge the maximum mud concentrations and deposition of mud in many cases is not found in the area of flood and ebb channels, but in the upstream meandering reach. With increasing river discharge the location of the turbidity maximum shifts downstream. In the case of very large rivers, which still carry a lot water at low discharge, such as the Rio de la Plata, the Amazon and the Yangste River, the turbidity maximum is found in the middle, or even the lower part of the estuary (Urien, 1972; Wells, 1995; Jiufa and Chen, 1998). However, this is beyond the scope of this analysis.

Amongst sedimentologists the definition of estuaries by Dalrymple et al. (1992) has been very influential. Therefore, it would seem logical to refine this definition with a formulation for the fluvial-tidal zone. A point of concern is that the definition only applies to systems embedded in an incised valley and under the influence of a rising sea level. The fluvial-tidal transition zone as we see it has a much wider occurrence. Recently, Dalrymple et al. (2006) abandoned the prerequisite that an estuary should be located within an incised valley, but still he excludes in his definition river deltas. As similarities will probably outweigh the differences between the two situations (transgressive and regressive) in the transition zone, we propose to use the term fluvial-tidal zone irrespective whether it is found in an estuary or on a delta sensu Dalrymple et al. (2006). For the sake of simplicity in the present analysis the zone seaward of the fluvial-tidal zone is supposed always to be an estuarine setting in the sense of Dalrymple et al. (2006). This is correct for outcrops of the Rhine discussed in this paper. With our focus on diagnostic structures and sequences, we propose the fluvial-tidal zone to comprise *that part of the river which lies between the landward limit of observable effects of tidally induced flow deceleration on fluvial cross-bedding at low river discharge, and the most seaward occurrence of a textural or structural fluvial signature at high river stage*. Note that the landward limit of the tidal zone in this definition extends far beyond the point of measurable dilution by salt water, being the limit of the estuary according to the well-known definition of Pritchard (1967). The upstream limit may reach far upstream as it implicitly includes all small de- and acceleration effects of the tide on the river flow, provided that these effects are observable in sedimentary structures In the case of the Rhine the effects on the water level can presently be felt up at low fluvial discharge up to 100 km upstream (Fig. 1). Mixtures of fluvial siliciclastic sands and gravels sands usually pass downstream into relatively fine estuarine sands within the size rage 180 - 300 microns. In the most downstream part of the fluvial-tidal zone the presence of sedimentary intervals of coarser sand may be an important diagnostic feature.

The definition thus proposed implies that fluvial processes govern channel dynamics in the fluvial-tidal zone. Only at low river discharge the flood current penetrates in the seaward part of the transition zone. It is however weak and of short duration and unable to scour channels. Therefore, both tides are concentrated in the same channel that gradually widens downstream. This contrasts with the typical estuarine morphology of shallow, straight flood channels that crosscut meander bends of winding ebb-dominated channels. Allen (1991) and Allen and Posamentier (1993) illustrated their definition with a sketch of a Gironde-type estuary. The sedimentation in this estuary could not keep pace with the Holocene sea level rise. It therefore still contains a low energy, muddy, central basin, which would classify it as a wave-dominated estuary in the sense of Dalrymple et al. (1992). In analogy with a schematic drawing of a wave-dominated estuary by Allen and Posamentier (1993), Figure 2 shows the main morphological features of a coastal plain - or tide-dominated - mesotidal Rhine distributaries type estuary. On top it shows the terminology proposed

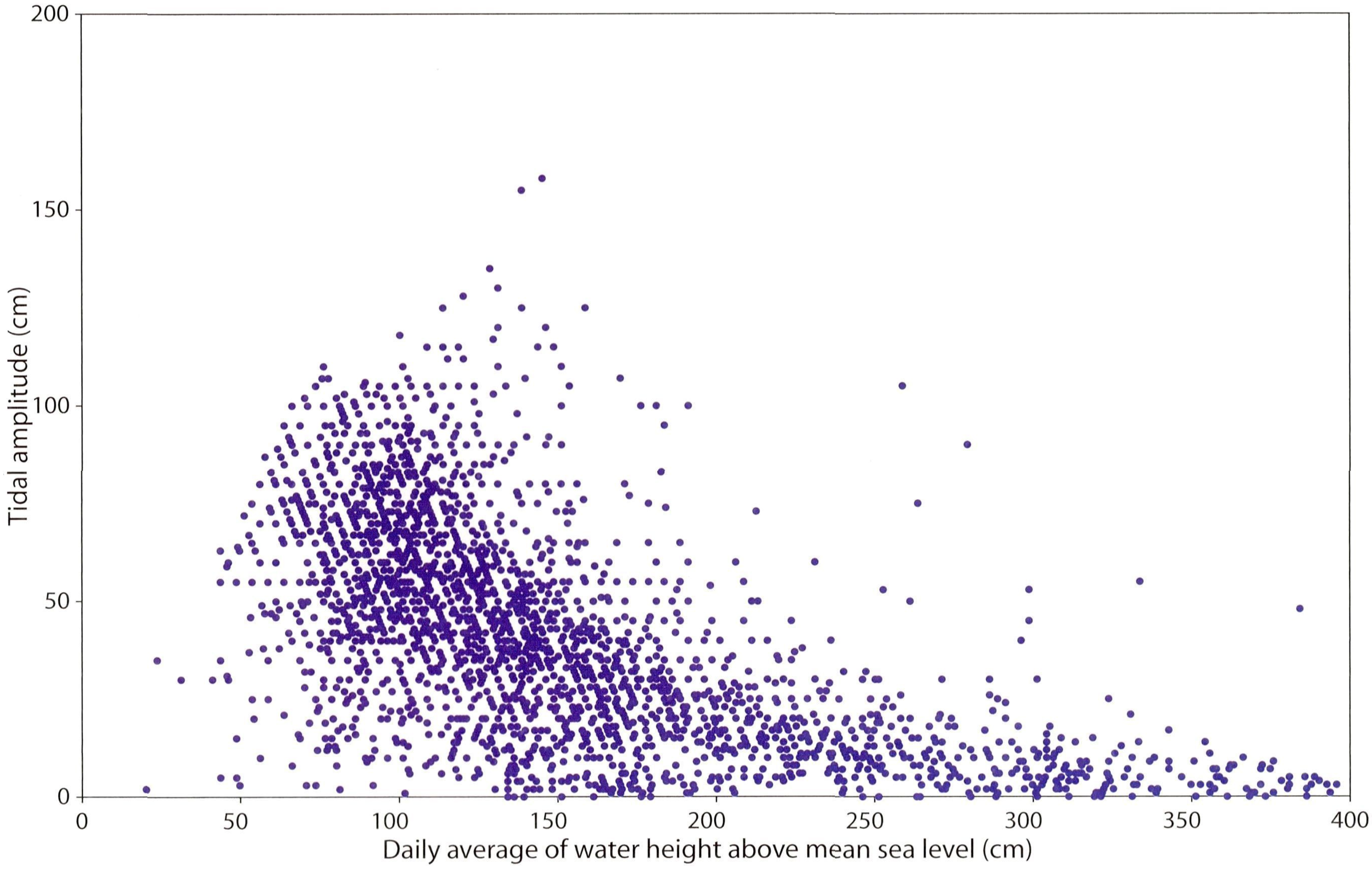


Fig. 1. Tidal range as a function of water level at Gorkum, 70 km upstream of the river mouth (for location, see Fig. 3). The data refer to 1840 - 1849 (Middelkoop and Ruessink, 2000).

by Allen and Posamentier (1993); at the base it shows the location of the fluvial-tidal transition zone according to our definition. Note that our definition implies a zone extending more seaward and landward as compared to the area of 'Upper Estuary Channels'.

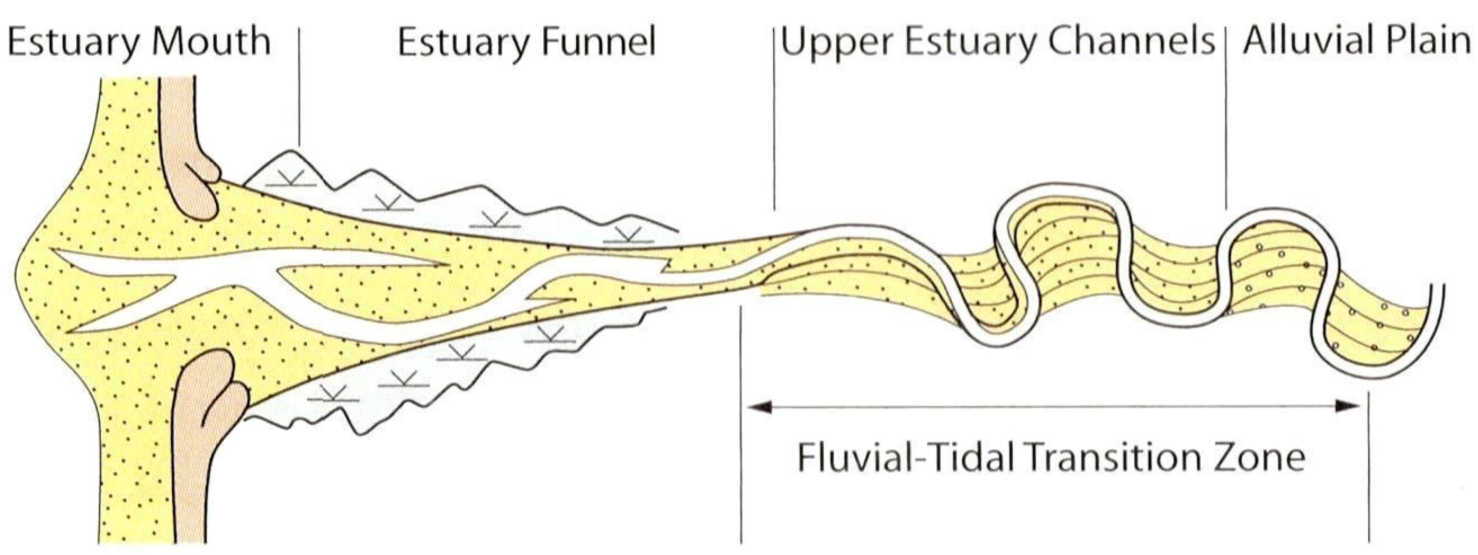


Fig. 2. Sketch of a Rhine/Meuse-type mesotidal tide-dominated estuary (modified after Allen and Posamentier, 1993).

