

TIDAL TRANSVERSE BARS BUILDING UP A LONGITUDINAL SAND BODY (MIDDLE EOCENE, BELGIUM)

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ABSTRACT. In the Middle Eocene shallow-marine Brussels Sands a long sand body is partly exposed, bordering a channel which marks the erosional base of the Formation. This 'Kraaiberg' facies shows a uniform sequence of metre-scale tabular, cross-bedded sets. Foresets dip parallel to the main axis of the sand body. The sedimentary structures suggest that the sand body was deposited during a short period, built up by a series of large, transverse bars. Their migration was governed by strongly asymmetrical tidal currents and was also affected by occasional storm erosion.

INTRODUCTION

The Brussels Sands (Brusselian, early Middle Eocene) outcrop in the central part of Belgium and have a tectonic dip of only 0.2° , NNE. The formation fills a 25 km wide, channelized depression trending SSW-NNE over a distance of 50 km (Fig. 1).

The Brussels Sands comprise a number of different sandy marine facies. The more calcareous facies yield an abundance of fossils indicating a continental shelf environment (50 m deep) in a subtropical climate. Some of the coarser facies have, as a result of differential erosion, given rise to the development of long hills striking SSW-NNE (Houthuys & Gullentops, 1985).

The wide depression and associated coarse sand facies is probably the result of strong tidal currents flowing through the 'Laon Straits', which temporarily connected the Paris Basin with the North Sea (Gullentops, 1983).

We present details of the medium to coarse sand facies exposed in the sand pit at Kraaiberg (Bierbeek, near Leuven; $50^\circ 50' 49''$ N, $04^\circ 45' 06''$ E). This exposure was visited during a pre-Symposium field trip to Luxembourg and Belgium, and its features are discussed here in the context of tidal transverse bar sedimentation.

Setting of the Kraaiberg sand pit

A particular facies of the Brussels Sands is exposed near the locality of Kraaiberg in the core of a low hill lying SSW-NNE. It is clear from the exposures and wells that the Kraaiberg Sand forms a longitudinal sand body, covering the eastern flank of the 'Archennes Channel' (Figs. 1, 2).

Figure 1.

Location map. Brussels Sands outcrop is in white. In the part marked with a star, the base of the formation overlies solid, Paleozoic rocks (Brabant Massif). Elsewhere, the Brussels Sands cover clays and clayey, fine sands. The three main depressions of the Brussels Sands base are drawn schematically.

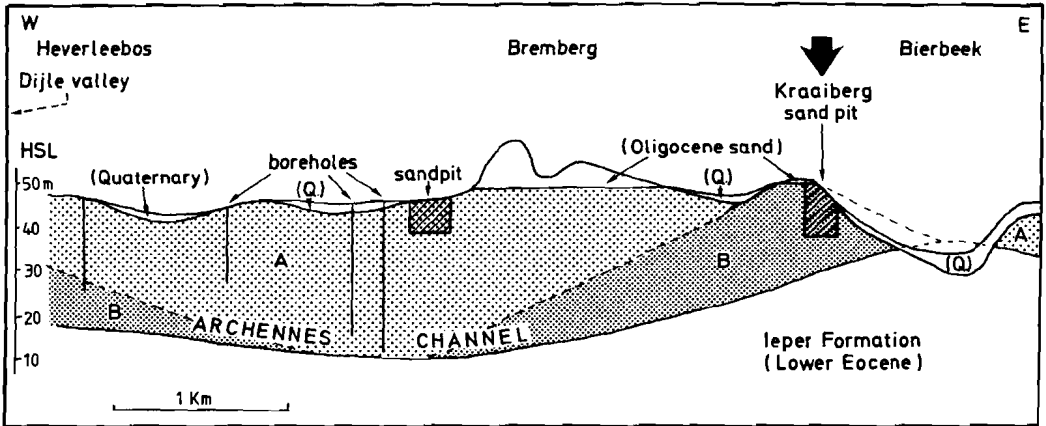
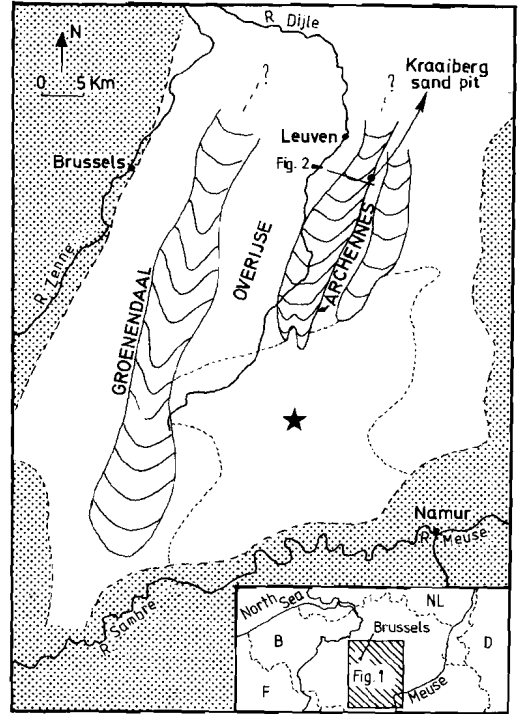


