GEOLOGICA BELGICA (2011) 14/1-2: 55-74

A SEDIMENTARY MODEL OF THE BRUSSELS SANDS, EOCENE, BELGIUM

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(18 figures, 1 table)

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ABSTRACT. New observations in the central Belgian Brussels Sands (transition Lower to Middle Eocene) allow to build a consistent model of the sedimentary processes and facies relationships of the deposit. The Brussels Sands fill a 120 km long and 40 km wide lowstand complex valley incision, correlated with the Yp10 50.0 Ma global lowstand. A marine transgression penetrated into the incised valleys transforming them first into estuaries and then into a tidal marine embayment. The sediment fill has a highstand signature. Filling started at the western bank, probably fed by a continuous coastal drift inferred to have existed along the southern North Sea coast. The West to East lateral progradation of the embayment shore created the "westerly lateral accretion" arrangement which dominates the Brussels Sands sedimentary record. This arrangement contains many gravity flow deposits, thought to be caused by breach failure. That mechanism conveyed coarser-grained sand from the embayment shore environment to the embayment floor. As the hydraulic section of the embayment narrowed, "flow-section restriction" events became more frequent, on either local or regional scale, depending on the presence and magnitude of intraformational relief and inherited paleorelief highs. Due to the section restriction, flow currents were increased locally causing lateral and vertical erosion to generate a short-lived accommodation space increase. Sedimentation outpaced the space creation rate and the narrowing channels and scour pits were filled with thick cross beds. Each time after filling the local space, the westerly lateral accretion resumed. The embayment closed with the deposition of the coarse glauconite sands in the East of the basin. A successive sea-level rise, following Lu1 at 48.1 Ma, caused a marine ravinement to truncate at least 10 to 20 metres of the top of the Brussels Sands.

KEYWORDS. Brussels Sands, sedimentary model, lateral accretion, breaching, flow section restriction.

1. Introduction

The early Middle Eocene (Lutetian) Brussels Formation (Laga et al., 2001) is a well-recognizable and well-exploited sand deposit in central Belgium. It consists of fine, medium and locally coarse sand characterized by the presence of hard siliceous sandstone concretions (Gulinck & Hacquaert, 1954). A division in members has been proposed (Houthuys & Fobe, 1988) but it has never been in general use. The present paper addresses the deposit by the single name of Brussels Sands.

In spite of their familiar presence in central Belgium, surprisingly little is known of their unique sedimentary structure and origin. The deposit occurs in a geographically limited part of central Belgium (Fig. 1), named here the "Brussels Basin". The Brussels Sands in that basin have been interpreted as a transgressive, estuarine to marine paleovalley fill (Houthuys, 1990). In the past twenty years, new sedimentological concepts have emerged and new outcrop and well evidence became available. They allowed to propose in the present paper an advanced, more consistent model for the deposition of the Brussels Sands.

2. Stratigraphic context

The Brussels Basin is narrow (40 km) and long (120 km) (Fig. 1). It is physically connected to the Eocene North Sea basin in the North (Gramann & Kockel, 1988; Ziegler, 1990). The base surface of the Brussels Sands has a complex valley morphology shown in Fig. 2. This map is an update of Fig. 4.5 in Houthuys (1990) and has been constructed in the same way. New wells only confirm the existence of at least five elongate depressions found earlier. Individual incised depressions appear to be asymmetrical, with a gentler west flank and a steeper east flank. The depressions contain elongate closed pits, as can be seen SE of Leuven. Also in the subcrop area in the North, at least one depression has been found east of Herentals (De Batist & Versteeg, 1999). It has the same morphology as the depressions in the South but, as data points in the intermediate area are sparse, it is not certain whether it is connected to one of them.

Most of the basin filled by the Brussels Sands cuts into the pre-Brussels Sands Ypresian depositional sequence. That sequence constitutes in Belgium a major (composite) cycle of transgression and regression (Vandenberghe et al., 1998).

The upper formations of the Ypresian Ieper group sediments of NW Belgium (Laga et al., 2001) show a marked transition from clay over clayey sands to fine sands, that contain in an increasing way wave sedimentary structures indicative of shallow, nearshore conditions (summary in Steurbaut, 2006), and thus represent a major regressive trend.

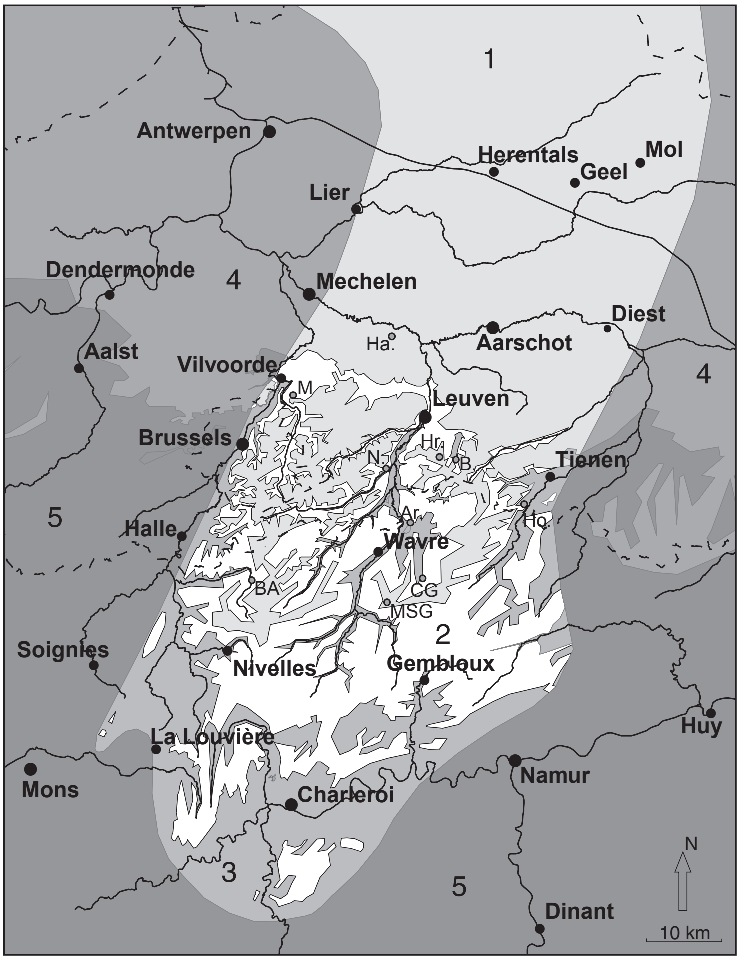

Figure 1. Occurrence of the Brussels Sands in Central Belgium. 1 = subcrop; 2 = outcrop; 3 = eroded outcrop; 4 = no Brussels Sands, with younger cover; 5 = no Brussels Sands, older outcrops. Brussels Sands basin = 1 + 2 + 3. Localities mentioned in text and captions : Ar: Archennes; B: Bierbeek; BA: Braine-l'Alleud; CG: Chaumont-Gistoux; Ha: Haacht; Ho: Hoegaarden; Hr: Haasrode; M: Machelen; MSG : Mont-Saint-Guibert; N: Neerijse.

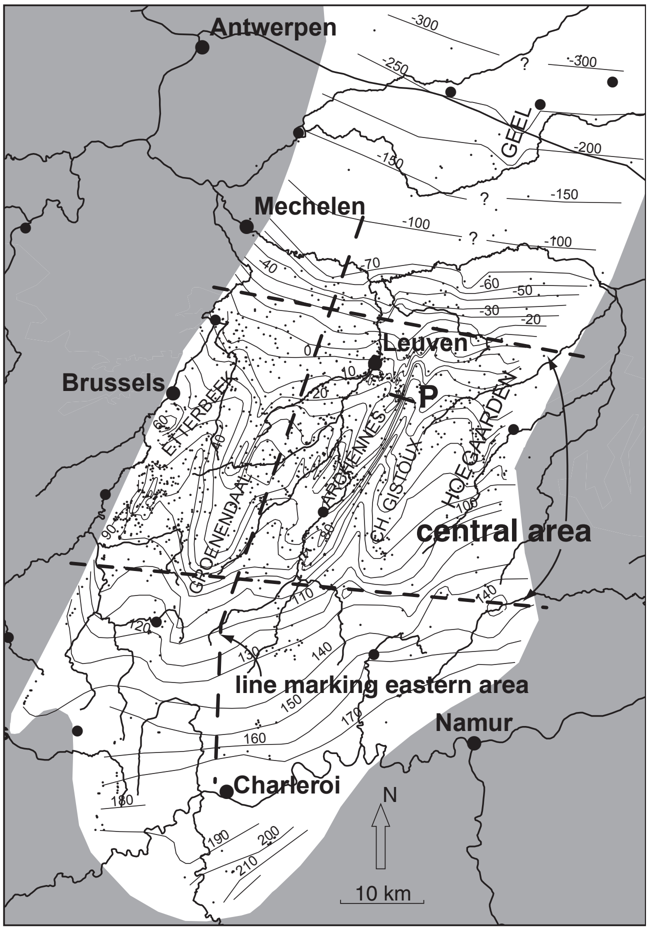

Figure 2. 10-metre contour lines of the Brussels Sands base surface (50-metre interval below –70 m TAW/DNG). Map updated from Houthuys (1990, fig. 4.5). Dots represent data density for updated part of map. Thick lines indicate subareas. The central area (indicated by short-dashed lines) has only an indicative boundary. This area has pronounced scour structures in the base surface, relatively coarse-grained sand, and the M facies intercalations are only found here. The eastern area (bordered by the long-dashed line) has coarse glauconite at the base and has a greater abundance of thick cross beds than the area west of the line. The bold, short line near "P" indicates the profile of Fig. 14.