The outcrops

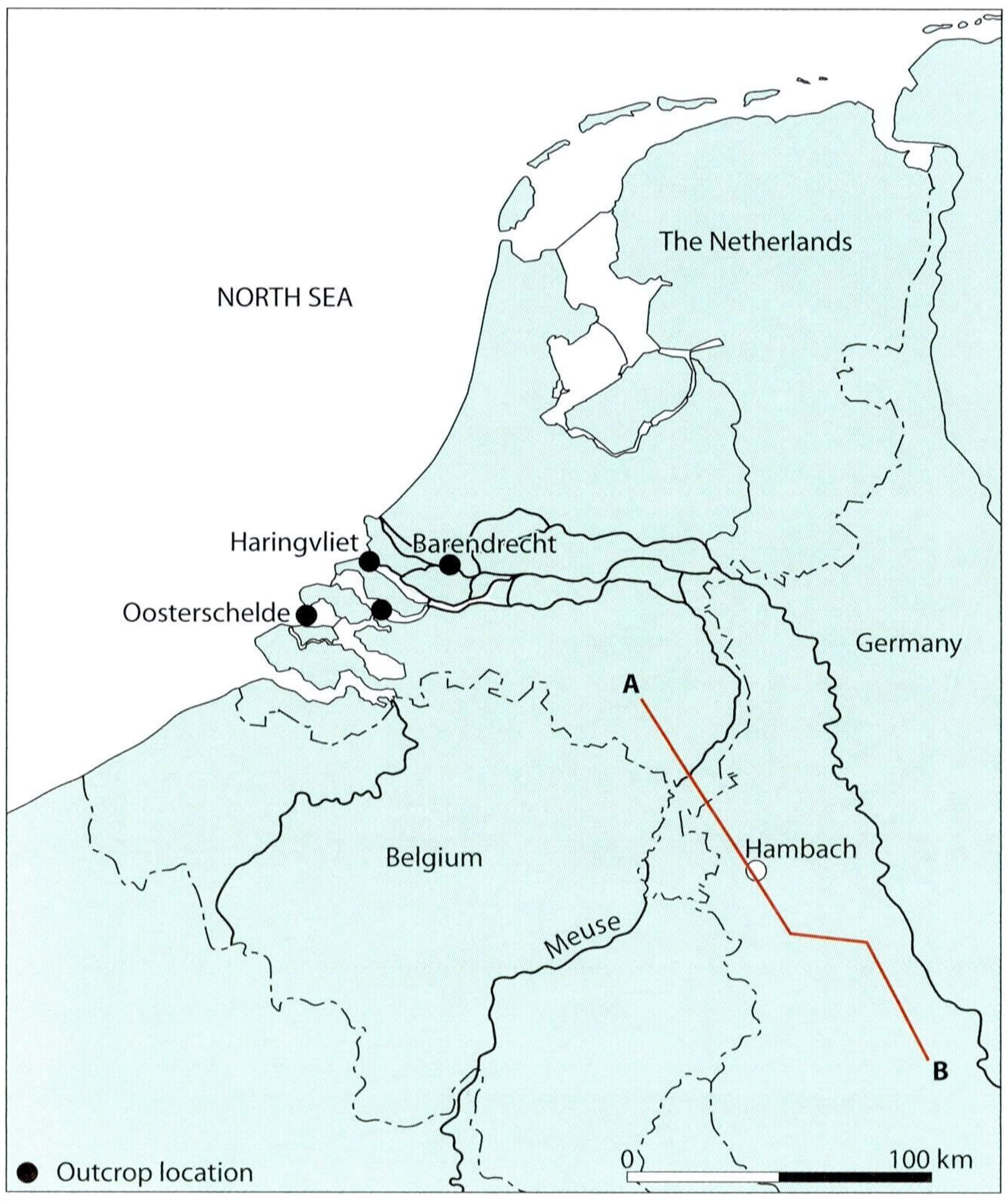
The outcrops we interpreted to represent fluvial-tidal facies come from exposures of Rhine or combined Rhine and Meuse sediments of Quaternary and Pliocene age. In this time period several incursions of the sea took place along different courses of the fluvial system reaching different inland transgressive positions. The location of the exposures is given in Figure 3. In most of our cases the transitional facies passes into a tide-dominated estuary. In the Hambach outcrop, however, a downstream transition into a clayey low-energy environment was observed, which suggests a river-flow expanding into a kind of basin. In the terminology of Dalrymple et al. (1992) this would be the central basin of a wave-dominated estuary.

Note: in our description of the sedimentary structures dune cross bedding (dm-m scale) and ripple cross-lamination (cm-scale) will be denoted by X-bedding and x-lamination respectively.

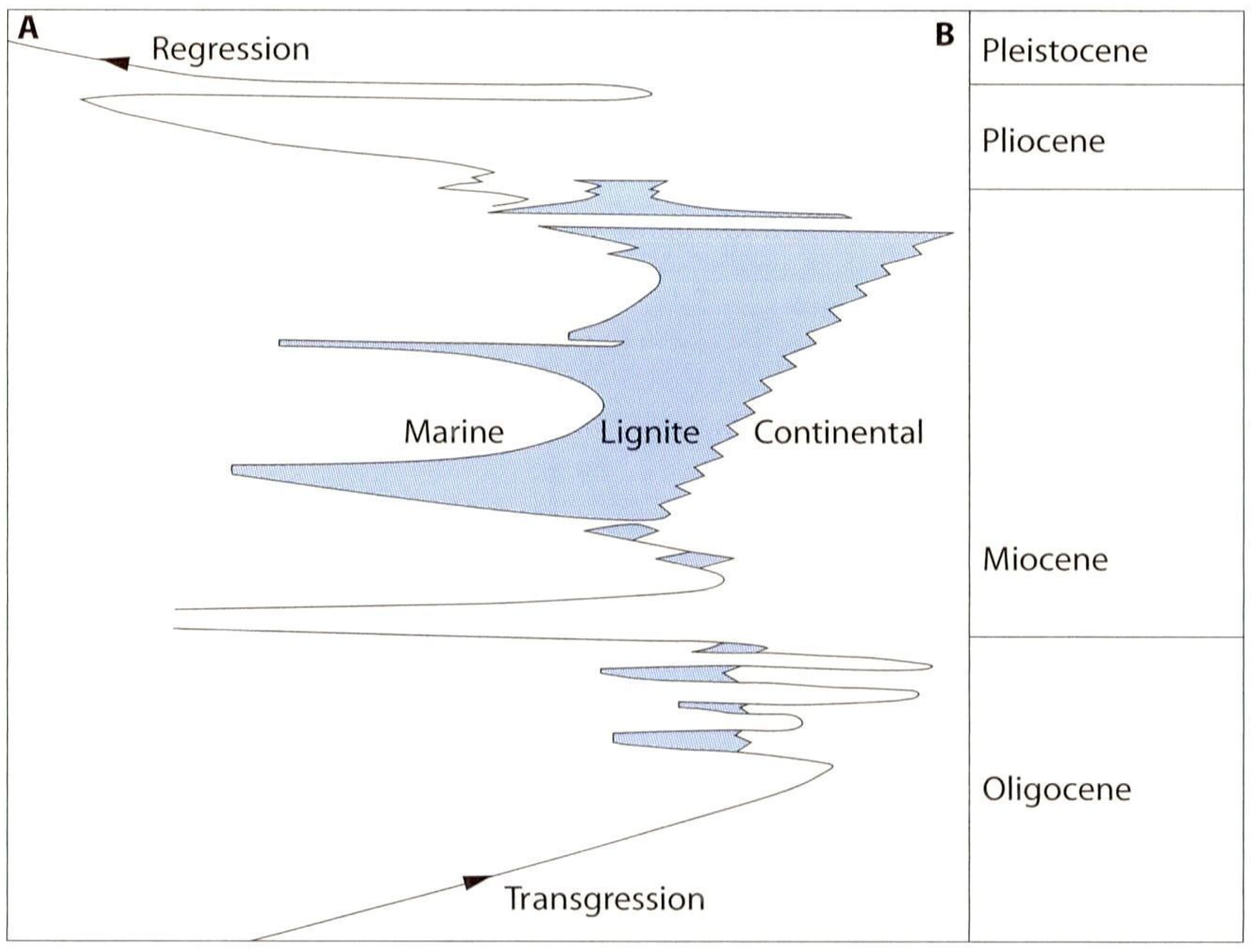
Barendrecht, the Netherlands

This exposure was in a pit made in 1966 for the construction of the 'Heinenoord' traffic tunnel below the Oude Maas, a distributary of the Rhine-Meuse system. (cf. Van Beek and Koster, 1972). The exposure showed deposits of the Oude Maas from the 14th - 19th century to a depth of 10 m below sea level. The present analysis is based on reports by De Raaf and Boersma (1971) and Van Beek and Koster (1972) and information from field notes, lacquer peels and photos supplemented by the second author.

Historic descriptions and maps suggest that in the period represented by the deposits fluvial discharges decreased. At the same time the tidal influence increased (Van Beek and Koster, 1972). These changes are related to a number of medieval dike bursts by which reclaimed lands turned into tidal flats and salt marshes. This resulted in a rather complex system of



a.



b.

Fig. 3: a. Locations of studied exposures of fluvial-tidal deposits. Also indicated are the locations of the well-studied sub-tidal deposits exposed in excavations in the Haringvliet (Terwindt, 1971; De Raaf and Boersma, 1971 and in the Oosterschelde estuary (De Mowbray and Visser, 1984; Van den Berg, 1981, 1982). b. Relative shoreline positions during the Oligocene-Pleistocene near the Hambach lignite mine (after Gliese and Hager, 1978). The sediments described are coincident with the transgressive phase in the uppermost Pliocene.

interconnected tidal channels, inshore tidal basins and fluvial distributaries, as is illustrated in Figure 4.

In the 19th century the mean and spring tidal range in this area was 1.5 m and 1.8 m respectively (Middelkoop and Ruessink, 2000). At high river discharge the influence of the tide became less, though was never completely suppressed. From the record of water level gauges of the 19th century it appears that at high discharge periods of the Rhine the tide still penetrated several tens of kilometres upstream of the study site (Middelkoop and Ruessink, 2000; Fig. 1).

Van Beek and Koster (1972) distinguish a tripartite vertical succession, (see also Fig. 5):

1. A 2 m thick lower unit of poorly sorted coarse sand and fine gravel, consisting of largely unidirectional, planar half-meter sets traceable over tens of meters. Foresets show frequent clay draping and pass into remarkably up to several dm thick bottomset-layers. Towards the top of the unit some reversely directed short sets appear. The base of this unit was not exposed.
2. A 1 m thick middle unit of relatively well-sorted medium fine to fine-grained sands, showing bipolar dm-scale X-bedding, with clay-draped pause planes.
3. A 4.5 m thick upper unit of fine-grained sands, silt and clay. The lower part is mainly composed of cosets of flaser-linsen (lenticular) bedding, alternating with horizontal clay beds. The uppermost 4 m of this unit is made up of well to medium sorted sand dominated by x-lamination, practically devoid of clay drapings.