Figure 2. Schematic geological section near the Kraaiberg sand pit. The Brussels Sands is shaded. A: Upper, fine-grained facies. B: Coarse, cross-bedded facies. HSL = height above sea level. For position of section see figure 1.

The Kraaiberg sand pit provides good, 14 m high vertical sections of this medium to coarse grained sandy facies. The dominant internal structure is planar cross-bedding, arranged in tabular sets (Fig. 3).

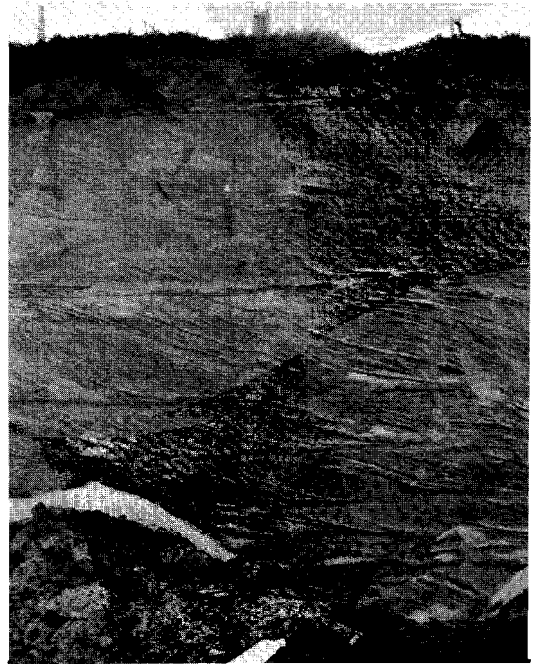


Figure 3.

A 14 m high section of the Kraaiberg sand pit showing parallel, tabular, cross-bedded sets.

The mean foreset dip is 26°, NNE (N9°E, ranging from N20°W to N45°E). Laminae dipping in other directions are very exceptional (less than 1% of the exposed area of foreset lamination). Neither foreset dip nor orientation vary significantly with height. The foreset lamination is visible because of differences in grain size, which are so well developed that a single grain-size analysis often allows the recognition of two subpopulations: one fine- to medium-grained (175 to 250 microns), the other coarse (400 microns and more, grains of 1 mm occur). The coarse-grained laminae are darker because of their higher glauconite content.

The Kraaiberg Sand has been decalcified. The original content of calcareous matter (mainly shell debris) is estimated to be less than a few percent. Thin mud layers were originally marly.

Depositional structures of the Kraaiberg Sand

The depositional structures were studied in longitudinal and transverse sections in the field as well as on lacquer peels.

a) The main sets

The exposed section (Fig. 3) consists of a coset of planar, large-scale cross-stratified sets. In general, the set boundary planes dip 1° - 1.5° NNE. All sets have

a wide lateral extent (at least 200 m) and rarely wedge out. The sets range from less than 1 m thick to 2.5 m.

The lower set boundary is overlain by a 10 cm - (rarely) 50 cm thick bottomset deposit of fine sand. The lower part of the bottomset shows indistinct horizontal lamination disrupted by bioturbation. The top part contains recognizable horizontal laminae, including mud laminae, which are connected to the toes of the most concave foresets. The upper part of the bottomset also contains vague, scattered units of ripple lamination. The units are 1 to 2 cm high. They are not mud-draped and do not extend into the foreset lamination. Their internal foreset laminae dip SSW.

The upper set boundary is an erosional plane truncating the large foresets. No topsets are preserved. Sometimes, scour pockets can be found in the top part of a set. These pockets are connected with the upper set boundary, have steep or vertical sides and are only a few dm deep and wide. They are mostly filled with homogeneous (mixed) sand, but sometimes they contain a unit of SSW-dipping foresets.

b) Tidal structures

Mud drapes are intercalated in the foreset lamination. Lacquer peels reveal mud-drape couplets, enclosing thin deposits of fine sand. Occasionally, very smallscale ripple lamination is found in this sand layer, especially near its toe, with foresets dipping SSW, contrary to the main foresets. The mud drapes are very thin and, in transverse section, mostly discontinuous (Fig. 4).