Vandenberghe et al. (1998, 2004) link the incised base of the Brussels Sands with a major global eustatic sea-level fall labelled "Yp10" and dated 50.0 Ma (Hardenbol et al., 1998). Another incision found in western (Mostaert, 1985) and offshore (De Batist, 1989; De Batist et al., 1989) Belgium, and reported to be filled with Vlierzele Sands, is thought to be due to the same lowstand (Vandenberghe et al., 1998, 2004). No major incisions are reported from the Paris Basin, which is completely continental at the time (Gély, 2008). The emersion of the Paris Basin is estimated to have lasted about 2 million years (Ma) near Laon and Noyon, where the oldest Lutetian sediments, dated at about 48 Ma, cover the most complete Ypresian succession of the Paris Basin (Gély, 2008). In the London and Hampshire basins, both still connected, a major sequence boundary within the upper Ypresian is represented by the erosional and locally deeply channelled surface between the London Clay Formation and the overlying Bracklesham Group. The event seems to contain no tectonic component and has therefore been linked to the prominent Yp10 eustatic sea-level fall (King, 2006).

The Brussels Sands are considered transgressive, because they penetrate relatively deeply into the continent, and marine, because of their marine fauna and the sometimes high content of glauconite pellets (Vandenberghe, 1998). Glauconite has an exclusively marine origin (Odin & Fullagar, 1988; Einsele, 2000).

The Brussels Sands have in most places no base gravel (Legrand, 1945; Gulinck & Hacquaert, 1954). The sands have, unless decalcified, a high calcium carbonate content. It is clearly linked to grain size, with maximal values tied to the fine-sand deposits, where carbonates may take up more than 50 % of the mass volume. Much of this carbonate was deposited as biogenic limy mud consisting of microfossil skeleton-derived silt-sized fragments (Fobe, 1986). The content in glauconite is variable. In the context of the Brussels Sands, the term "glauconitic sands" is reserved for those deposits showing a considerable content (>2 %) of coarse, dark green glauconite pellets. A fine, pale green, minor fraction (<1 %) occurs throughout the formation.

The Brussels Sands yielded numerous marine and land-derived fossils, though of a limited diversity. Damblon & Steurbaut (2000) summarize the fossil content and the image that arises of the paleoenvironment : a tropical, rather shallow, mangrove fringed, marine bay with rapid sedimentation, in the neighbourhood of a land

Facies	Main features	Sub-facies	Secondary features	Typical outcrops	Interpreted sedimentary envrionment
X *(X1, X2, X3)*	• cross-beds, mostly between 0.5 and 1.5 m thick • medium to coarse sand • scarce bioturbation • relatively rare siliceous concretions			Bierbeek, Bouillon sandpits (near E40) Hoegaarden, near "De Kluis" Archennes, 0.5 km East of church	• floor of narrow channel • tidal migration of large and superposed medium subaquatic dunes
Xb *(XB)*	• 2-3 dm thick cross beds • beds dip 4-10 % across the basin to the ESE • medium sand • many burrows • many siliceous concretions			Mont-Saint-Guibert (2.6 km NNE of church), top of lower part	• accretion at western shore of tidal embayment • tidal migration of small subaquatic dunes
B *(B, HB)*	• completely bioturbated • many siliceous concretions • carbonate cemented stone layers in subfacies Bf • 0-4 % ESE-dipping master bedding	Bx	original thin cross beds still recognizable	Neerijse (0.9 km west of church), lower-middle part	• Bx, Bc, Bm : foot of western shore of wide basin • Bf : floor of wide basin • slow, occasional tidal migration of small subaquatic dunes; important suspension fall-out for Bf
		Bc	coarse sand	Chaumont-Gistoux (1.5 km south of Chaumont church), lower and middle part	
		Bm	medium sand	Meerdaalbos (0.8 km NW of boshuis Warande), top part	
		Bf	fine sand, carbonate mud	Mont-Saint-Guibert (2.6 km NNE of church), top part	
M *(H)*	• massive or faint, broadly undulate lamination • medium to coarse sand, no fine fraction • no bioturbation, sometimes burrowed from the top • rare siliceous concretions, often spherically shaped			Chaumont-Gistoux (1.5 km south of Chaumont church), near top	• breaching deposits • breach failure occurs at top of slope

Table 1. Overview of sedimentary facies and their sedimentary interpretation. Facies code used now is in bold. Facies code in italics is the equivalent in Houthuys (1990). The typical outcrops contain often more than one facies as the facies strongly interfinger.

surface covered with paratropical humid forests. Nannoplankton fossil datings place the Brussels Sands at the transition NP13-NP14a (Vandenberghe et al., 1998, 2004) around 49.5 Ma (Neal & Hardenbol, 1998).

The Brussels Sands are succeeded by the Lede Sands, that have a relatively flat (Houthuys, 1990), well developed base gravel. The topmost part of the Brussels Sands described by Herman et al. (2000) is NP14a and thus older than 48.5 Ma (Neal & Hardenbol, 1998), whereas the Lede Sands base gravel shows traces of an eroded NP14b. As the Lede deposits are situated at the NP15a-15b transition which is dated at about 46 Ma (Neal & Hardenbol, 1998), a relatively long hiatus spanning 2 Ma is present on top of the Brussels Sands in Belgium (Vandenberghe et al., 1998; Herman et al., 2000; Vandenberghe et al., 2004). The Calcaire Grossier in the Paris Basin has age NP15 (Gély, 2008) (between 44.5 and 47.5 Ma, Neal & Hardenbol, 1998). The Lede Sands base gravel contains rolled fragments of Brussels Sands carbonate sandstones. As the carbonate cementation is considered diagenetic and occurred in freshwater conditions, this indicates an emergence of the area before the Lede Sands transgression (Fobe, 1986). Herman et al. (2000) describe perforated stones at the base of the Lede Sands. During emersion these have been subject to the dissolution of the perforating organisms and oxidation of the surface.

Figure 3. Facies X : thick cross beds, here in tabular beds. Note burrows of the *Ophiomorpha* type, either vertical or perpendicular to the foreset laminae. Bouillon sandpit, Haasrode, 1989. Scraping tool for scale is 40 cm long and the blade is 12.5 cm wide.

In the eastern part of the Brussels Sands outcrop and subcrop area, the Lede Sands and its successor, the Maldegem Formation, have been removed by a slightly discordant ravinement surface at the base of the Sint-Huibrechts-Hern Formation (35 Ma; Laga et al., 2001). This ravinement also cuts through the top of the Brussels Sands there.

3. Summary of Brussels Sands sedimentary facies and environments

The facies description is based on the scheme proposed by Houthuys (1990). The scheme has slightly been adapted after many qualitative observations made by the author in new outcrops (Table 1).

Sedimentary facies X (Fig. 3), Xb (Fig. 4), Bx, Bc (Fig. 5), Bm and Bf (Fig. 6) are prominent members of a gradual series. Because of the gradual transitions between these facies, one may, when in doubt while making field descriptions, have to assign the codes of the two facies that best match a particular section, e.g. Xb/Bx. Facies M (Fig. 7) is always unequivocal.

The foreset laminae of cross bedding in the Brussels Sands dip predominantly to the NNE, with some spread over the sector NNW to N to NE. Very exceptionally, cross beds dipping in the opposite direction, SSW, can be observed, and this more often in the upper part of individual outcrops. In all facies but M, remnants of mud drape couplets can be found, which typify a tidal environment (Visser, 1980; de Mowbray & Visser, 1984). Tidal lateral sequences are present (Houthuys, 1990). Herringbone cross-stratification, however, has never been observed.

Cross beds of the X facies (Fig. 3) are found in trough-shaped or tabular sets, usually between 0.5 and 1.5 m thick, consisting of medium to coarse sand. Sometimes, they grade downstream into a coset of thin tabular beds. The trace fossils of the X facies belong to the *Skolithos*

Figure 4. Facies Xb : thin cross beds with many biogenic burrows. Bedding planes dip gently to the right (ESE). Exposed section is approximately 4 m high. Mont-Saint-Guibert sandpit, 2008.

Figure 5. Facies Bc : coarse, bioturbated sand. Rounded structures (arrows) may have been produced by sea urchins. Scraping tool blade is 12.5 cm wide. Hoslet sandpit, Chaumont-Gistoux, 2009.

Figure 6. Facies Bf, decalcified : some remnants of mud drapes (arrows) indicate the original horizontal bedding. Some biogenic burrows are mud lined. The part of the scraping tool blade in the left is 5 cm long. Mont-Saint-Guibert sandpit, 2008.

ichnofacies, typical of clean, loose, highly dynamic shallow nearshore environments (Frey & Pemberton, 1984). Trace fossils in the finer-grained bioturbated facies (Fig. 6) pass to the *Cruziana* ichnofacies, indicating moderate energy levels in shallow waters, below fair-weather wave base but above storm wave base, to low energy levels in deeper, quieter waters (Frey & Pemberton, 1984). The Bf subtype is the facies that also contains subhorizontal levels of carbonate cemented sandstones (the "Diegem" and "Gobertange" sandstones, often used in historical buildings).