The present analysis of transitional facies stems from units 1 and 2.

Hambach, Germany

In 1982 a northwest-southeast trending outcrop on the upper excavation platform in the northern part of this open cast lignite mine was investigated. The interval concerned is in the middle of the Reuver Series (Pliocene), just below the final fining-up sequence leading to the Reuver Clay (Gliese and Hager, 1978; Fig. 6). The interval could be traced over a kilometre in northwesterly direction to change from gravely sand, roughly X-bedded with discontinuity planes, to stacked decimetre scale successions reflecting low and high-energy alternations. The deposits probably correspond to a high stand that following an Upper Pliocene regional transgression deep into the Lower Rhine Embayment.

Diagnostic features of the fluvial-tidal zone

Distinctive features of fluvial-tidal facies can be grouped in internal special features of the X-bedded sets and typical decimetre-metre scale sequences. In table 1 the predominance of diagnostic structures is shown with respect to the position in the fluvial-tidal zone. In the following these diagnostic features will be described and a hydraulic interpretation will be given.

Fig. 4. Historical map showing the complicated system of tidal inlets and fluvial distributaries in the SW part of Holland in the middle of the 16th century. The inset measures about 26 x 18 km (Map made by Jacob van Deventer,1558).

Features of the X-bedded sets

X-bedded sets in the fluvial-tidal facies typically show a broad spectrum of foreset types. In longitudinal or dip-section (parallel to flow) these range between continuous and apparently uninterrupted to rather discontinuous more or less pause plane-dissected types, contained in trough-formed sets, such as shown in Figure 7. The pause planes usually do not arrange in lateral sequences in the consistent way of the ideal neap-spring cycle of mud-draped tidal bundles well known from the estuarine domain. These mud-drapes, often more than a mm in thickness, reflect the high-suspended mud concentrations generated by conditions of estuarine circulation and their presence is an indication of estuarine conditions. If, because of fluvial avulsion, an estuary turns into an inshore tidal basin, the turbidity maximum will disappear. This results in a strong reduction in suspended mud content, which explains the virtual absence of slack water clay drapes in tidal deposits of the northern branch of the Oosterschelde estuary, after it loosed its connection with the Rhine due to dam construction (Van den Berg, 1986).

Our data suggest that superposition of oppositely directed X-beds (herringbones or herringbone X-bedding) is a rather

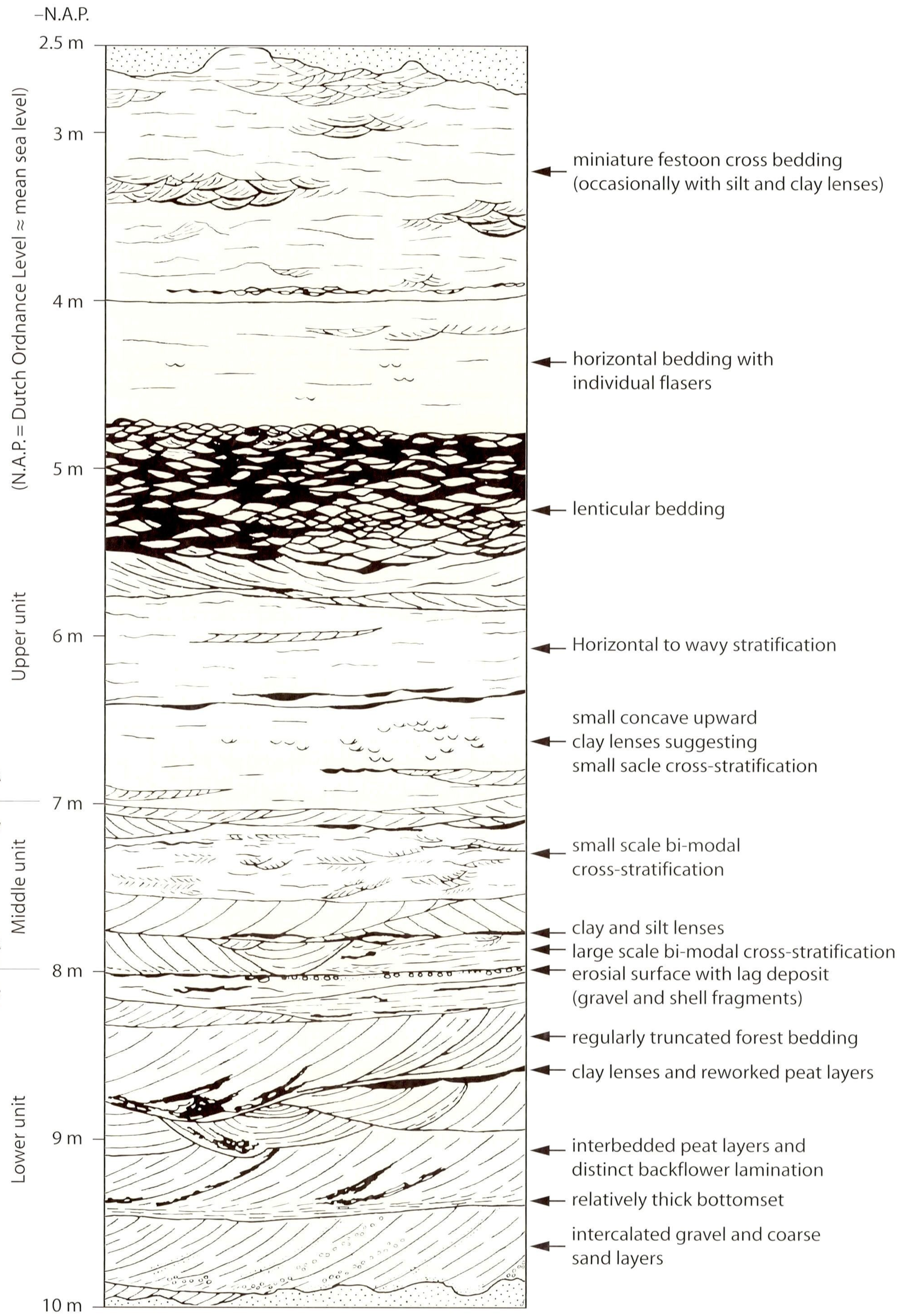


Fig. 5. Schematic representation of the sedimentary succession in the Barendrecht excavation (after Van Beek and Koster, 1972).

common feature of the fluvial-tidal zone (Figs 7 and 12). Some supporting evidence of herringbone occurrence in the transitional zone also comes from observations of bipolar X-bedding in point bar units of single-thread channels (Cuevas Gozalo, 1985; Shanley et al., 1992) and the fluvial-tidal zone of the present-day Gironde estuary, France (Allen and Posamentier, 1993). The structure is often considered as typical for tidal environments (e.g. Nichols, 1999; Gosh et al., 2005). By contrast, in several large outcrops of recent tidal deposits in the Haringvliet and Oosterschelde estuaries of the SW Netherlands it was hardly found (Van den Berg, 1982; Terwindt, 1971). Therefore, we postulate that the occurrence of herring-bone structures possibly is much more a diagnostic feature of the fluvial-tidal zone. It is a logical consequence of the fact that periods of ebb dominance during times of high river discharge alternate with periods of flood dominance during low river discharge. The pattern of mutual evasive channels in an estuary will result in preserved deposits entirely composed of either ebb or flood dominated structures. Unlike in the estuary, the flood and ebb (river) flow in the transitional zone is forced into one and the same channel, in which the flood current is relatively weak. This will result in the production of thick cosets displaying the dominant ebb-direction.

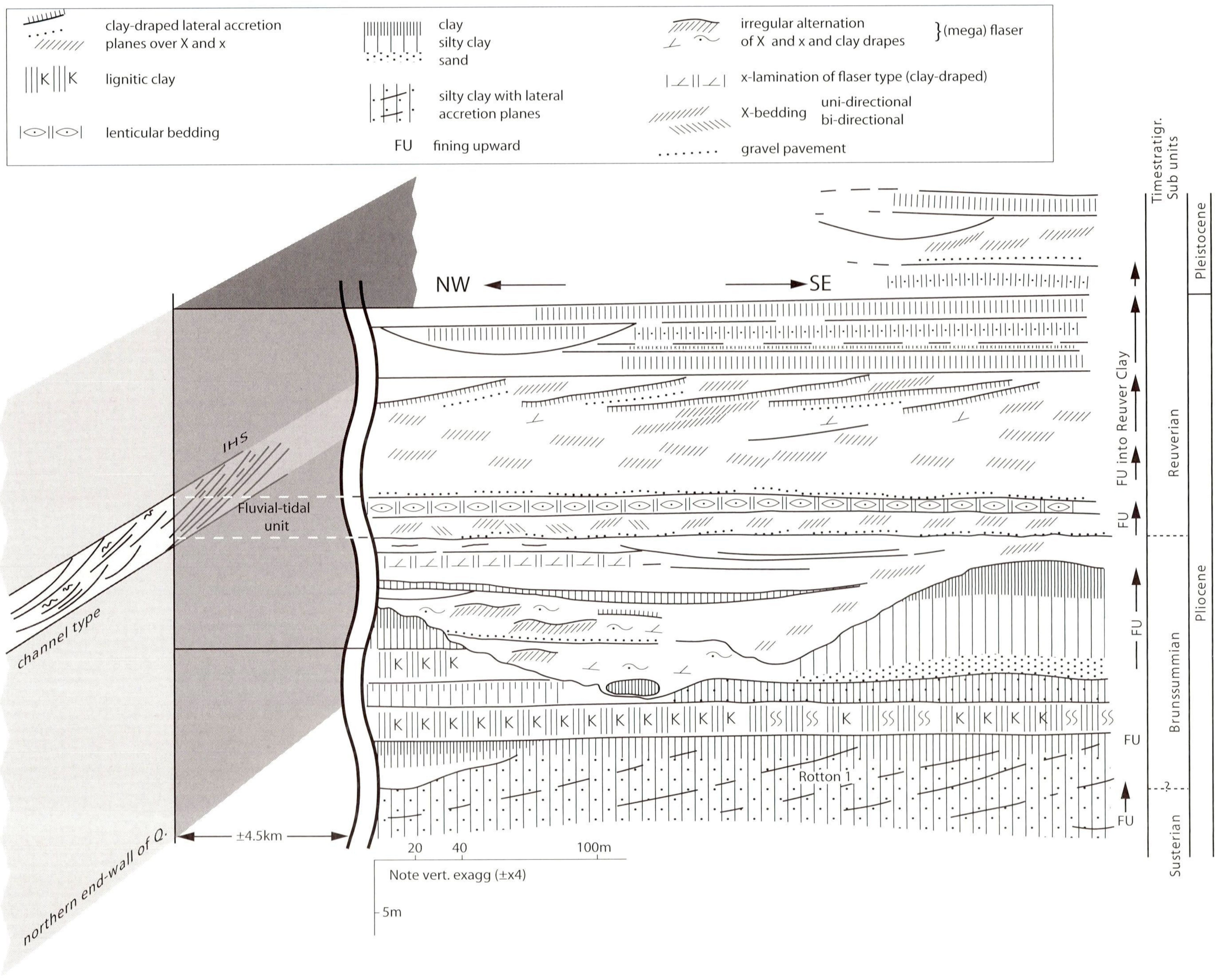


Fig. 6. Schematised sedimentological and stratigraphic characteristics of the Pliocene-Pleistocene succession at the Tagebau Hambach (Lignite Quarry), Germany. Longitudinal section: The Pliocene deposits are highly differentiated and incised by successive river stages. The 4 - 5m thick fluvial-tidal interval is located near the bottom of the Reuver deposits just below its last fining-upward sequence leading into the Reuver Ton (clay). The tabular fluvial-tidal unit can be differentiated from bottom to top into: 1) planar bedded gravely interval; 2) coarse-sandy X-bedded interval with slightly inclined sets off-shooting into bipolar x-laminated and clay-draped sets and 3) a 2m-thick clayey unit of lenticular bedding with opposite directions. Strike section: the fluvial-tidal unit in its distal appearance accumulates in 4 - 8 m narrow channels and wide IHS units. Micro dm-sequences are of frequent occurrence here.