In longitudinal section, groups of concave foresets containing many mud drapes alternate with groups of angular foresets almost devoid of mud (Fig. 5).



Figure 4. Transverse section of the foreset lamination of a thick set. Limonite cemented mud layers protrude from the exposure. The blade of the spade is 12 cm wide.

The number of mud drapes, contained in one such cyclically arranged group, is variable and often indeterminate. There are generally not more than twenty. The horizontal spacing between successive groups of concave, mud-draped foresets is from 0.1 to 0.5 m in a thick set (about 2 m) and often exceeds 1 m in a thin set (about 0.5 m thick).

Exceptionally, thin sets can be seen to contain successive reactivation surfaces dipping about 10° , NNE. These surfaces are covered by small current ripples whose foreset laminae dip SSW (Fig. 6).

Both the reactivation surface and the thin covering unit of small-scale laminations may be mud-draped, but this is unusual.

c) Reactivation surfaces

Apart from the ripple-covered surfaces, two more types of reactivation occur. Convex-upward reactivation surfaces are frequent in the top part of any set. These surfaces dip NNE. Their basal part merges with the foreset lamination. Near the top the angle of dip gradually decreases. Convex-upward reactivation surfaces of different sizes may occur jointly (Fig. 7). They are never mud-draped over their total length. Several mud drapes may occur in the overlying unit of foresets.

Certain thick sets show local groups of low-angle internal bounding surfaces

Figure 5.

Groups of concave foresets and mud drapes, deposited around neap tide (arrows), alternate with more angular foresets, representing groups of spring tide bundles.

The set containing the arrows is about 40 m thick.

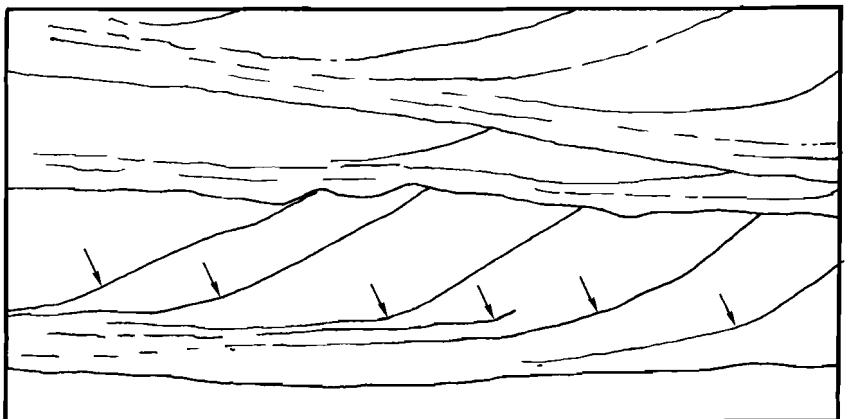
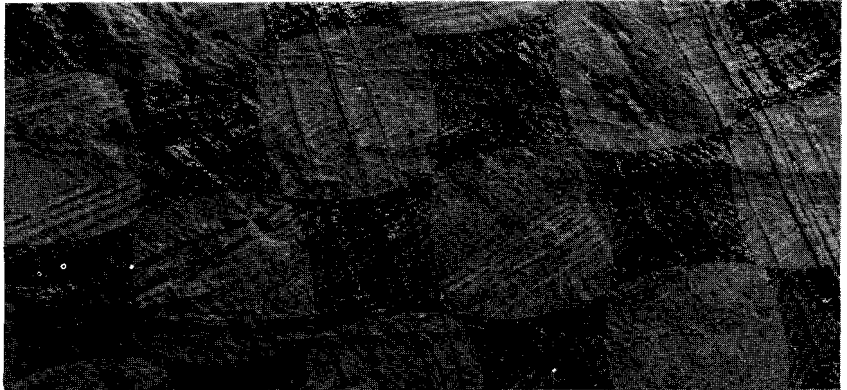


Figure 6.

Tidal reactivation surfaces. Dominant flow is to the right. Note opposite-current ripple 10 cm left of spade (the blade is 12 cm wide).