The M facies is easily recognized due to the complete absence of cross bedding or bioturbation, in clean, well-sorted sand (Fig. 7). Especially in this facies, locally several metres thick iron-cemented sandstones are found. Sometimes, mud drape flakes and shell fragments or, in the case of decalcified sands, shell ghosts mark the faint subhorizontal or broadly undulate lamination. Locally, thick shell beds can be found, at the base or on top of internal boundaries inside this type of sand.

It is noted that the diversity in sedimentary facies occurs independently of the content of coarse glauconite grains.

Sedimentary structures related to wave action, such as wave-ripple lamination, upper-bed planar lamination or hummocky cross-stratification, that are indicative of shallow beach and nearshore environments, are completely lacking in the Brussels Sands. A lack of storm signature in the grain fabric was also noted in the carbonate cemented sandstones, as opposed to carbonate sandstones belonging to both the underlying Ypresian and the overlying Lede Sands sediments (Fobe, 1986).

Facies X is a deposit made by hydraulic sand dunes (sand waves, megaripples, megaripples superimposed on sand waves) and/or transverse bars migrating to NNE. The coarse grain size, the bed geometry and the foreset characteristics suggest relatively rapid sedimentation in a rather narrow channel showing strongly asymmetric tidal currents.

Facies Xb (Fig. 4) represents the deposit caused by the migration of medium (order of 3-5 dm in height) hydraulic dunes. They migrated under bipolar, strongly asymmetric tidal currents whose dominant flow was to NNE. The migration of the dunes was slow enough to allow extensive burrowing, especially of the *Ophiomorpha* type. The dunes migrated in the strike direction of a sloping surface.

The deposits showing facies B developed in deeper water under milder currents. The coarser subfacies Bc and Bx originated from the migration, mostly to NNE, of small hydraulic dunes with a maximum height of 1-2 dm. The driving current was tidal, but the migration of the bedforms was intermittent allowing intense burrowing to take place. The finer-grained Bm/Bf subfacies show occasional 10 cm-scale vertical grain-size cycles that are

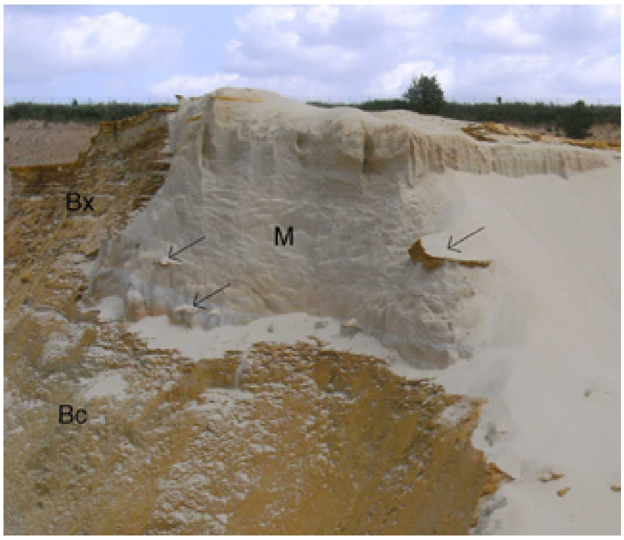

Figure 7. Erosive incision filled with well-sorted, massive sand (facies M). The massive sand embeds lumps (arrows) eroded of adjacent layers that consist here of facies Bc grading vertically into Bx. Note irregular erosive contact showing nearly vertical wall in upper part of the section. Exposed section is approximately 6 m high. Hoslet sandpit, Chaumont-Gistoux, 2009.

Figure 8. ESE-ward dipping bedding planes exposed in a construction pit in Machelen near Zaventem airport. Some bedding planes are highlighted in red. Here, facies Bx grades laterally into Bf. The bedding plane slope decreases in a downdip direction. Construction works of the Diabolo high-speed railway link to the airport, near Machelen exit on the E19, exposed in March 2009.

thought to represent the stacking of intensely burrowed, thin cross beds. Benthic life was abundant. The action of burrowers, tunnel builders and sediment feeders was such that very often the complete original stratification was disrupted and homogenized. The mechanism responsible for the observed grain-size subtypes in facies B, giving rise to coarse (Bc), medium (Bm) and fine-grained versions (Bf), is not well understood. It might just represent distance to shallower parts in the basin, with the coarser subfacies occurring near the slopes of the shallower parts.

For facies M, Houthuys (1990) proposed a tentative interpretation as a storm or hurricane related mass deposit. It is now interpreted as a mass deposit from a dense suspension occasioned by a sand gravity flow. The simultaneous lack of fines, well-developed lamination and of any bioturbation traces are a first indication. Sometimes, plastic deformation structures are present near the upper boundary of internal beds that had been sealed by a thin mud layer. Such structures are indicative of the high original water content and therefore the rapid sedimentation. More arguments from the geometrical arrangement of this kind of deposit follow in section 4.2.

4. Facies spatial relationships

All facies families appear in every vertical thickness from less than 1 m to several tens of metres. Thickness variations can be considerable over a short distance. Also, the facies occur intricately mingled. In fact, this variability is one of the hallmarks of the Brussels Sands and trying to make sense of the spatial arrangement of the facies is the very subject of this paper.

4.1. The westerly lateral accretion

The most common spatial arrangement of facies is the lateral succession Xb-Bx-Bf. “Lateral” is used here to designate the cross-basin direction WNW-ESE. Bioturbated cross beds belonging to facies Xb, observed in a large outcrop, always dip 4-10 % to the ESE. Downdip they are often seen to grade into Bx and finally into Bf. The direction of this grading is invariably from WNW to ESE. The sloping surface of the bedding plane associated with this arrangement is concave upwards, i.e. the slope decreases from about 10 % near the top of the formation to horizontal near the base (Fig. 8).

The lay-out principle of this arrangement is depicted in Fig. 9A. Successive planes downlap to the ESE. A thin

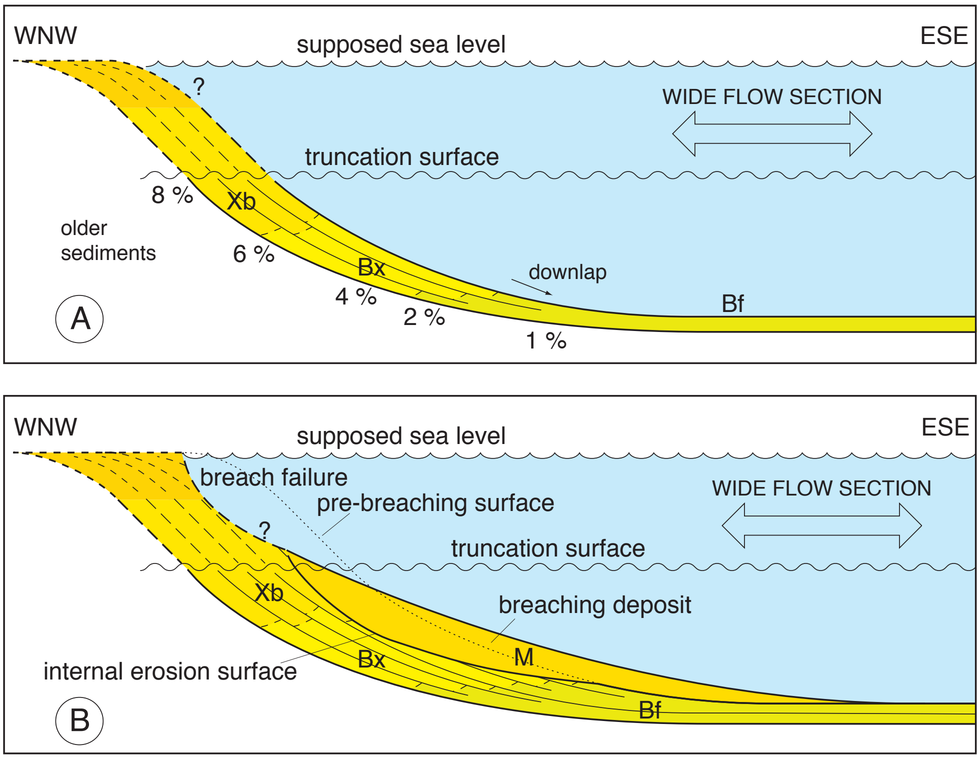

Figure 9. Principle of westerly lateral accretion. A : general layout of the lateral accretion arrangement forming a progradational, western shore of the Brussels Basin. Main flow direction is SSW-NNE, perpendicular to the profile. B : Slope apron of facies M partly cut into the westerly lateral accretion arrangement and covering the foot of the shore slope. The truncation surface in A and B is posterior to the deposition of the Brussels Sands.

layer of Bf (order of 10 cm) corresponds laterally with a thicker (30 cm or more) layer of Xb. The grain-size decreases gradually along the bedding planes with the coarsest (often medium-sized) grains in Xb near the top of the formation, laterally grading downslope into the very fine sand of Bf. The stacking of this kind of bedding planes results in a coarsening-upward sequence.

Clearly, the observed arrangement results from the lateral progradation of an inclined depositional surface accumulating sand thus causing the sloping surface to migrate from West to East. Hence the adjective “westerly”, which is used here to indicate a sediment source area situated in the West and the style of internal layering showing a progradation from West to East.