Sometimes the pause planes in X-bedded sets are associated with x-lamination, which frequently ascend high up the X-beds. This we call the 'set-climbing' phenomenon (Fig. 8). In an extreme case, the X-bedded set is entirely constructed by ascending ripples (Fig. 8c). Directions of ripple movement parallel to foreset-strike are also found. Curiously, the set thus formed does not deteriorate rapidly in a longitudinal sense by flattening the foreset angle, as it normally does in the tidal environment (Boersma & Terwindt, 1981; Van den Berg, 1982; Fenies et al., 1999; De Mowbray and Visser, 1984). Ripples interspersed with steeply inclined foresets do occur in the fluvial facies, but in a different way, that is as backflow ripples produced by the vortex return flow of the dune. These backflow ripples, unlike the 'set-climbers' mentioned above, interfinger with the lower foreset only.

Thick bottomset layers have a comparable way of occurrence in the transitional and fluvial environments, although in the latter case they seem to be mainly restricted to the upper pointbar deposits. The structural content of the thick bottomset layers differ for the two environments. In the fluvial regime, an ideal bottomset layer shows an upward arrangement of downstream directed (co-flow) sets followed by the upstream directed, climbing backflow ripples, which interfinger with the dune foresets (Boersma, 1967). The imperfect bottomset layer may consist of co-flow or backflow ripples only. Contrastingly, in the transitional environment the bottomset layer tends to be irregularly stratified. Up- and downstream-directed ripples and parallel lamination are superimposed in an unpredictable way. Probably this irregularity of bottomset structure is caused by the deterioration of the flow vortex in the dune's

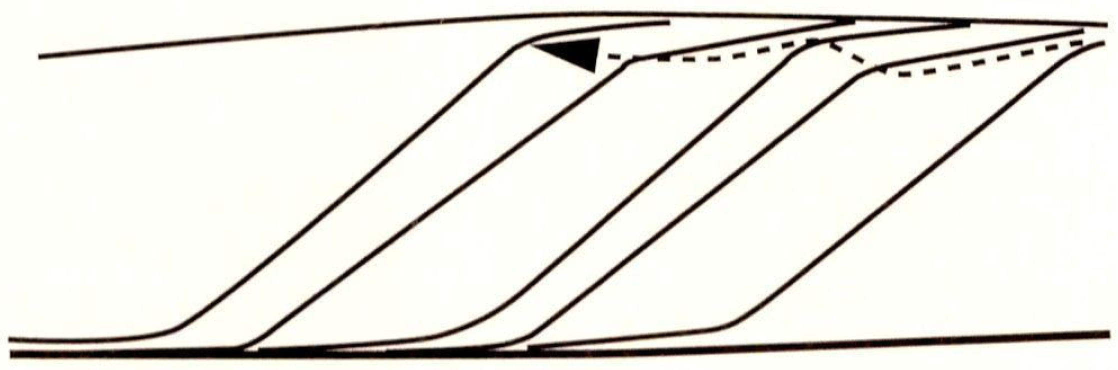
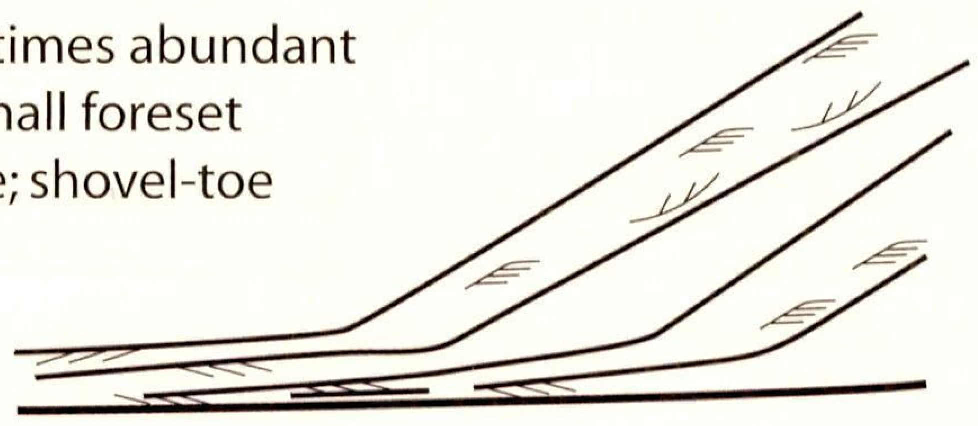
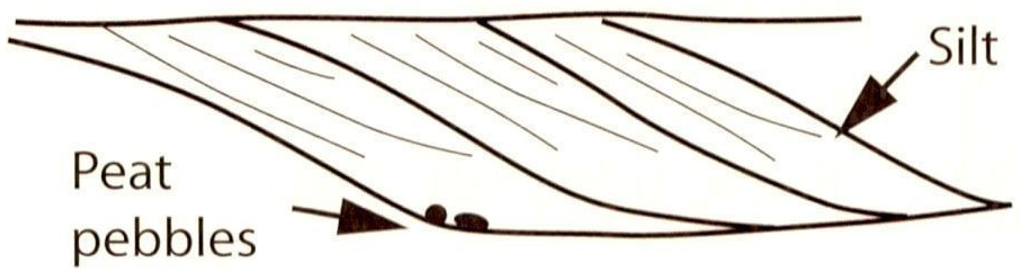
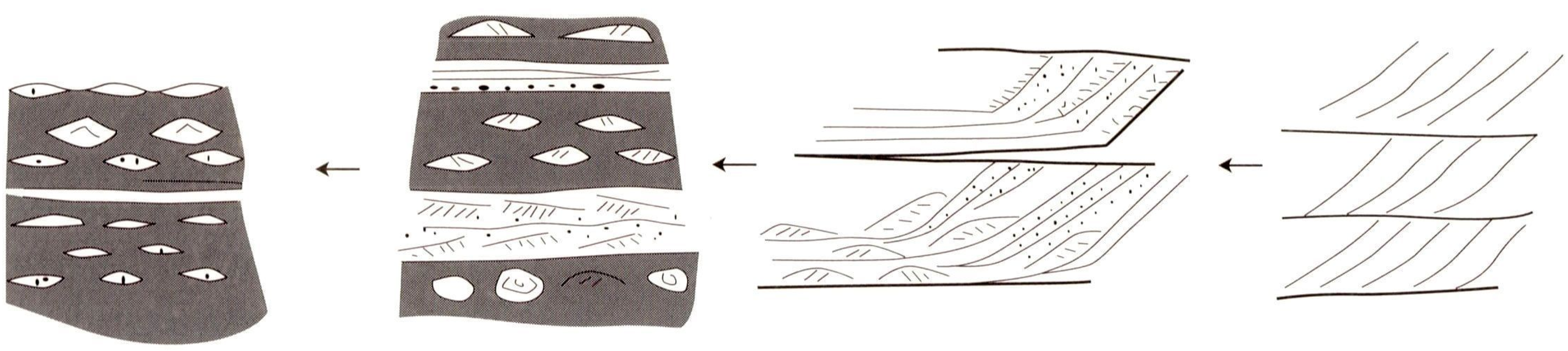
	← downriver
Foresetting	 Cyclic variation in brinkpoint height Set climbing ripples, sometimes abundant and/or also descending; small foreset bundles with varying slope; shovel-toe and thick bottomset layer.  0.5 m  Landward directed foreset bundles: finer sand and mud-draped
Ripple-mud transitions	 0.1 m Landward directed ripple form sets with laminae interfingering into mud
Vertical sequence at dm-m scale	 Abruptly, stacking of sedimentary units, without system 0.5 m
Longitudial sequences (in the case of a bay-head delta)	 0.5 m Very marked (over ~0.5 km) longitudinal transitions from X-bedded sand to clay-dominated lenticular bedding

Table 1. Diagnostic sedimentary structures of the fluvial-tidal zone.