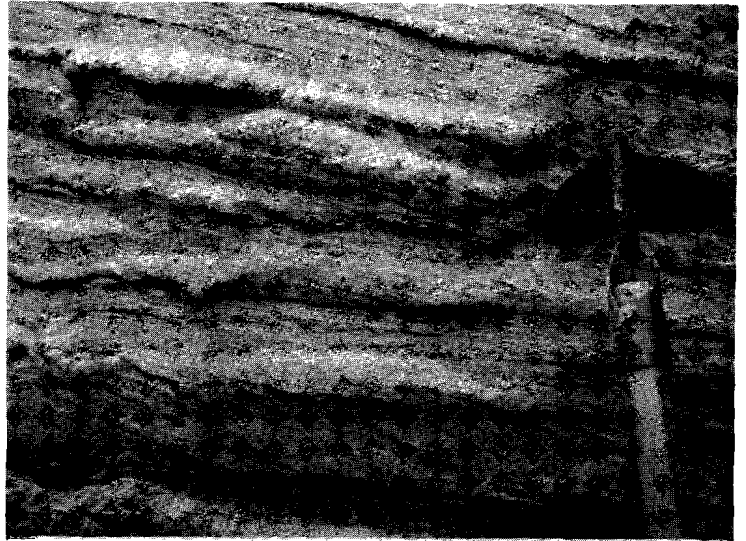
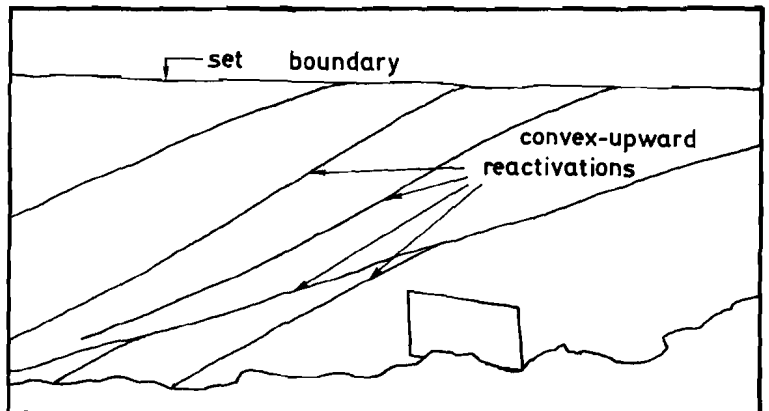


Figure 7.

Convex-upward reactivation surfaces. The slate is 25 cm long.



(Fig. 8). They dip $5^\circ - 10^\circ$, NNE. The beds they bound are only 5 cm - 20 cm thick. Several mud drapes occur within each bed. The mud drape spacing is typically wide (about 1 m). Topsets are often preserved in the foreset lamination of these beds. The beds may also contain small-scale convex-upward reactivation surfaces.

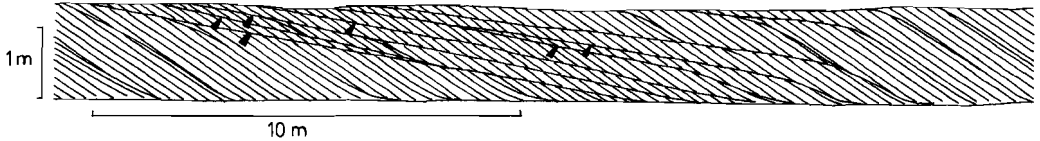


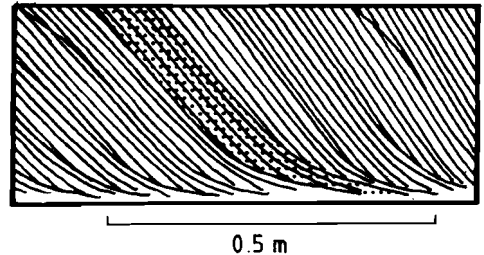
Figure 8. A group of low-angle reactivation surfaces (arrows). The dominant flow is from left to right. The reactivation surfaces gradually merge into the normal cross-stratification, in a downstream direction.

d) Details of the foreset lamination

The most common foreset laminations consist of long, normally-graded, continuous, planar foresets. Their transition to the bottomsets shows successions of angular, tangential and concave toes (Jopling, 1965; Kolsiek & Terwindt, 1981) (Fig. 9). The mud drapes occur especially on the concave foresets.

Figure 9.

Sequential arrangement of foresets. Each string of foresets begins with angular laminae and terminates with concave laminae. Most of these strings probably comprise one bundle.