The westerly lateral accretion is interpreted to have taken place in a relatively open and flat sedimentary basin, at least several kilometres wide. From the absence of any wave structures, it is inferred that the preserved part occurred at relatively great water depth (several tens of metres), well out of reach of wave action, below the local storm-wave base. *Ophiomorpha*, very abundant here, was often considered indicative for the littoral or sublittoral environment, but was later recognized to have a very broad bathymetric distribution (Frey et al. 1978, *in* Dodd & Stanton, 1990). Therefore, in Fig.9, this sloping surface is seen as a prograding shore, with sediment accretion filling the basin from West to East. Because only these relatively deep facies are preserved, the upper shallow-water part of the section is assumed to be truncated by later, post-Brussels Sands erosion.

4.2. Intercalations of structureless sand

Frequent intercalations of units consisting of massive, almost structureless sand (facies M) occur in the westerly lateral accretion deposits (Fig. 9B).

Outcrops exposing facies M often show several beds consisting of facies M, repeated over the vertical direction (Fig. 10).

The massive sands occur geometrically in either canyon-like scour fills or slope aprons.

The canyons are predominantly found in the upper part of the sedimentary record. They have very steep, erosional sides, with irregular morphology (Fig. 7). This morphology is somewhat guided by the degree of compaction of the sediments into which the canyon was cut. Sometimes, the sides are even overhanging, which is the case when the canyon was cut through supposedly more cohesive sediments, such as those belonging to facies Bf. In that case, often sediment clasts, sometimes metre-sized, are found near the lower contact of facies M. They are clearly lumps of the adjacent, eroded sediment. The long axis of these canyons is difficult to establish in outcrops but observations so far are consistent with their being perpendicular to the main flow direction, i.e. WNW-ESE. The canyon width is typically about 20 to 40 m and the incision may be as deep as 15 to 20 m. It is often in these canyon fills that up to a few metres thick, massive ferruginous sandstones can be found.

The slope aprons are found predominantly in the middle and lower part of the sedimentary record but they also occur near the top. They are long asymmetrical bodies with the long axis parallel to the basin axis, i.e. SSW-NNE. The aprons are thick at the west side (from a few decimetres to over 10 m) and taper out to the ESE over large distances, in the case of thick units at least over several hundreds of metres. The lower base of the M slope aprons is erosional, but relatively flat. A slope apron probably consists of several coalescing fans of sediment. A single depositional fan has its apex at the west side. Such a fan-shaped upper boundary plane for facies M was observed in an outcrop near Machelen (Fig. 11). At the west side, the contact of an M slope apron with lateral facies is always sharply erosional. The erosional contact can be a vertical surface, just like in the canyons (Fig. 10, upper part). The top boundary slopes gently in an easterly direction (Fig. 9B; Fig. 10, upper part).

The sediments into which M units cut, belong to any other Brussels Sands facies. The top surface of an M deposit is obviously a surface of non deposition. Quite intensive burrowing, showing many decimetres long, branched specimens of *Ophiomorpha*, may originate from this top surface. Each of the other facies can be found to overlay an M unit. Often, near the base of the formation, facies B (Bf, Bm, Bc) is found to conformably cover the massive sands. Higher in the outcrops, the covering facies

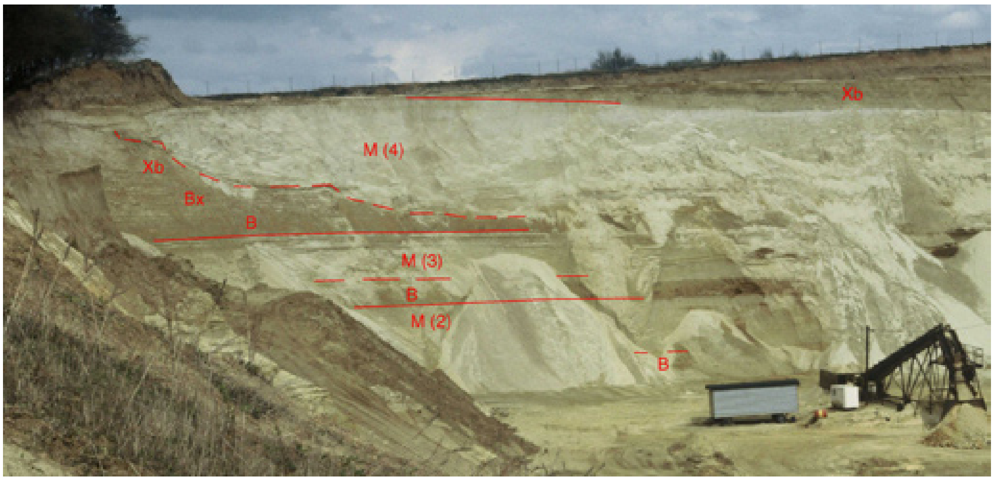

Figure 10. The Alconval sandpit in Braine-l’Alleud showed 5 stacked units of facies M, three of which can be seen in this picture taken in 1994. Note incision of M(4). Sandpit face is about 30 m high and oriented N (left) -S (right).

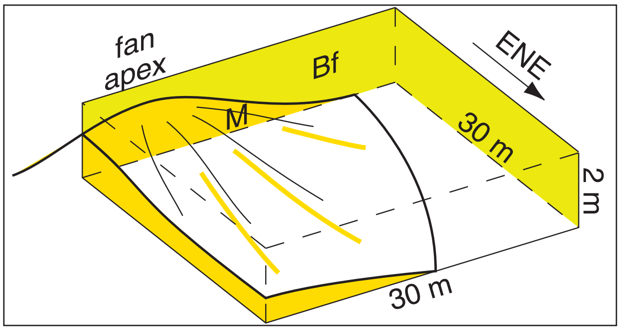

Figure 11. Reconstructed contact surface of facies M top plane and conformal cover of facies Bf, such as observed in a temporary construction pit for the Diabolo high-speed railway at the Woluwelaan crossing, Machelen. Exposed in March 2009. The top part of the M fan is bioturbated.

is often Xb. Also here, the cover is conformable. The master bedding planes of the Xb unit, dipping to the ESE, are parallel with the top plane of the M unit. Rather exceptionally, some thick cross beds can be found covering the top of an M unit. The contact is then often incised.

In a flow-directed outcrop (SSW-NNE), the M slope apron units have parallel boundaries (Fig. 10, lower part).

The way in which M units are interwoven in the lateral accretion arrangement is illustrated by the profile in Fig. 12. This profile links some twenty outcrops, many of which were large well-exposed sandpits opened in the 1970s and 1980s. The profile is representative of a wide area of the western part of the Brussels Sands basin, but also in the east part of the basin, this general arrangement dominates the deposits.

The M facies sand is often a bit coarser than the surrounding facies. The well-sorted, well-rounded quartz grains indicate a sediment that is typical of a beach environment. As no beach deposits are found in the Brussels Sands, this is another reason to suppose a rather important truncation, such as suggested in Fig. 9B. Many M units contain shell concentrations and layered shell debris. They have clearly been transported.

Puzzling together the geometry of the canyon- and the wedge-shaped units of facies M, a mass-transport process like depicted in Fig. 13 is proposed to best account for the observed relationships. The amounts involved in each mass-transport event must have been huge to account for thousands of cubic metres found in some M units. A recently described process that involves a self-maintaining density flow of sand is *breaching* (van den Berg et al., 2002). This is a form of large bank failure that can generate high-density sediment-water flows that deposit thick, rather structureless sand masses at the foot of a bank in a very short time.

Two mechanisms of bank failure are discussed by van den Berg et al. (2002). A *liquefaction slope failure* involves the sudden liquefaction of a large mass of very loosely packed sand. An external triggering agent, such as an earthquake, additional stresses produced by the tidal flow or outflowing groundwater during an extreme low tide, may cause the pore water pressure to increase suddenly. The sediment's supporting framework collapses and a slope instability may result, usually along a rotational glide plane. The event is mostly a relatively short-lived process that produces a single depositional unit.

In the case of the Brussels Sands, no evidence is found for a basal, rotational glide plane and the M facies deposits often seem to be of a composite nature.

Therefore, an origin following van den Berg et al. (2002)'s *breach failure* is proposed here. Breach failures are known from the dredging world. Van den Berg et al. (2002) define a breach failure as a gradual retreat of a subaqueous slope, which is steeper than the angle-of-repose near the top of the slope, in fine non-cohesive, dilatant sands. In nature, a breach failure may result from a liquefaction slope failure. When a steep subaqueous slope forms in slightly compacted sand deposits, this may be a stable, retrograding feature for some time. Slope retreat in the upper, steepest part of the breach is dominated by the failure of thin slabs of sand. Lower down the gradually decreasing slope, the slabs disintegrate into a dense suspension flow. This flow accelerates and dilutes, thereby increasing its erosive capacity and transforming into a turbidity current.

Arguments for proposing a breaching origin for the M facies in the Brussels Sands are:

- from the arrangement of sloping master bedding planes, and the thickness of some M deposits, reaching up to 15-20 m, it is clear that a pronounced topography was present during the deposition of the Brussels Sands;
- the overall geometry of the M facies reconstructed from outcrops (Fig. 13) fits well the breaching mechanism :
  - in the upper reaches of M units, vertical cliffs are found which may be relics of the steep retrograding wall of the breach;
  - the erosive canyon-like channels filled with M sand may be caused by the density flow from the breach;

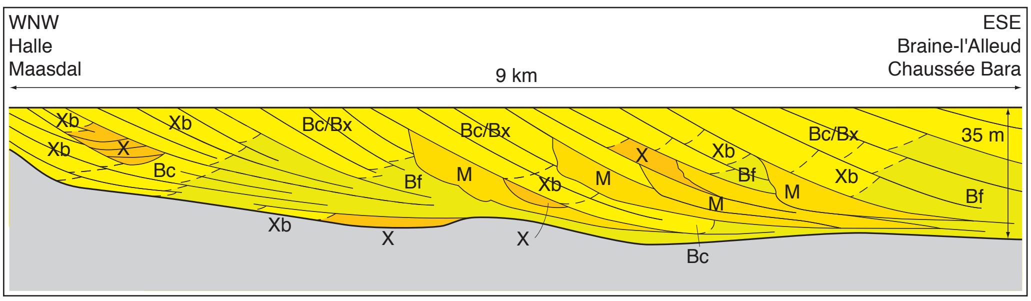

Figure 12. Cross section in the western part of the basin, between Halle and Braine-l'Alleud. Reconstruction of facies spatial relationships based on observations in 20 outcrops.