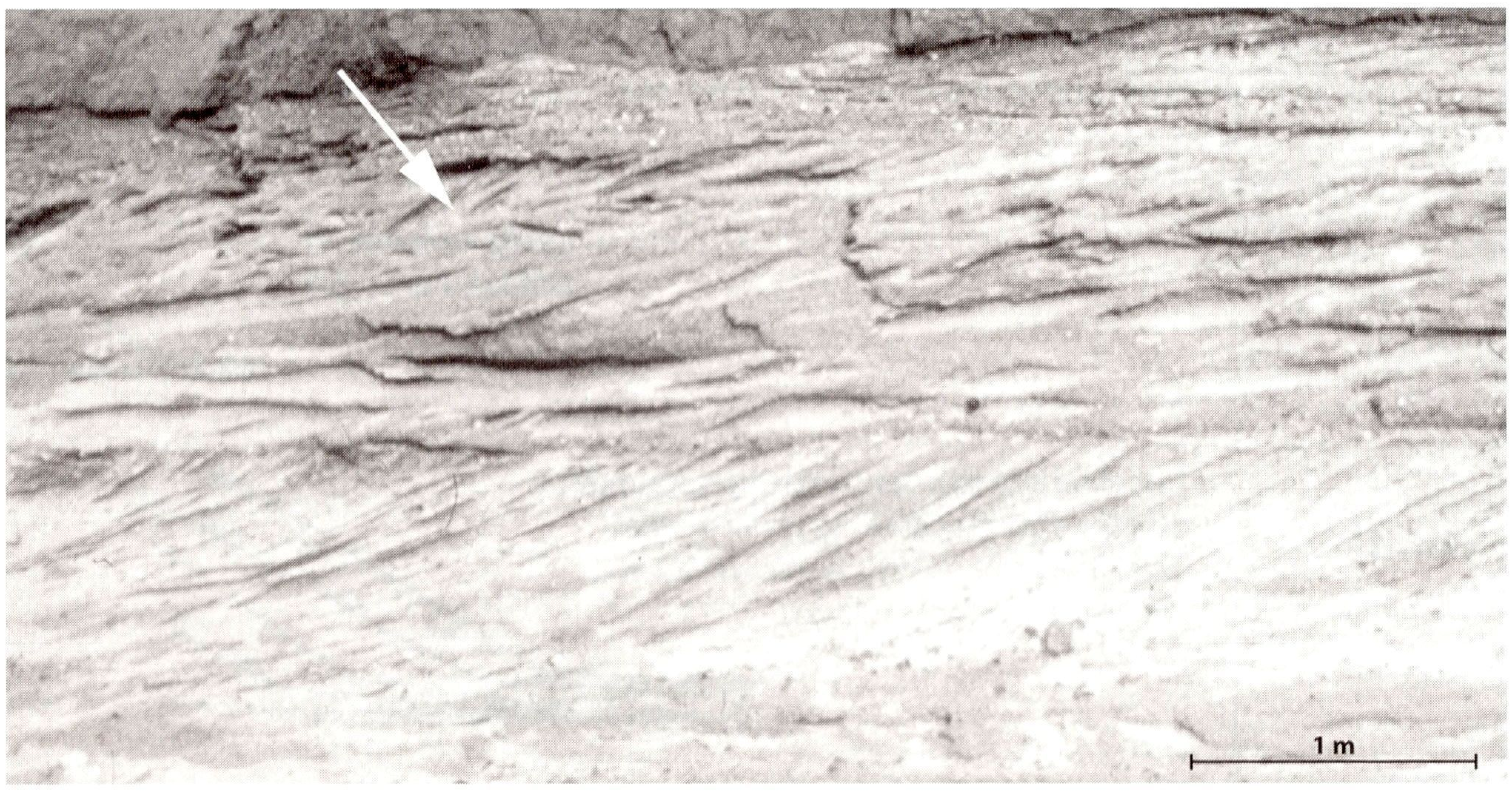
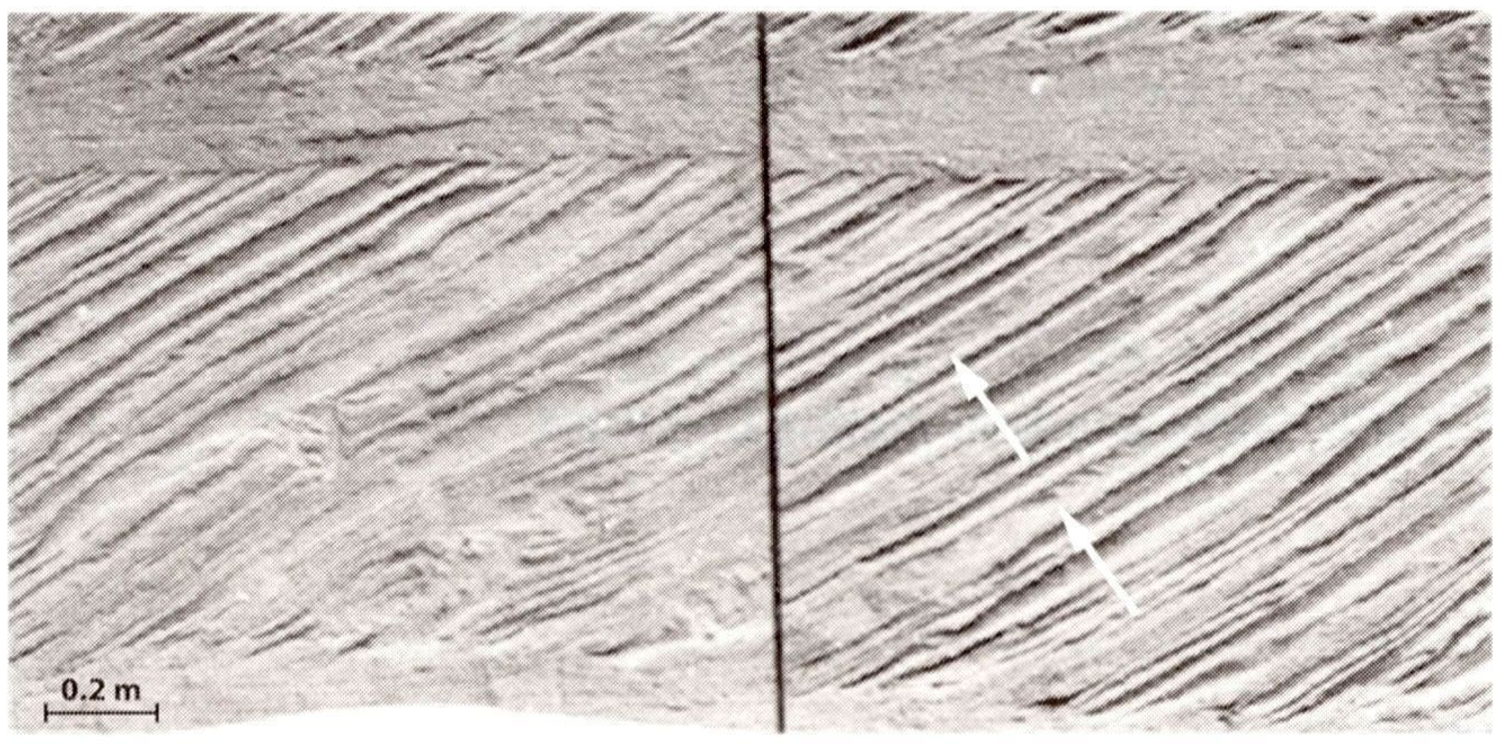
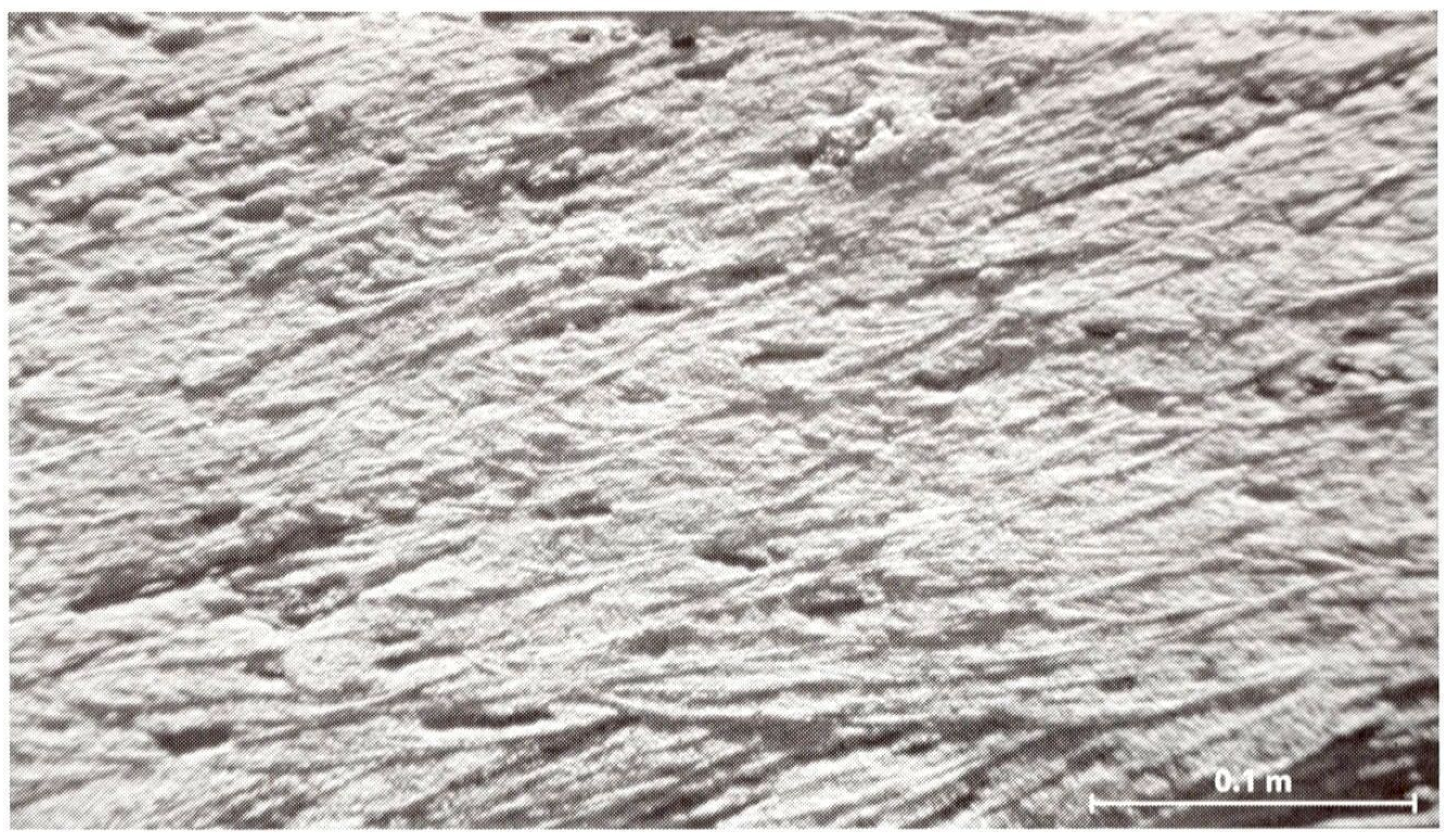


Fig. 7. Irregular mud-draped pause planes in X-bedded units. In the uppermost unit oppositely directed X-bedding is visible in herringbone X-stratification (see arrow). Hambach exposure.



a.

b.



c.

Fig. 8. Set-climbing. a. Solitary trains of set-climbing ripples. For location, see Figure 9; b. Alternating large-scale foresets and set climbing; c. X-bedding entirely made of set climbing (Barendrecht exposure).

trough area by a temporal weakening or reversal of the flow during rising tide. Deposition of suspended load during such periods of weak currents probably contributes to the thickness of the bottomsets, which in places reaches several decimetres in thickness. As is shown in Figure 9 the foresets often display a knicked, 'shovel' appearance as they pass into such extensive bottomsets. Similar shovel-toe foreset to bottomset assemblages and set-climbing features have been described from a supposed fluvial-tidal zone in Permian deposits of central India (Gosh et al., 2005).