A different lamination consists of tongues of fine sand that dip like the most common foresets; the tongues are surrounded by an envelope of coarse sand. In transverse section, these tongues appear as wide lenses (Fig. 10). The base of the tongue foresets is angular. The tongue-lamination characterizes the dm-scale beds bounded by low-angle reactivation (Fig. 11). Within one such bed, the tongues are clearest near the base of the foresets.

e) Biogenic primary structures

The biogenic structures are summarized here with respect to the sedimentation process. Three types of animal traces are discerned:

- (1) Branched tunnels or passages, reinforced by a thin mud lining (Fig. 4), with a diameter of about 1 cm, and up to 1 m long. They are most abundant near the top planes of sets, from where they extend vertically downwards. A 'colony' of similar, but smaller-scale burrows (diameter 1 mm) is sometimes preserved on a foreset plane.
- (2) Long, horizontal, sinuous burrows, about 2 cm wide, mostly within or just below a bottomset. Glauconite particles are concentrated in the centres of these burrows (Fig. 11, near base).
- (3) Vertical, V-shaped marks, situated in continuous foresets. A vertical burrow which is not mud-lined, starts from the bottom of the V-shaped cavity. The V-shaped marks are filled with concordant laminae. The marks are up to 10 cm wide and 10 cm to 30 cm high.

INTERPRETATION

The bedforms that produced the main sets of the Kraaiberg Sand (Fig. 3), had steep (26°), straight lee sides which accreted towards the NNE. The arrangement of foresets and internal bounding surfaces reflects the direction and rate of lee face progradation.

Mud drapes and mud drape couplets are found in many tidal deposits (Visser, 1980; Allen, 1980, 1981; Terwindt, 1981; De Mowbray & Visser, 1984; Allen & Homewood, 1984; Teyssen, 1984), including deposits that are very similar, in setting and structures, to the Kraaiberg Sand (e.g., the Lower Greensand in England, Allen & Narayan, 1964; Allen, 1981; Buck, 1985).

The mud-drape couplets prove that the environment was subtidal (Visser, 1980). The lee side deposit from one phase of dominant current is named a bundle (Boersma, 1969). The cyclic arrangement, of groups of concave laminae containing many mud drapes alternating with more angular foresets, is interpreted as a lateral sequence of bundles, reflecting the neap-spring cycle (Fig. 5) (Visser, 1980; Terwindt 1981; Allen, 1981; Nio et al., 1983).

The recognition of the exact neap-spring periodicity is complicated because not every slack water phase produced a mud drape, especially around spring tide. From the number of mud drapes we may assume that the period of a neapspring cycle was about 14 days and that the tides were semi-diurnal. By measuring the distance between successive neap-spring cycles we estimated the progradation rate of the large bedforms. The thin sets of cross-strata prograded faster than the thick sets.

The internal structure of a Kraaiberg Sand tidal bundle (Fig. 9) shows little differentiation. Only a few, long, continuous foreset laminae drape the lee face.