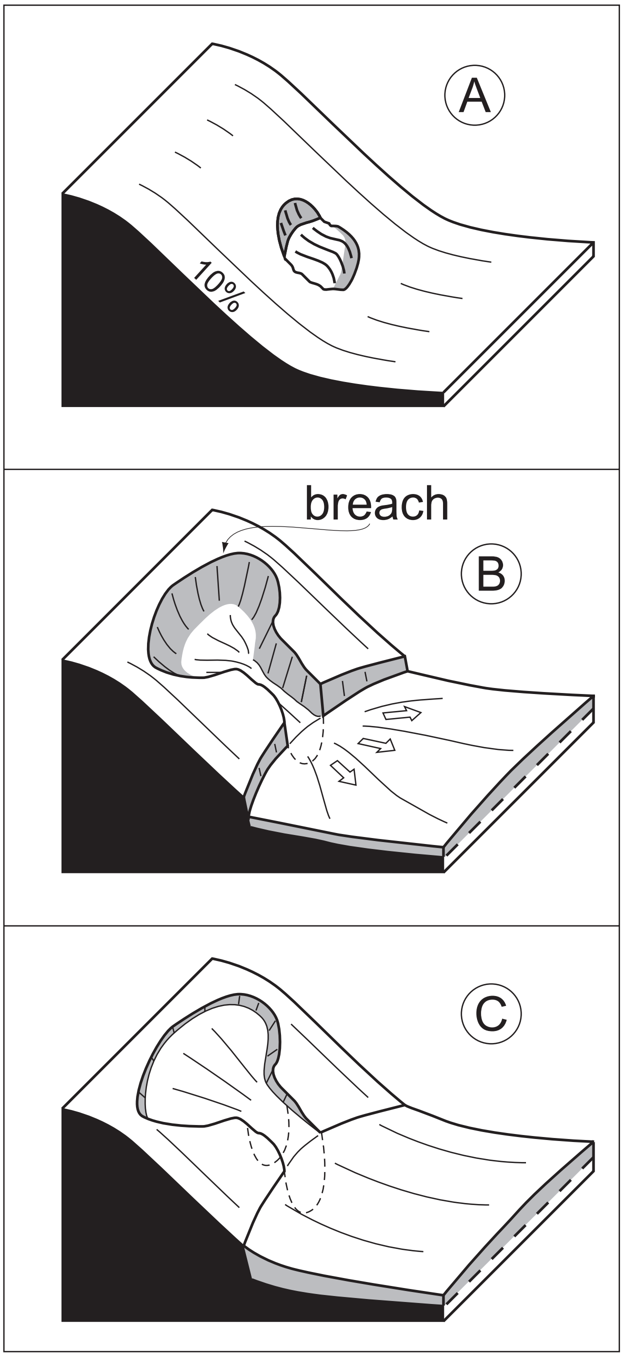

Figure 13. Processes reconstructed for explaining the observed facies M geometry fit well van den Berg et al. (2002)'s breach failure mechanism. Depicted is the western bank of the Brussels embayment. Slope angles are relatively steep as a result of continuous lateral accretion. A : some initial slope failure causes a small breach with vertical walls. B : the breach grows into the bank sediments. Slices of sand dropping from the receding walls create a high-density, sandy turbidity flow that cuts a canyon and quickly drops its load at the foot of the bank. C: the process goes on for some time, until the transport canyon is choked. A slope apron and a canyon fill of facies M have developed.

- the M slope aprons may constitute the major deposit body at the foot of the breach;
- the faint lamination often observed in M facies may be produced by pulsations in the density flow, fed by successive slices of sand caving in at the breach.

The M facies in the Brussels Sands would constitute an example of breaching deposits formed in relatively coarse sands. Van den Berg et al. (2002)'s original examples are in fine sand.

The observed canyons may contain the lower part of the breaching source area. They can be interpreted as the supply channels that form during the flow of the sand to the basin floor. The aprons are the deposits of the sand flow at the foot of the slope. As the slope is not too high (some tens of metres at most), rapid accumulation of the fan deposit leads to the choking of the supply channel, which will ultimately stop the breaching.

4.3. Thick units of cross bedding

In some places, metre-thick exposures of facies X can be found. The internal arrangement is well described in Houthuys (1990). More recently, some good outcrops near the classical Bierbeek sandpits have permitted to relate facies X with the other facies.

In a majority of cases, X units are related to the bottom of the formation. The facies is consistently more found in the eastern half of the basin (Fig. 2). In some small areas, the X facies makes up the entire vertical succession of the formation; this is the case at the east flanks of the Archennes and Hoegaarden channels (Fig. 2). The Bierbeek sandpits, situated about 5 km SE of Leuven, are located in one such area.

The Bierbeek high-speed railway trench and tunnel exposures crossed this area. The outcrops were oriented in a flow transverse direction. They were key in understanding the lateral arrangement of facies.

Fig. 14 illustrates the shift in interpretations related to the X facies geometry in Bierbeek. The general shape of the Brussels Sands' basal surface and the occurrence of different facies was known from a series of wells dug in 1988 (Houthuys, 1990). The main challenge was to fit the occurrence, next to each other, of fine, carbonate-rich sands in the West and a body of thick cross beds in the East, known to fill a very local depression and, at that location, to take up the entire thickness of the formation.

While observers in the first half of the 20th century hinted at folding and faulting (Halet, 1932), Houthuys (1990, his Fig. 4.26, copied here in Fig. 14A) clung to the widely accepted view that coarse, cross-bedded glaucony sands must be attached to the base of the Brussels Sands (Gulinck & Hacquaert, 1954) and thus constitute a lower member. Indeed, thick bodies of coarse glauconite sands are always found near the base of the formation. This observation has also been implemented in the profiles to the latest geological map (Leuven sheet, Vandenberghe & Gullentops, 2001, their Fig. 9.2 and 9.3). In order to assign a basal position to the glauconitic sands, Houthuys (1990) inferred a stacked channel deposition sequence (facies X) to be flanked by an abandoned channel filled later with finer sand under quiet flow conditions (Bx/Bf) (Fig. 14A). As one borehole hinted at a vertical cyclic repetition of facies, a shaded area was introduced to indicate the uncertain interpretation.

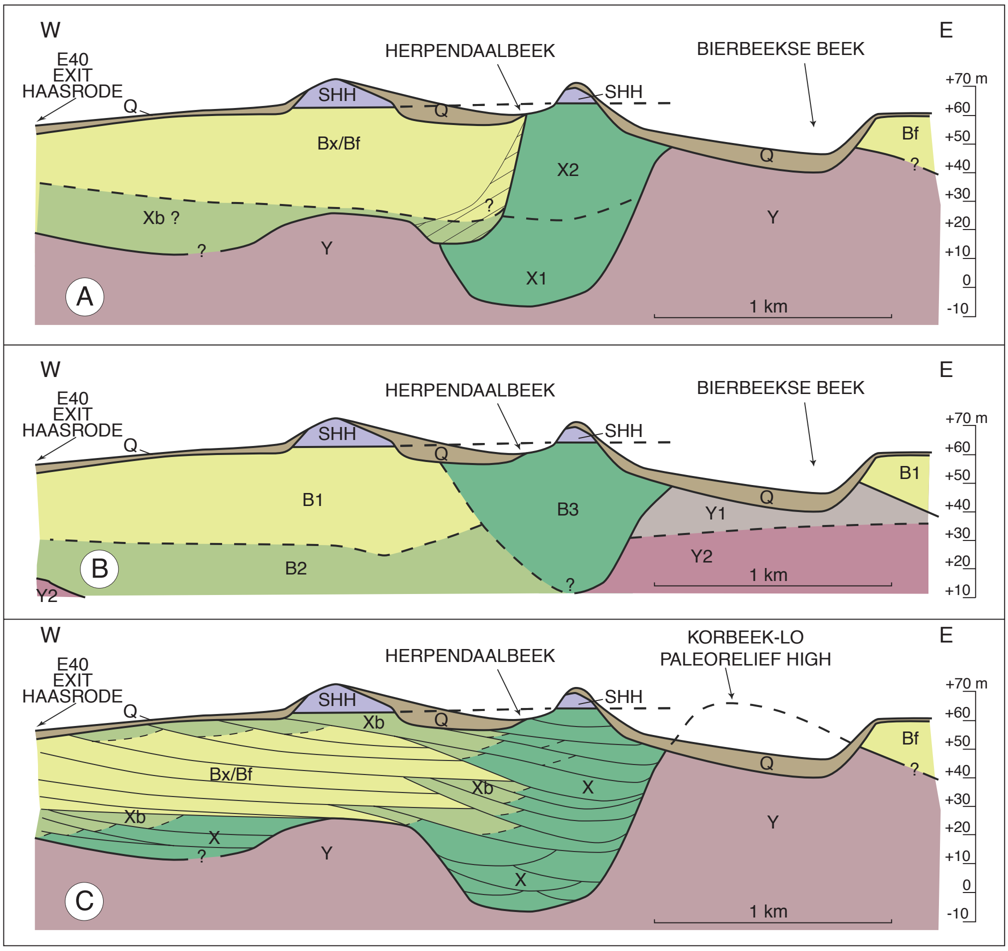

Figure 14. Successive interpretations of a profile situated along the E40 motorway SE of Leuven (position : see Fig. 2). A: interpretation by Houthuys (1990). B : interpretation by De Geyter for Tucrail NV/SA (1993, unpublished). C : author's current interpretation. Y, Y1, Y2: deposits of pre-Brussels Sands Ypresian age. SHH: Sint-Huibrechts-Hern Formation, base Oligocene. Q: Quaternary sandy löss and alluvial and colluvial deposits.