Shovel-toe bottomsets are not restricted to the fluvial-tidal zone. They can also be found in purely tidal deposits. Here, they are laterally associated with intervals of thin bundles. This indicates that the thick bottomset intervals correspond to neap tide conditions, when dune height decreases and the dune trough is partly filled in (Van den Berg, 1982). Thick bottomsets in tidal deposits can be distinguished from their counterparts in the transitional zone by a much better organization. Instead of a disorder in directions a regular vertical alternation of flood and ebb directed x-lamination is present (De Mowbray & Visser, 1984). The above evidence suggests, that thick bottomset layers are related to decelerating flow conditions, either in time (neap-spring tide cycles), or space (upper point bar conditions in the fluvial domain). As bottomsets consist of fine-grained sand transported as suspended load, they can only be formed if appreciable amounts of fine sand are available and if a strong vortex movement does not prevent its sedimentation. In the fluvial-tidal transition zone both conditions are fulfilled: fine sand is generally available in large quantities and flow energy is moderate. The prerequisite condition of a non vigorous vortex movement is supported by the fact that in literature thick dune bottomsets have never been reported in conjunction with foresets of very coarse sand and fine gravel: dunes of this material can only exist in relatively strong flow conditions, impeding the settling of fines in dune troughs.

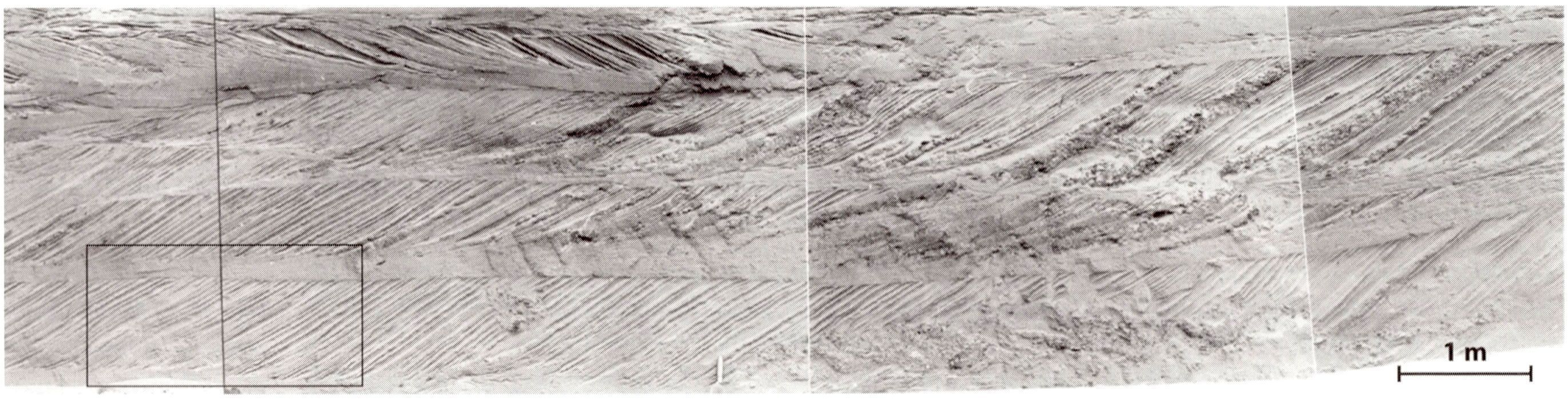


Fig. 9. Tabular X-beds, revealing extremely thick bottomsets (Barendrecht exposure). Note the wedge-shaped bottomset of the shovel-shaped foresets in the centre of the photo. Inset shows location Fig. 8.

Typical decimetre-metre scale sequences

There appears to be a gradual transition in the sequential arrangement of sedimentary structures and texture going from the estuarine through the fluvial-tidal to the pure fluvial zones. Estuarine deposits do not show a distinct vertical sequence at metre scale, apart from a progressive transition into clayey intertidal and salt marsh deposits in the upper one or two meters (Terwindt, 1971). Sediments of the fluvial-tidal domain, when viewed on an outcrop scale, may show a fining upward sequence, though in a rather rough and stepwise fashion involving units in the dm to m-order. Van Beek & Koster (1972) correlated this superposition with changes in morphology and physiography in a coastal area due to a number of catastrophic floodings in late medieval times, when large parts of the embanked areas in this part of Holland were temporarily added to the tidal system.

Tidal deposits often show regular vertical repetitions at the dm-scale, of two or more lithologic units with different sedimentary structure and texture. Sometimes also a difference in biogenic structure is denoted. Many examples of this are published. Small-scale cyclicity is attributed to change in flow energy related to the neap-spring cycle (e.g.Tessier, 1993; Ehlers and Chan, 1999; Kvale et al., 1991; Roep (1991); Dalrymple et al., 1991; Williams, 1989; Lanier et al., 1993) or to seasonal changes in the production and mineralization of organic matter (De Mowbray, 1983; Van den Berg, 1981). In the latter case, photographs reveal both seasonal and spring-neap tide cyclicity (Fig. 10). In fluvial environments dm-scale cyclicity may be found in crevasse splays, but more commonly in the fills of abandoned channels, such as oxbow lakes. An example of such cyclicity is presented in Figure 11. It is related to the alternation of relatively high and low flow energy conditions, reflecting periods of high and low river discharge.

Decimetre scale rhythmic bedding has also been reported from fluvial-tidal zone (Thomas et al., 1987). Characteristic micro sequences of this zone are the result of the alternations of high and low river discharge periods. An example is shown in Figure 12. During periods of low river discharge the flood tide, possibly helped by the density flow of an intruding salt wedge, may result in an upriver (flood) directed flow of sufficient strength to produce dunes. Probably the upriver flow is only active during a short period of the incoming tide, because of the asymmetry of the upstream travelling tidal wave (Wright et al., 1975; Allen, 1991; Brenon and Le Hir, 1999). The intrusion of the salt wedge is always accompanied by high concentrations of mud in suspension, related to the estuarine turbulence maximum. This may lead to the development of a thick fluid mud layer around slack water, as documented for the turbidity maximum in the Gilbert River (Jones et al. (1993), in the Weser, Germany (Schrottke et al., 2006), in the Humber, England (Uncle, 2006) and in the Fly river (Dalrymple et al., 2003). It explains the thick mud drapes without sand partings, deposited during a single high-water slack period (cf. Shanley et al., 1992), as, for instance, shown on top of the flood directed cross-stratification of Figure 12.

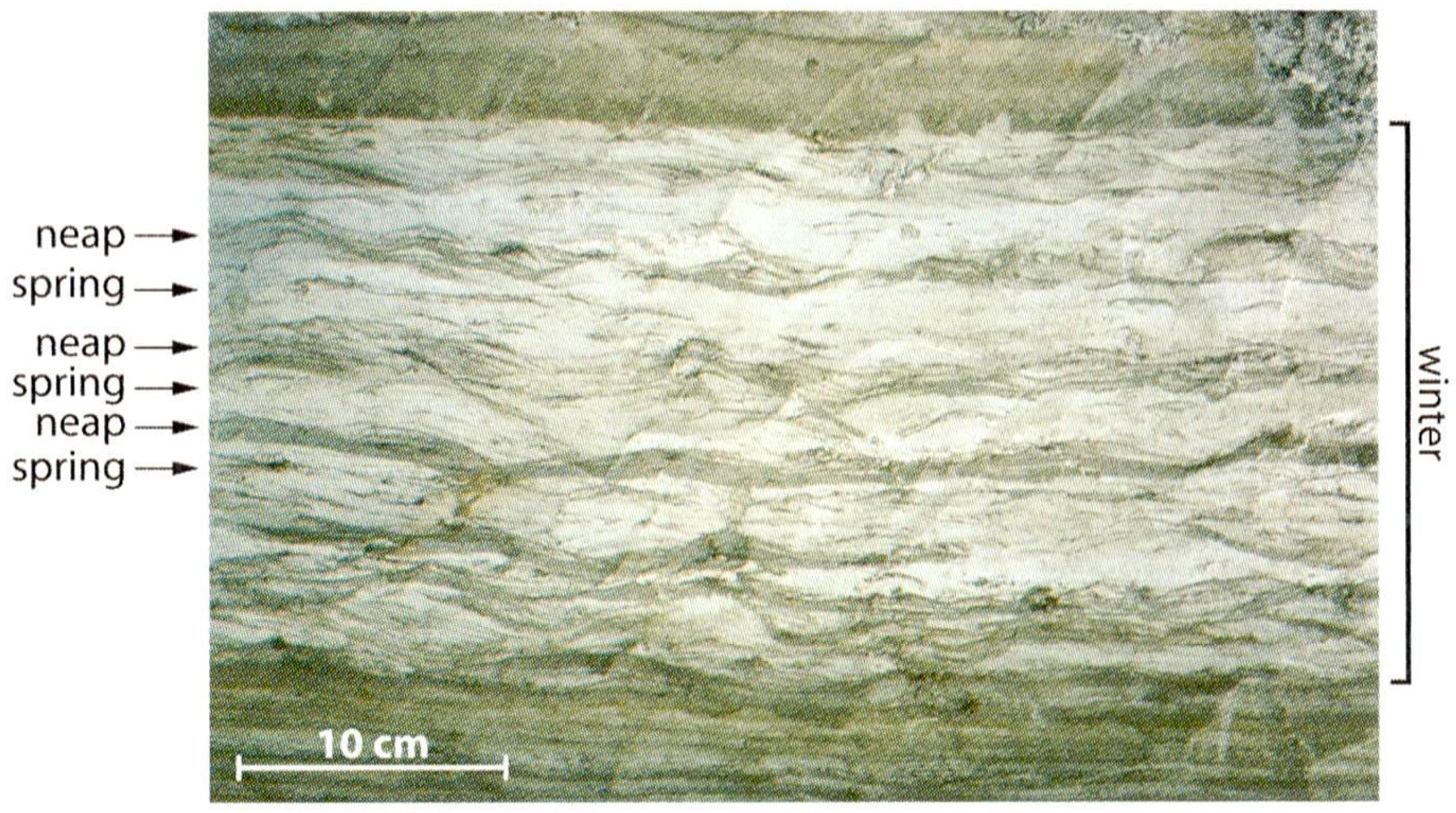


Fig. 10. Seasonal rhythmites with superimposed neap-spring cycles, expressed by alternations in mud drape intensity in the flaser bedding (winter) and the laminated layers (summer). 8 or 9 neap-spring cycles can be counted in the flaser bedding, representing the 2-month winter season. Recent deposits, Oosterschelde estuary.