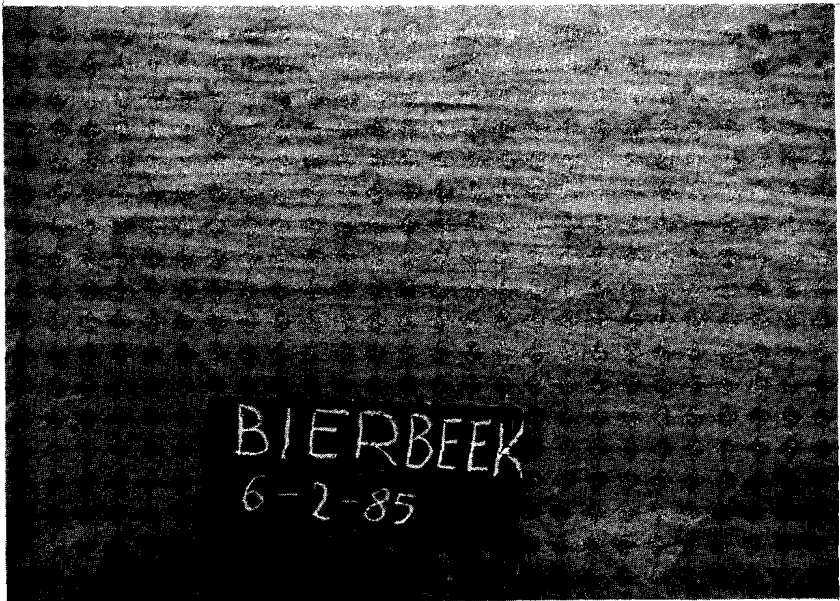


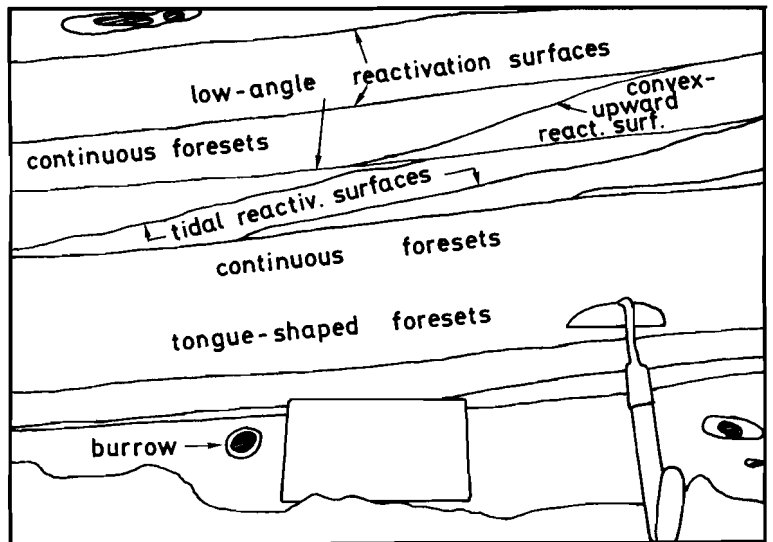
Figure 10. Transverse section of tongue-shaped foresets. A bed boundary plane is situated 7 cm above the slate (slate is 25 cm long).

No reactivation structures (Boersma & Terwindt, 1981; Kohsiek & Terwindt, 1981) were observed. The last lamina of a bundle is concave; it is formed by fallout of an excess of suspended sediment (slackening structure, Boersma & Terwindt, 1981; Kohsiek & Terwindt, 1981). The few bioturbation traces related to the foreset lamination start from bundle boundary planes.

The subordinate current, flowing SSW, was mostly too weak to erode even a small quantity of sand. Occasionally it was strong enough to create ripple-covered tidal reactivation surfaces or pause planes (de Mowbray & Visser, 1984; Boersma & Terwindt, 1981), truncating the lee face of the smaller bedforms (Fig. 6).

Figure 11.

Gently dipping beds separated by low-angle reactivation surfaces. A single bed may contain convex-upwards and/or tidal reactivation surfaces. Tongue-shapes occur only near the base of the central bed. Note: this section is slightly oblique to the direction of flow. The slate is 25 cm long.



The continuous, normally-graded laminae are formed as described by Allen (1965) and Jopling (1965): the traction carpet that moves downstream toward the brinkline of the bedform during the fast-flow stage of the dominant current, is dispersed over the brink; the lower part of this dispersion cloud settles out through the lee vortex zone to add a new lamina to the lee face. The vague ripple lamination in the top part of the bottomset is ascribed to backflow. The ripples are not very conspicuous and only the fine sand fraction was susceptible to reworking by backflow.

The convex-upward reactivation surfaces (Fig. 7) are thought to result from vortex erosion in front of a superimposed megaripple when this spilled over the brink of the large bedform (McCabe & Jones, 1977; de Mowbray & Visser, 1984).

The low-angle reactivation surfaces (Fig. 8) are formed by a different process. The first (most upstream) of a group of these is thought to be a scour surface, due to exceptionally high dominant flow velocities (presumably storm-enhanced): the front of the large bedform is scoured and flattened to a surface with a reduced dip of 5° to 10° , NNE. The overlying low-angle beds are interpreted as the subsequent infilling by downstream-moving megaripples (cf. Banks, 1973). These 2 dm - 3 dm high bedforms move quite fast, as shown by the thick bundles and the general paucity of bioturbation. The foreset laminae are either continuous, angular and normally-graded; or, when many low-angle beds are superimposed, they are tongue-shaped.

Well-differentiated tongues develop only when some sliding occurs over some distance. The coarse grains filter out during the slide (Allen, 1965). This explains the lower position taken by tongue-laminae within a bed (Fig. 11).

The tidal transverse bar model

There exist two distinct classes of metre-scale, simple bedforms formed by subaqueous deposition of sand particles on a steep lee slope: (1) ripple-shaped bedforms, characterized by a relatively short, steep, aggradational lee face and a long, gently sloping, erosional stoss side, and (2) delta- and sand bar-like (Twenhofel, 1932, p. 620) bedforms that have a flat, or even slightly downcurrent dipping, top plane instead of a stoss side.