Next, an interpretation by De Geyter of geotechnical tests carried out for the new high-speed railway is shown (Fig. 14B). The original profile, made in 1993 for Tucrail NV/SA, has been projected onto the profile of Houthuys (1990). A superposition of the coarse glaucony facies containing few concretions (B3) on the fine-grained, carbonate facies with many concretions (B1) and a medium-grained facies containing an intermediate amount of concretions (B2), was observed. Here, the configuration was interpreted as a final incision stage followed by filling with coarse, glauconite sand, thus making of the coarse glauconite sand a final member.

Based on the observations in the outcrops during the high-speed railway construction works, it is clear now that the thin, bioturbated cross-beds of facies Xb show a transverse-basin grading into the thick cross beds (Fig. 14C). Let's first focus on the top 15 m of the section. The thick cross beds occupy the easternmost part of the section, where they could be seen in erosional contact with the older Ypresian very fine sands that crop out more to the East (Halet, 1932). Individual thick cross beds could be traced laterally to the NW in the outcrop, where they, while sloping upwards, graded into thin cross beds with many burrows belonging to the facies Xb. In the westernmost tip of the outcrop (below "H" of Herpendaalbeek in Fig. 14C), the fine, completely bioturbated, carbonate rich facies Bf/Bx was exposed below facies Xb, showing subhorizontal bedding. The master bedding planes of the Xb facies sloped 6 to 8 % to the SE. An erosion plane at the base of facies Xb can thus be inferred, though a single major erosion plane was not prominent in the outcrops.

A cored drilling situated 6 km to the NW (Leuven Artois borehole, ref. kb32d89e-B340 of dov.vlaanderen.be) showed a package of 6 m of thick cross beds of facies X, inserted between slightly finer-grained bioturbated cross beds of facies Xb, thus demonstrating that packages of thick cross beds occur intercalated in finer grained, strongly bioturbated sand.

Based on the observations in this well and the uppermost 15 m of the section, an interpretation of the deeper part of the section was made, that respected the well evidence used for interpretation A of Fig. 14.

It follows that the facies families B, Xb and X must simultaneously have occurred next to each other in the sedimentary environment. The section is then a vertical stacking of these juxtaposed occurrences.

This interpretation has been summarized in an "easterly closure arrangement" which is depicted in Fig. 15. The arrangement is the lateral disposition of facies at the east side of a deeper area of the sedimentation basin, bounded to the East by a submerged paleorelief high. The arrangement shows a lateral grading of the prograding slope facies Xb into the channel floor facies X.

The longitudinal variation of the facies X is less well known. In longitudinal sections, bedding planes are often

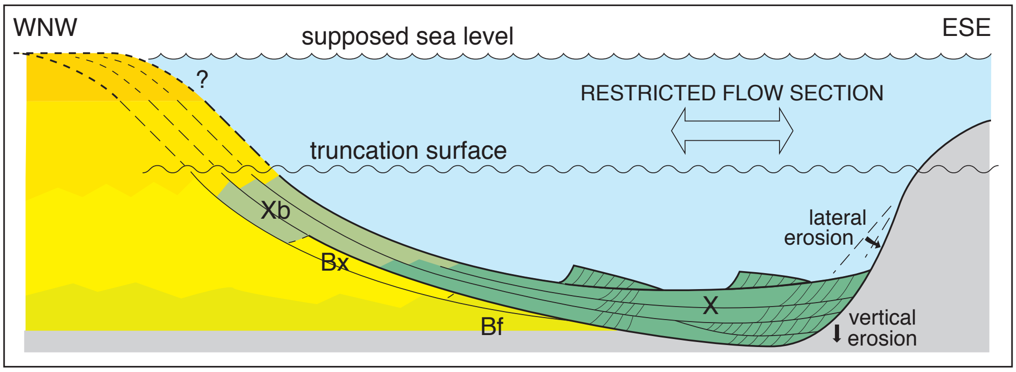

Figure 15. General layout of the "closure arrangement" at an eastern submerged paleorelief scarp in the base of the Brussels Sands. Main flow direction is SSW-NNE, perpendicular to the profile. The truncation surface is posterior to the deposition of the Brussels Sands.

subhorizontal or dip a few percentages to the NNE. The thick cross beds of Archennes seem to be connected with the Bierbeek X facies to form one long body of coarse-grained, thick cross-bedded sand, which hugs the steeper east flank of the Archennes channel (Fig. 2). This body appears to continue to the North.

5. Towards a coherent interpretation

The Brussels Sands basin filled essentially by lateral accretion of its western shore from WNW to ESE (Fig. 12). No outcrop evidence for other fill styles has ever been found. Inclined master-bedding planes dipping a few degrees to the ESE have early been described (e.g. Legrand, 1945, who saw the arrangement as a tectonic eastward tilt and associated differential subsidence), but Houthuys (1990) recognized them as primary sedimentological master bedding planes. The inclined planes have also been found in the Campine underground where seismic profiles indicate that the clinoform arrangement makes up the entire Brussels Sands at seismic scale (De Batist & Versteeg, 1999). In the present paper, this lateral progradation is the key for reconstructing the depositional history of the Brussels Sands. The fill signature has several immediate implications for the sedimentary history :

1. the filling occurred under constant and relatively high sea levels;
2. the supply of sediment was from the West;
3. the overall fill of the Brussels Sands' basin has a younging direction from West to East;
4. the filling process led to narrowing of the basin's flow section as time progresses.

5.1. Depth of the deposition

As the inclined sedimentation surfaces inside the Brussels Sands cut through the thickness of the formation, sea level during deposition must have been above the Brussels Sands top boundary, and as no change in sedimentary depth indicators is found from West to East, sea level must have been constant throughout the duration of the deposition.

It is inferred that the preserved truncation surface at the top of the Brussels Sands is situated a few tens of metres below the sea level at the time of deposition (Fig. 9). For this, we have three sedimentological arguments :

- M packages of the slope-apron type occur near the top of the formation, yet they are lower basin flank deposits;
- in Bierbeek (Fig. 14) and Archennes, thick cross beds interpreted as channel base deposits occur near the top of the formation;
- in spite of their marine signature in sediments and paleoecology, and an inferred relatively important width of the basin, the Brussels Sands are characterized by the absence of wave-produced sedimentary structures.

For the amount of truncation, it is thought that 10 to 20 m are lower estimates. As the deposit fills an important incision, the constant sea level well above the preserved top of the formation suggests the Brussels Sands are a highstand deposit with respect to the sequence to which it belongs.

Before now, at least the thick cross beds of the Brussels Sands have been interpreted, also by Houthuys (1990), as a transgressive deposit. However, our actual argumentation suggests the entire formation is a highstand systems tract.

5.2. Sediment supply from the West

The lateral accretion from West to East can only be explained if there was a considerable and constant sediment supply at the west side of the Brussels Basin. As the basin is believed to be a marine inlet penetrating into the mainland, the supply must have been from outside the inlet, either via a northern or a southern pathway. The preserved Brussels Sands show no pronounced grain size gradient in the North-South direction, so no information can be obtained here. The interpretation we adopt of the paleogeography during the deposition of the Brussels Sands will then be decisive on the pathway.

Some information on the kind of the pathway is stored in the sedimentary composition of the Brussels Sands. The majority of grains are well-rounded quartz grains of sizes typically found on exposed beaches, often called "mature" sand. Therefore, a coastal pathway of considerable length is put forward. Such a pathway (outside of the Brussels Basin, but feeding the western shore of the basin at its entrance) supplies the basin essentially with beach-like sand near the water surface. To a lesser degree, finer-grained sediment enters via the shoreface and the seafloor.

5.3. Younging direction from West to East

The inferred younging direction from West to East seems to be supported by paleontological evidence. Leriche (1922) called a subarea east of the line Charleroi-Tienen the "zone de transgression du Bruxellien supérieur à *Nummulites laevigatus*" as opposed to the other, western half of the Brussels Basin which he characterized as a lower zone devoid of Nummulites. Hooyberghs (1992) placed the westerly Woluwe section in the top of NP13 while the Neerijse section, situated 13 km ESE of the former section, showed fossils of NP14. Herman et al. (2000) found the age in an exposure at Nederokkerzeel younger than the top of the Brussels Sands Formation at Zaventem, even though the first outcrop is situated hardly 6 km NE of the latter. More detailed paleontological evidence may further support the fill history from West to East, but the time scales involved may be too small to detect any relevant variations.