Mud drapes in the fluvial-tidal zone seem to be of a more silty nature as compared with estuarine slack water deposits. Another lithological difference refers to the largest particles. Our experience is that in tidal environments generally these consist of clay pebbles, whereas in the fluvial-tidal zone peat lumps dominate. Except for extremely low discharge periods, fluvial flow is always much stronger than the opposite current.

Fig. 11. Fluvial rhythmites in a channel fill deposit (oxbow lake). Light bands are made of x-laminated sands. The darker bands are muddier, with incidental foot imprints and escape structures of mussels. The sand bands represent incidental river floods. They alternate with low fluvial discharge periods (Hambach exposure).

Fig. 12. Two successive cycles of flood directed cross-stratification followed by downriver fluvial X bedding. Note the presence of clay drapes in the flood-directed sets (formed by migration of ripples and dunes to the left). The sets generated by the upriver flow have a fine sand texture, whereas the fluvial X-beds consist of coarse sand. This demonstrates the much stronger downriver flow (Hambach exposure).

This is reflected by a difference in structure and texture or lithology: the fluvial sediment being coarser than the sediment deposited by the flood.

Depending on the local conditions many variations on the example as presented in Figure 12 are possible. An interesting variant is generated when in downstream (seaward) direction the fluvial-tidal zone comprises a bay-head delta that progrades into the central basin of a wave-dominated estuary. In a longitudinal section of the Hambach exposure unidirectional X-bedding over a distance of one kilometre passed into such a low energy environment. This strongly suggests the expansion of the river flow into a wide body of water that could very well be the basin adjacent to a bay-head delta. In Figure 13 we present a dip-section sequence of dm-scale cycles, which have been documented in lacquer peels made at this location. In plate d and e of this figure laminae of flood directed ripple form sets interfinger with thick mud layers, indicating that most of the mud layer that covers a train of landward directed ripples was deposited shortly before and during the slack water period following the deposition of the ripple. This strongly suggests the presence of the turbidity maximum and the drowning of the ripple bedforms in a thick layer of fluid mud. During ebb, the zone of maximum turbidity dispersed while moving down the river, which explains that this structure of drowning ripple form sets is only found in flood directed structures.

Discussion and conclusions

The recognition of tidal signatures in fluvial sediments is important as it enables the determination of the farthest extent of a transgression, or in terms of sequence stratigraphy, the maximum flooding surface. Notwithstanding its importance, in the current literature not much attention is given to the sedimentary characteristics of fluvial-tidal transition zone at outcrop level. Our study is based on deposits of the Pliocene and Recent Rhine and adjacent inshore tidal environments. As data from other settings with a reliable paleogeographic control are not known to us, we tend to restrict the conclusions of this study to the transition zone between a mesotidal setting at the seaward side and a medium sized river such as the Rhine at the landward side. Unlike the seaward tidal zone, the transition zone is characterised by a single meandering channel that guides the main flow of both tides. Except for periods of high river discharge, the estuarine turbidity maximum travels over some distance up and down the transition zone with each tide. In the case that the creation of the accommodation space generated by sea level rise exceeds the rate of deposition, the seaward part of the transitional zone may take the shape of a bay-head delta sensu Allen and Posamentier (1993). Hydraulic and morphologic characteristics make the transition zone different from the 'pure' fluvial and tidal environment and make as such it distinguishable on the basis of sedimentary structures and textures as a separate environment. We propose the fluvial-tidal environment to comprise the part of the river that lies between the landward limit of observable effects of probably tidal-induced flow deceleration on fluvial cross-bedding at low river discharge and the most seaward occurrence of a textural or structural fluvial signature at high river stage.

In the foregoing we have listed some diagnostic criteria for the fluvial tidal zone on the basis of sedimentary structures and sequences. None of the distinctive structures of the fluvial-tidal zone can be considered as exclusively diagnostic for the recognition of the transition zone. Such an interpretation can be only warranted if a greater array of features is seen together. The question should be addressed whether the listed criteria comply with our definition of the fluvial-tidal zone. The crucial point in our definition is what exactly should be conceived in the notion of 'visually observable effects of, probably tidal-induced, flow deceleration'. In a strict sense one may adopt the viewpoint that flow reversals are essential to tidal currents. There seems to be reason enough to widen the definition to the weaker side of the spectrum where the tidal flow only stops or decelerates fluvial flow. These conditions, which are known to occur many tens of kms up a river, are gradational with true upstream flow. What sedimentary signatures indicating tidal influence might be expected in deposits generated in this upper part of the fluvial-tidal zone where the tide is reduced to temporal discontinuities in the strength of the downriver flow? In our record we have no deposits that represent this zone, and in the available literature clear examples are lacking. As a possible candidate for structures that reflect these tide-induced fluctuations in flow strength might act cyclic patterns of weak discontinuities in X-bedding. Dalrymple and Choi (2006) suggest that stream-wise alternations in fining and coarsening of X-strata reflect tide-induced variations in flow strength. They admit, however, that the diagnostic value of such alternations is not large as they might also be formed by the periodic arrival of ripples at the dune's brink. Evidence from a large amount of data from medium to large sand-bed rivers indicates that with increasing flow strength the hydraulic roughness of fluvial dunes diminishes, whereas dune height hardly changes (Van Rijn, 1984; Julien and Klaassen, 1995). This points to a reduction of the size and shape of the vortex behind the dunes with increasing flow strength. This in turn can only be caused by a lowering of the brinkpoint, at the start of flow separation at the lee-side of dunes. A lowering of the brinkpoint during an increase in flow strength was assumed for preserved sedimentary structures in ancient deposits of fluvial dunes by Røe (1987) and Fielding (2006) and was established for recent intertidal dunes of the Scheldt estuary (a.o. Boersma and Terwindt, 1971; Van den Berg et al., 1995). This change in position of the brinkpoint can be considered as an initial stage in a transition of dunes to upper-plane bed, thought to be caused by suppression of turbulence by suspended bed material (Bridge and Best, 1988). This hypothesis finds already some support in the classical experiments of Jopling (1966). Thus, in the fluvial-tidal transitional zone, tidal fluctuations of flow strength might be reflected in minor cyclic up and down migrations of the brinkpoint in the top set structure of dune or bar deposit (see uppermost drawing in Table 1).

Cyclic decimetre sequences in tidal and fluvial environments and in the fluvial-tidal transitional zone generally are forced by neap-spring or seasonal variations. Their preservation implies a steady and high rate of ongoing sedimentation, without the interference of any important erosional event. Favourite subenvironments that offer these conditions are abandoned channels and inner bends of meandering channels. In the latter case the microsequences are superimposed on the inclined master bedding planes of a point bar. On a larger scale of observation this would classify these deposits as Inclined Heterolitic Strata (IHS). This term was proposed by Thomas et

a.

b.

Fig. 13. This Figure shows a number of photos made from a single stratigraphic level in the Hambach exposure. The distance between photos a and e is about 1 km. The outcrop was parallel to the paleoflow direction (downriver is to the left). In strike section a wide multichannel architecture was visible, displaying IHS. (see also Fig. 6), the structures shown in this figure are part of the filling of one of these channels.

a. Upper region of fluvial-tidal zone: a stack of coarse-grained X-bedded sets partly with low foreset angle can be seen associated with pebble lags. In the middle of the photo a set, indicated by A, with numerous weak discontinuity planes marks the remote tidal effect.

b. In the lower half of this lacquer peel X-bedded sets of the type shown in photo a contain a few clay drapes. Upward the lithology becomes increasingly clayey while grading into lenticular bedding.