Bedforms of class (1) are basically made of sand in transit. The lower part of the bedform can be preserved when there is a net sand input into the environment. These bedforms include megaripples and dunes. Sand waves, *sensu* Allen (1980; especially his figure 8, classes I-IV), also belong to this class.

The present authors consider that Allen's sand waves, related to symmetrical tidal currents (1980; his figure 8, classes V-VI), belong to a different group of bedforms, i.e., metre-scale composite bedforms. These are large, flow-transverse bedforms, whose relatively flat slopes carry active, smaller, simple bedforms (megaripples). In a tidal environment they were called sand waves, as early as 1936 by van Veen (1936). We would prefer the term 'sand waves' to be restricted to this class of composite bedforms, that are widely recognized in modern tidal environments (literature summarized in Allen, 1984), but of whose internal structures little is known (Allen, 1984). One should be cautious when applying this name to ancient sediments.

The Kraaiberg Sand structures could initially be ascribed to the progradation of giant, simple megaripples. Some features, however, indicate a more complicated origin:

(1) The set geometry. The bedform has a straight, depositional foreset plane. The

process that causes accretion of the lee face does not erode the surface over which the latter migrates; instead, the surface is covered by a thick bottomset, homogenized by bioturbation. The bedform thus progressed NNE over a flat, even slightly downcurrent dipping (1° to 1.5°) surface.

(2) The intense burrowing near the top of a set can only be explained if the top of the bedform has been stable for a period of several months. It is therefore improbable that the Kraaiberg Sand bedform was ripple-like, because then the bedform would have been immediately succeeded by the next ripple in the 'train'.

(3) The multitude of large-scale and, more importantly, small-scale convex-upward unidirectional reactivation surfaces prove that there was little erosion at the top of the bedform. The convex surfaces can only be preserved if erosion is limited to a few decimetres.

The bedform thus belongs to the second class of step-like bedforms, the sand bar-type. It resembles the transverse bar, which is well-known from sandy rivers (Allen, 1970; Smith, 1971; Harms et al., 1982). We suggest that transverse bars can also be found in the shallow marine tidal environment, especially in channels governed by strongly asymmetrical tidal currents. We therefore propose to call the marine bedform, described in the model below, a transverse bar.

The Kraaiberg Sand transverse bars are parallel, straight-crested and up to 2.5 m high (Fig. 12). Their progradation to the NNE was determined by an asymmetrical (Allen, 1980; de Mowbray & Visser, 1984) tidal flow system. Several successive transverse bars were active at the same time, the distance between the brinks being at least a hundred of metres.

Process of formation of the transverse bars

During the high-velocity stage of the dominant current, sediment is added to the lee face of the transverse bar. Near the brinkline, small and medium megaripples may be formed; those reaching the brink, spill over to feed the lee face (thus creating a convex-upward reactivation surface). Most of the sediment in motion is carried further downstream; only the lower zone of the sediment in transport contributes to this particular lee side. The sheltered area downstream of the lee face receives a small quantity of fine (less than 175 microns) sand. The same area is colonized by burrowing and sediment-feeding animals.

Deceleration of flow causes the last concave laminae of the bundle to be produced. The traction load comes to a standstill and the coarse grains in suspension fall out; eventually the suspended mud settles out to drape the sea floor.

The subordinate flow (to the SSW) is weak and does not often interfere with the existing bedforms.

The onset of the consecutive dominant tide brings the sediment into motion again. The upper part of the transverse bar near the brinkpoint is slightly eroded whereas the sheltered deposits of the lee face and the nearby bottomset are preserved. This process is comparable to normal megaripple progradation (Reineck & Singh, 1973).

The speed of the bedforms, migrating under these conditions, is from a few decimetres to over 1 m per neap-spring cycle. The bundles of the neap part are thinner, more concave and contain more mud.