5.4. Narrowing of the flow section

Continued sedimentation under a constant sea level leads to a reduction of the hydraulic flow section in the basin (Fig. 15). The subareas of the Brussels Basin, mostly situated in the east part of the basin, that must have been affected by reduced flow sections are precisely those where thick cross beds are found. As these are the product of high flow velocities, flow velocity increase must have been related to the reduced flow sections.

The narrowing of the hydraulic flow section as a result of rapid sedimentation at one side of the section, while the section is bounded at the other side, is named here *hydraulic flow-section restriction*. As a result of the flow-section restriction, and under the hypothesis of equal discharges through the basin, currents are reinforced and erosion takes place. Under the continuing sedimentation at the western side, the erosion is focussed at the eastern side of the flow section. Such a process is similar, allowing for the scale and morphological differences, to what happens in the bends of meandering rivers.

But the Brussels Sands' base shows a complex multi-channel morphology. The observation that the eastern flanks of the depressions present in the formation's basal surface are often steeper, supports the hypothesis that subaqueous, flow-section restriction-related, erosion has taken place. This process is believed to have acted on three different scales of magnitude (Fig. 16) :

- small-scale, local restriction leads to local stronger flow that tries to maintain a small-scale channel or depression by eroding its eastern flank. Under continuous sand supply, quickly the local channel is filled with relatively coarse-grained, cross-bedded sand. The westerly lateral accretion sedimentation, which never ceased, overrides the filled depression. Small-scale flow restriction may be related to synsedimentary, intraformational obstacles, caused by shifting channels and also by breach failures (see X occurrences in Fig. 12);
- larger-scale flow-section restriction is related to pre-existing longitudinal topographic ridges in the basin floor morphology. If the ridge is not too high, it can cause local flow-section restriction, higher flow velocities and a body of cross-beds, but once the depression is filled up, lateral accretion deposits override the fill (Fig. 16, steps 2-3);
- finally, when sedimentation fills up most of the basin space, a narrow channel remains. In this stage, apart from lateral erosion, also deep scour pits may be eroded (Fig. 16, step 4). No straightforward hydrodynamic reason is known to us to explain that the flow starts to dig downward

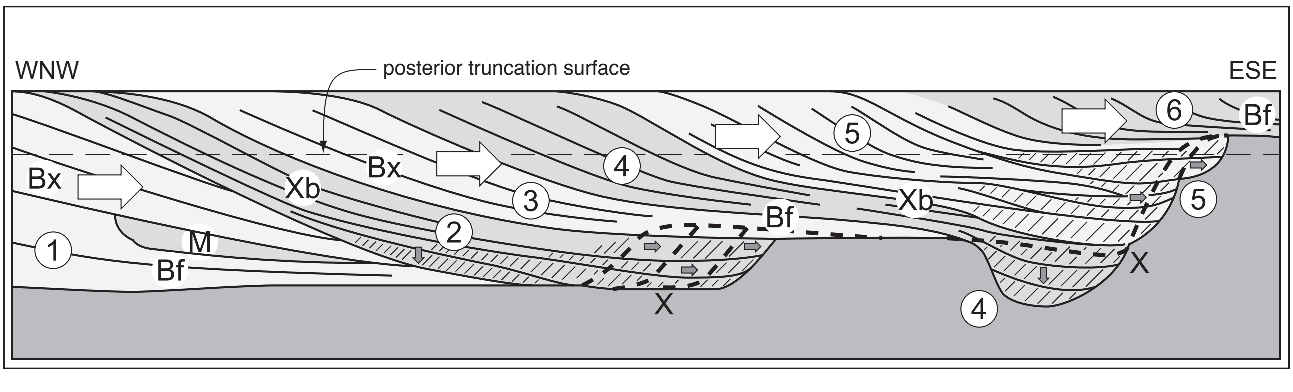

Figure 16. Profile resulting from different scales of hydraulic flow-section restriction. Thick white arrows represent the westerly lateral accretion. Small shaded arrows indicate the lateral and vertical erosion caused by flow-section restriction. This figure reads from left to right. Shades in the Brussels Sands fill indicate the following steps : 1: the continuing accretion from WNW to ESE causes the Brussels Sands basin to fill rapidly. The resulting westerly lateral accretion consists predominantly of facies Bf, Bc, Bx and M. 2: caused by the sedimentation and the inherited fluvial incision morphology (thick dashed line), a locally restricted flow section arises near the bottom. The flow is locally enhanced and cuts both vertically and laterally (shaded arrows). Sedimentation from the West outpaces the locally created accommodation space. Thick cross beds are the rapid filling of the created space. 3: the westerly lateral accretion, which never ceased to function, causes the westerly arrangement to roll over the filled local channel. Facies Bf covers directly facies X. 4 and 5: sedimentation from the WNW continues and the flow section is now seriously restricted as a high inherited morphological feature is met. Now, vertical incision is more important than lateral erosion. Again, sedimentation outpaces creation of accommodation and the scour pit is filled rapidly with thick cross beds. 6: while the embayment is not entirely filled, the westerly lateral accretion continues to function. Due to posterior truncation, these particular sediments are no longer present (e.g. in Bierbeek, Fig. 14C).

to create closed bottom depressions, instead of eroding laterally. It is simply observed that closed depressions, several tens of metres deep, occur in some deep channels near their east flank (Fig. 14, to be consulted together with Fig. 2). They are filled with coarse sand in large-scale cross-beds but often also contain small transported lumps of marl, very similar to the fine carbonate facies Bf mud that occurs in the immediate neighbourhood, to the West (Fig. 16, step 1). Such marly lumps in thick cross-beds are often observed in Archennes and Hoegaarden. This observation is a further argument for supposing the scour of the deep closed depressions occurred intraformationally. The presence of considerable paleorelief highs is thought to be crucial to the vertical erosion followed by building a vertical stack of thick cross beds, hugging the east side of some major channels. The high-energy flow with narrow channels and large dunes is thus the final stage of the basin fill. The rapid fill causes the closure of the channel (Fig. 16, step 5).

It is inferred that the process of flow-section restriction, local scour and fill by cross-bedded sand repeated itself many times, guided by the advancement of the sedimentation front from the West in relation to pre-existing, inherited, longitudinal morphological ridges. But the frequency of flow-section restriction events increased in time with the filling of the basin.

6. Deductions about the paleogeography

The long, relatively narrow basin filled by the Brussels Sands (Fig. 1) that show abundant marine, tidal characteristics suggests the basin was a strait, estuary or tidal embayment.

A relatively narrow strait, similar to the present-day Dover Strait, might have connected the North Sea with the Paris Basin. Though no physical connection exists in the preserved sediments, a configuration like this has been proposed in the past (Gullentops, in Houthuys, 1990; Vandenberghe & Gullentops, 2001). The arguments in favour of such a seaway are listed in Houthuys, 1990 (his section 4.2.4), who countered the arguments (his section 4.9) and settled for an estuarine configuration, where no marine connection existed between the two basins, and that subsequently developed into a shallow marine setting.

The localized occurrence of thick glauconitic beds, rather connected to the North than to the South (Houthuys, 1990, his figure 4.28), constitutes a further argument against a seaway connection.

The present observations and the facies architecture provide two more arguments :

- supposed strong seaway currents, associated with coarse, cross-bedded sand, followed by highstand more open marine conditions, would result in two separate sand facies, the one superposed on the other. But the different sedimentary facies of the Brussels Sands show an intricate intermingled pattern, thus proving unambiguously they co-occurred in a complex depositional environment;
- if a strong south-north marine current was the dominant force determining the (first stage of the) deposition of the Brussels Sands, a south-north gradient or progradation signature (in the form of northward prograding, downlapping strata) should be found. Actually, the progradation is from West to East.

A definite answer to the paleogeography will strongly depend on the exact age equivalences across both basins. According to Gély (2008), the youngest marine sediments present in the North of the Paris Basin, based on radioactive dating on the glauconites of the Glauconie Grossière, are age dated 48 Ma, and thus postdate the Brussels Sands. If correct, the Paris Basin was entirely continental at the time the Brussels Sands were deposited. But some uncertainty still hovers around the correlations. Steurbaut (pers. comm., 2009) found NP14a microfossils in a Paris Basin Glauconie Grossière outcrop, which would set the base of the formation close to the base of the Brussels Sands. New and more absolute and paleontological datings will ultimately settle this question.

The present paper favours an estuarine to marine embayment setting for the Brussels Basin, connected to the North Sea and closed to the South (Fig. 17).

An estuary forms when continent-derived sediment supply cannot cope with the increasing accommodation created by sea-level rise in a drowning river mouth. While estuaries are widely used as paleoenvironment models for sandy incised-valley fills with a strongly tidal signature, such as adopted by Houthuys (1990) for the Brussels Sands, Yoshida et al. (2004) suggest a more open marine embayment depositional environment for some levels in the Lower Cretaceous Woburn Sands in England, that display many sedimentary structures that are similar to the Brussels Sands. They refer to the Wash embayment in England as a recent analogue. In a study of that present-day environment, Ke et al. (1996) restricted the use of *embayment* to a system that receives nearly all of its sediment (both suspended and bed-load sediments) from marine sources and in which fluvial input (both water and sediment discharge) is negligible. Although the centre of the Wash system contains an incised valley, the present-day Wash is not confined in the initial incised valley with most of the sediments occurring above the valley. Yoshida et al. (2004) use such a configuration as an additional criterion to distinguish between estuary and embayment. In the tidal embayment, residual current directions at a given locality are virtually identical throughout the water column, while lateral variations do exist. This water and sediment transportation pattern contrasts with highly variable lateral flow patterns in an estuary, with mutually evasive flood- and ebb-dominated channels. In a marine embayment, a few relatively deep tidal channels are flanked by large, laterally accreting and commonly long-lived sandbanks. The sandbanks are more laterally extensive than those found in estuaries (Yoshida et al., 2004). Most of the arguments used by these authors to interpret part of the Woburn Sands as a tidal marine embayment, also apply to the Brussels Sands :

1. the absence, in the thick cross beds, of a clear channel-fill facies with concave erosion surfaces indicative of typical estuarine channel bases;

2. the widespread occurrence of low-angle, inclined bed planes (dipping uniformly across the basin, to the ESE), lateral to seaward migrating large sand dunes, is comparable to the lateral migration of large sandbanks;

3. the strongly marine character of the trace-fossils, fossils and sediments;

4. the bimodal flow with a strong ebb flow dominance.