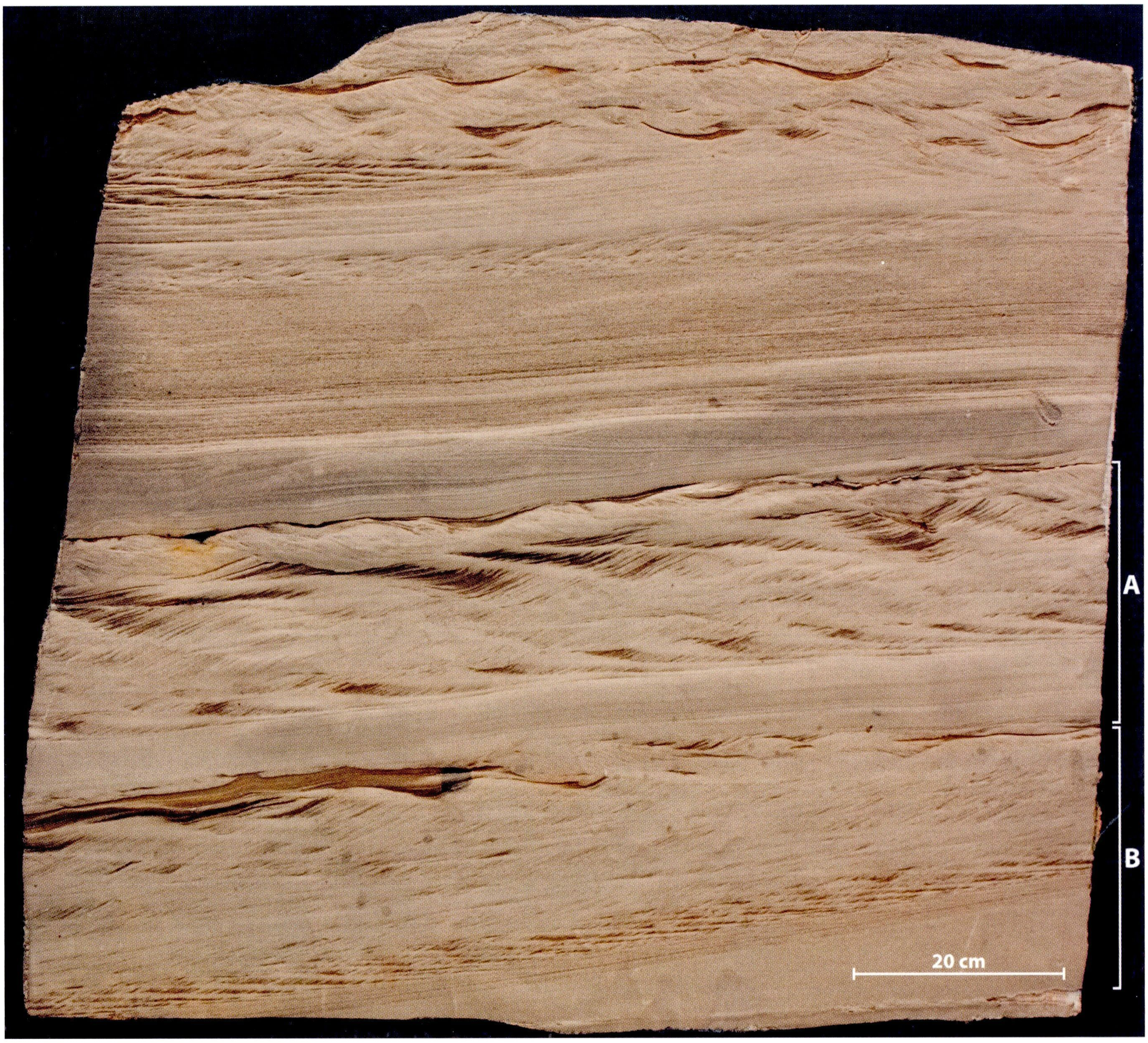


Fig. 13c. This lacquer peel constitutes several decimeter-scale successions The deposits belong to a channel system 2 meter deep and 5 - 10 m wide. The most complete sequences, A and B, show a succession of structures starting with a slightly erosional base. This is overlain by even lamination, which merges upward into increasingly climbing x-lamination. At the top of some of the sequences wave ripple sets occur which rework some of the climbing ripples. Each decimeter-scale succession is topped by a mud drape, partly eroded by the next sequence. The even lamination has discrete laminae, as normally produced by selective sorting during bedload transport. The same holds for some very thin heavy mineral streaks. This points to upper plane bed. At one place evidence of antidune conditions is preserved (set on top of sequence A). We suggest that deposition took place in a shallow crevassing mouth-bar environment under both fluvial and tidal influence. Each decimeter-scale succession then might represent a tidal cycle, starting with slight erosion at ebb-stage followed by deposition of even lamination by swift flows in very shallow water. As during rising tide the water was deepening and flow was retarded, climbing ripples increasingly developed. With further rising of the water level the depocenter migrated upstream and basinal waves started to rework the upper part of the climbing ripple set. A similar series of stacked decimeter-scale succession was described for comparable conditions from the Yellow River delta (Van Gelder et al., 1994).

al. (1987) to denote heterolitic beds generated on a sloping surfaces perpendicular to the flow. The term soon became part of the common sedimentologic vocabulary (Reading, 1996). One type of IHS is the well-known sigmoidal lateral accretion deposit (epsilon-cross-stratification) of creeks in tidal marshes (Van Straaten, 1954; Reineck, 1970). Thomas et al. (1987) acknowledges that IHS can be formed in various environments, but claims that the majority of its occurrence is generated on tidally influenced river point bars and inner bends of tidal creeks. This is explained by the favourable combination of the gradual accretion in bends of meandering channels, regular flow retardation or reversal of the flow by the tide and

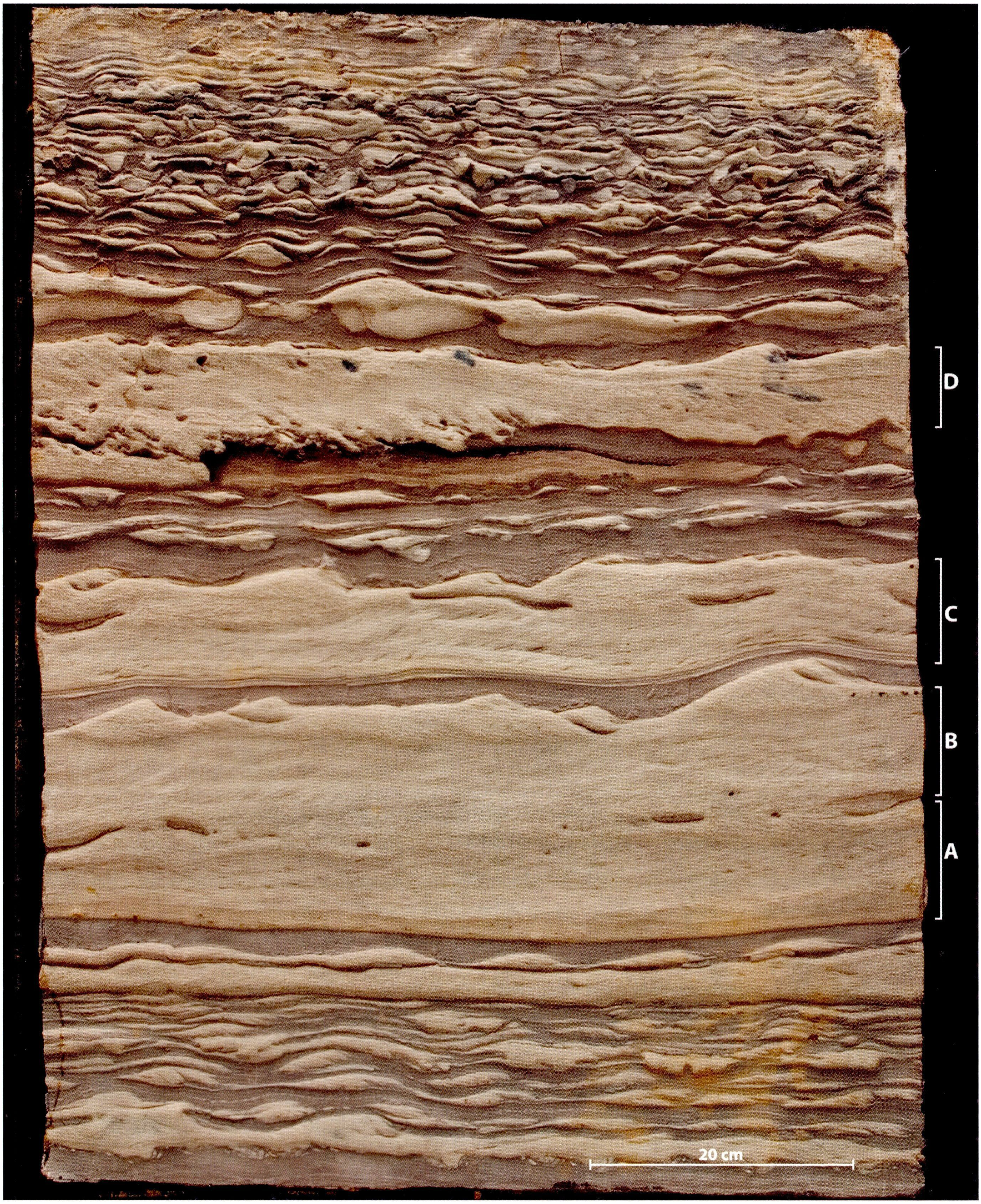


Fig. 13d. The dominant facies has changed into low energy lenticular bedding, generated by alternating bipolar flow directions and slack water periods. This is interrupted by some dm-order sand influxes (A - D). The lower three of these are of the parallel to climbing downstream directed type similar to that of photo c. They probably represent high run-off phases. Both are topped with flood-directed ripples, that drown into very thick slack water clay drapes, that possibly reflect the very high-suspended mud concentrations of the estuarine turbidity maximum. The upper dm influx (D) contains upstream-directed X-bedding with numerous intraformational pebbles. This set may be attributed to a high-energy storm set-up stage in the basin. In the upper part of the lacquer peel structures are affected by load casting.

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Fig. 13e. Lower region of fluvial-tidal zone. Basinal deposits, developed in wide, ill-defined channels. Swollen bi-directional ripples overly a very low energy alternation of suspension fall-out parallel lamination with isolated ripple sets in peat-silt background sediment. Note that flood-directed ripple form sets drown into slack water clay layers, similar as in photo d.

high-suspended mud concentration. After this claim was made, the presence of IHS sometimes has been interpreted as an important diagnostic feature of tidally influenced rivers (e.g. Nouidar and Chellaï, 2001). However, IHS comprises a much wider spectrum of facies, and its occurrence is reported from the upper parts of fluvial point bars (e.g. Thomas et al., 1987; Makaske and Nap, 1995; Brooks, 2003; Therrien, 2005), inchannel fill deposits of meandering (Allen, 1965; Gosh et al., 2006) and braided rivers (Lynds and Hajek, 2006) and in deposits produced by delta progradation (Stanley and Surdam, 1978; Martinius et al., 2001). Our beds as described in the Figures 13c - d may be listed under the IHS heading (Fig. 6), although they seem to have a wide multi-channel appearance in strike section, rather than being accretional point bars.

This leads to the question how steeply the inclined master bedding should be to receive the IHS qualification. For the Hambach channel fills the inclination of the master bedding goes down to horizontal in the centre of the channels, and only part of it would qualify, though we are dealing with one type of facies. Another objection against the use of IHS is, that it has not much diagnostic value, because of its wide occurrence. It is not the IHS structure as a whole, but the structures superimposed on it that provide diagnostic clues. Thomas et al. (1987) listed a series of distinguishing characteristics of these superimposed structures in the fluvial-tidal zone. They mention the abundant occurrence of (inclined) linsen and flaser bedding, the rhythmic alternation of sand-mud interbedding and indications of the reversal of flow, such as herringbones in x-laminated beds. This is in accordance with our experience. The IHS structure itself may only be indicative for accretion on point bars. As such, IHS-units formed by creeks crossing tidal marshes may not exceed a thickness of 2 m, whereas those of point bars in the fluvial-tidal zone can be an order of magnitude larger (Smith, 1987).

Our observation of the sedimentology of the fluvial-tidal zone is restricted to a rather narrow spectrum of boundary conditions of mesotidal estuaries and medium large rivers in the temperate climatic zone. However, the diagnostic features can be explained from hydraulic conditions that are not unique to the restricted set of examples presented in this paper. Therefore, we suppose that our criteria have a rather generic value. Unfortunately, this conclusion cannot be decisive, as detailed description of deposits that with certainty were generated in other types of fluvial-tidal transitions is lacking.

The recognition of the fluvial-tidal zone from sedimentary structures would be simple, if all diagnostic structures would be found together in a small outcrop. Unfortunately this is not to be expected, as the distinguishing structures are not spread equally along the fluvial-tidal zone (see Table 1). For instance, the lateral recurrence of pause planes and varying angles of dune cross bedding associated with them seems to be of preferent occurrence in the higher parts of the fluvial fining-upward succession. The reason is that in the upper point bar, stage variations make themselves more strongly felt and cause resident dunes to move and halt intermittently. In fact, irregular foresetting is the first sign in fluvial deposits that announces tides in the most upstream part of the fluvial-tidal zone. Conversely, the upstream (flood) directed single clay-draped X-bedding, contained in the overall fluvial X-bedded interval belongs to the spectrum of structures of the downstream part of the fluvial-tidal zone. Bidirectional heterolitic beds with the preservation of swollen ripple form sets drowning into thick clay drapes as shown in photo C and D, when only present in one of the two directions, may be the most obvious diagnostic feature of the fluvial-tidal zone in its most downstream part.

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