Exceptionally, the dominant flow is so strong that the brink of the transverse bar is eroded. The subsequent normal flow regime restores the transverse bar profile. Overriding megaripples cover the eroded lee side (Fig. 13) during the following tidal cycles. The sediment supply is so great that avalanches fall in

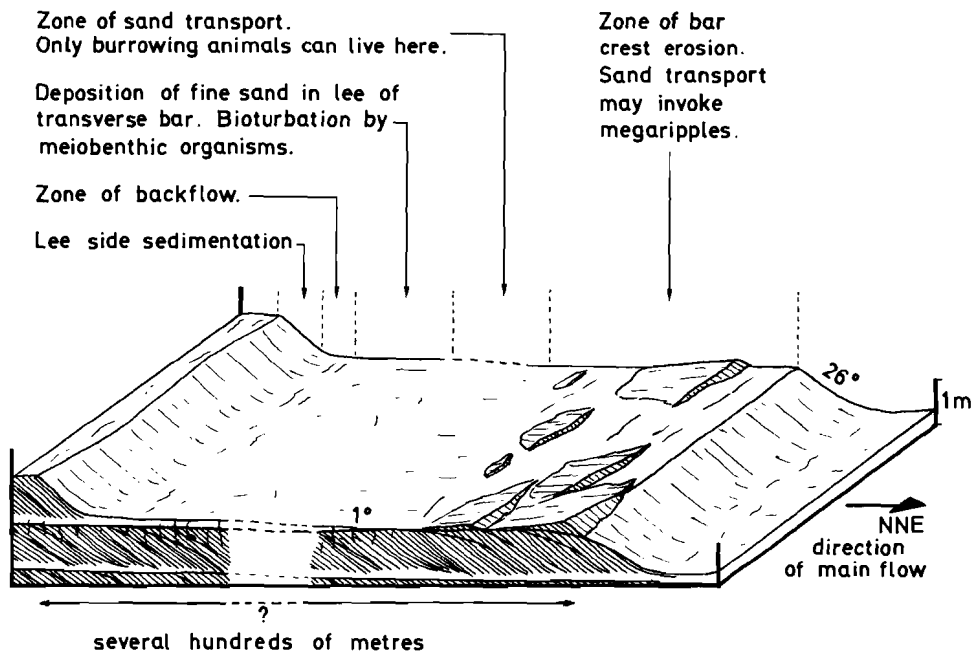


Figure 12. Reconstruction of the Kraaiberg Sand transverse bars. Note the break in the horizontal scale, which reduces the width of the zone of sand transport. The zonation arises under dominant flow conditions.

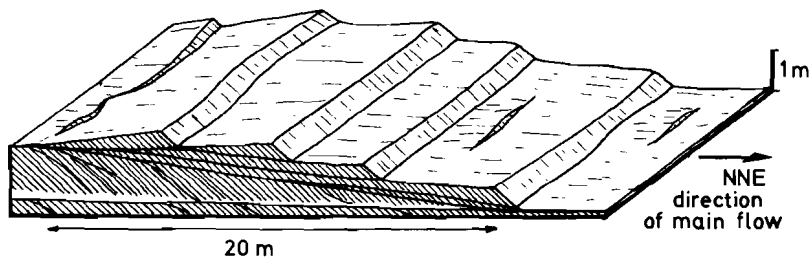


Figure 13. Descending megaripples repairing the transverse bar front after a stage of severe dominant-current erosion. A group of low-angle reactivation surfaces is generated.

rapid succession down the relatively short megaripple lee sides. During this stage aggradation occurs on the lee side of the bar, comparable to the lateral accretion of sand waves. The beds thus produced contain tongue-shaped foresets (Fig. 11), resulting from avalanching (Allen, 1965; Buck, 1985). The occurrence of tongue-shaped foresets in an environment of rapid sedimentation disagrees with Buck's (1985) model, which suggested that tongue-shaped foresets are indicative of relatively low current velocities and little sediment supply. This discrepancy, however, may be related to differences in the overall bed configuration. Buck's

(1985) observations were on lee slopes where only a narrow zone at the top of the lee face was supplied with new sediment. The sediment supply to the Kraaiberg Sand transverse bars came from the entire zone of sediment dispersion above the lee face.

CONCLUSION

The Kraaiberg Sand is essentially a channel fill and consequently the deposit had a high preservation potential.

Long sand bodies were formed parallel to the axis of the channel, which was situated at the NNE mouth of a tidal seaway connecting the Paris Basin with the North Sea. One of these sand bodies is the core of Kraaiberg hill.

The sand body was built up by the progradation of broad, straight-crested, flat-topped bedforms (transverse bars) under conditions of strongly asymmetric tidal flow and an abundant supply of medium to coarse sand. Features indicating deposition in a tidal environment are: mud-drape couplets, neap-spring bundle thickness variations, sporadic reactivation surfaces, and (exceptionally) smallscale foresets of fine sand deposited by the subordinate current.

The transverse bars acted as very effective sand traps. Due to its high sedimentation rate the sand body represents only a short period 'overrepresented' by the thick deposit.

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