The strongly linear (as opposed to sinuous) character of the flow in an embayment results in a well developed directional polarity displayed by foreset dips, which is the case for the Brussels Sands. Moreover, the Brussels Sands seem to extend beyond the basal incised valleys, e.g. in the SW and SE of the Brussels Basin (Fig. 2).

The low-angle inclined surfaces prograding from West to East are interpreted as the (basal part of) a prograding shore. They might equally well be produced by a prograding sandbank or channel shore. However, as no remnants have yet been found inside the Brussels Basin of the opposite (western) flank of a sandbank, we think a prograding embayment shore is the best interpretation.

The bidirectionality and magnitude of the currents, such as indicated by the cross bedding, also fit this kind of tidal environment. One might wonder at the overwhelming dominance of cross beds with laminae dipping NNE, now interpreted as ebb-produced. However, the few flood-oriented cross beds that are found in the Brussels Sands, are close to the top of the preserved sequence. This is consistent with the flood current being the predominant flow in the shallow parts of the embayment. An overall flood dominance carries in the sediment from the mouth inside the embayment. The main reason for this flood dominance in estuaries and tidal embayments is the fact that the influx during rising tide happens in a far shorter time than the subsequent draining during falling tide. Transport capacity is an exponential function of the flow current speed. The net result is that flood carries in the sediment, while ebb pulls it out a short distance before dropping its bed load with an ebb-signature. It is this signature that is preserved in the sedimentary record.

In a tidal embayment, waves must certainly have occurred. Only, the intense, daily tidal dynamics wipe out any structure that might be attached to wave action, especially in the preserved, deeper part of the embayment.

As our interpretation as a tidal embayment environment seems now the most plausible, the coastal sand pathway inferred to have fed the massive sand input from the West must necessarily be situated at the only, North Sea, entrance to the embayment. Here, a long, coastal pathway connecting the English Channel with the embayment entrance, is deduced. This hypothesis is certainly compatible with the presumed general configuration that a connection with the Atlantic Ocean was open via the English Channel (Gramann & Kockel, 1988; Ziegler, 1990) and a possible source area for the heavy minerals being Brittany (Gullentops, in Houthuys, 1990).

The connection with the Atlantic has been called in to explain the southern fauna influxes. To this, similar to the arguments used to explain the Paris Basin's Lutetian biological hot spot (Merle, 2008), the somewhat sheltered environment provided by a marine embayment and the climatic optimum that occurred during the Ypresian may be additional factors to explain the relatively high biological production and warm faunas observed for the Brussels Sands.

The coastal pathway must have been active during highstand sea level, at the same time of filling of the embayment. The present-day total longshore sand transport at the Belgian southern North Sea coast is of the order of 10^5 m³/yr (author's observations for the Flemish Coastal Division). Verwaest et al. (2010) find $4 \cdot 10^5$ m³/yr

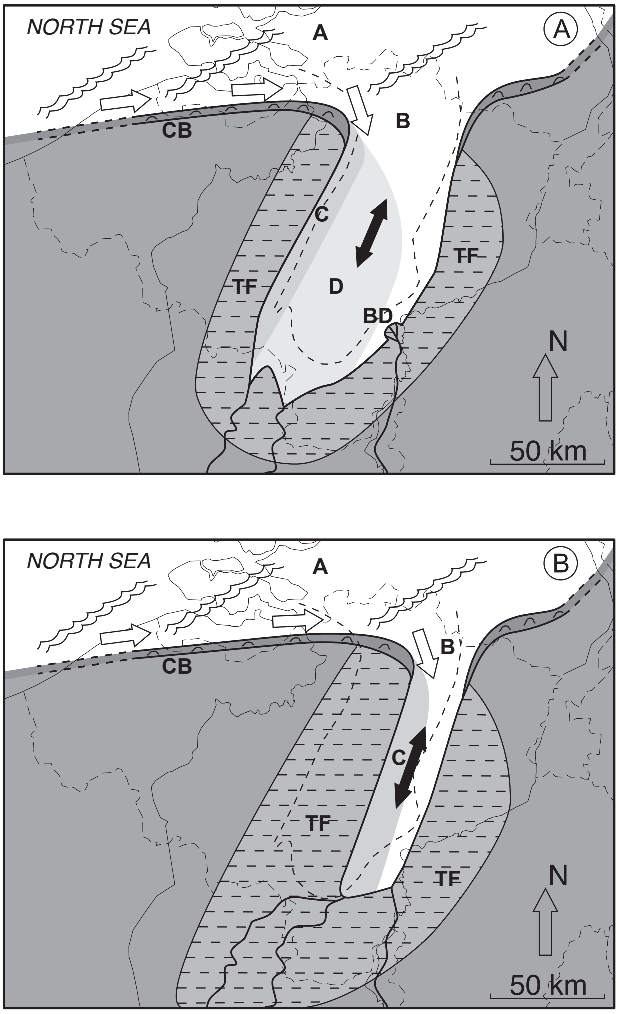

Figure 17. Inferred paleogeography during deposition of the Brussels Sands. (A) : during initial highstand with beginning sedimentation at west shore of tidal embayment; (B) near closure of the tidal embayment. Explanation of letters : A : open sea; waves and wind from sector W-NW causing west-east littoral drift; B : relatively narrow entrance to bay shelters it from swell; C : area of rapid sand deposition in westerly lateral accretion arrangement; D : area of slow deposition of fine sand and carbonate mud; BD : bayhead delta; CB : coastal barrier and beach; TF : tidal flats and marshlands; white arrows : sediment transport; black arrows : tidal currents in embayment. Darkest shade is wooded flat lowland. All areas and lines outside preserved Brussels Sands basin are indicative. Present-day national boundaries, North Sea coast and main rivers for reference.

west of Zeebrugge. Also at the Dutch coast, figures ranging from $1\text{-}5 \cdot 10^5$ m³ are put forward (van Rijn, 1997; van de Rest, 2004). These rates may be considered low estimates of natural transport, because many artificial constructions hamper the natural sand supply and transport at the present-day coast. If a transport rate of $5 \cdot 10^5$ m³/yr is accepted to be relevant for the ancient coast, the Brussels Basin volume, which can be estimated at 10^{11} m³, may have taken 200,000 years to fill.

The angular grains found predominantly in the SE, near Namur, and mixed in decreasing proportions with round quartz grains both in the Archennes and Hoegaarden channels, have probably been derived from a bayhead delta. They represent the clastic influx from rivers. The depositional structure of all outcrops with angular grains, however, definitely bears the signature of tidal dune migration and thus tidal reworking.

The tidal embayment environment also fits well the sequence stratigraphic position of the Brussels Sands (Vandenberghe et al., 1998, 2004). Lowstand river incision is logically followed by estuary conditions (Catuneanu, 2006), at least when they are tributaries to a tidal sea, which is the case for the Cenozoic North Sea. The estuary is then followed, during further sea-level rise and highstand, by the tidal embayment stage and the filling of the basin.

The channel fills near Brugge (Mostaert, 1985) and offshore Belgium about 20 km north of Oostende (De Batist, 1989; De Batist et al., 1989), some 100 km West of the Brussels Sands, have been correlated with the upper Ypresian Vlierzele Sands, but the incision may be time-equivalent with the incision at the base of the Brussels Sands (Vandenberghe et al., 2004). The fill of the offshore-detected incision has a stratigraphic signature that is similar to the large-scale fill style of the Brussels Basin (De Batist & Versteeg, 1999). The exact time relationship with the proper Brussels Sands remains to be established, but a near-time equivalence is evident. The fill history may then simply have proceeded from West to East, first filling the westernmost incisions and progressively filling other, more eastern incisions. No remnants of the supposed beach system between the English Channel and the mouth of the Brussels embayment are left. They must have been eroded during the large hiatus following the Brussels Sands deposition, though some lower shoreface parts may have been preserved in the Aalter/Beernem/Oedelem deposits.

Finally, a word on the increase of flow velocities associated with narrowing flow sections. It is now clear, in the overall tidal embayment environment, that high flow velocities presuppose that the amount of water going in and out with the tide, i.e. the tidal prism, remained relatively constant. This in turn implies that a large upstream intertidal basin existed, and/or a large intertidal area fringing the Brussels Basin.

All the deductions made in this paragraph result in the picture of the paleogeography shown in Fig. 17 and the following scenario for the origin of the Brussels Sands.

7. Model : highstand tidal embayment fill with increasing hydraulic flow-section restriction

7.1. Step 1 : normal regression

After the regressive final stages of the Ypresian, a continental regime was established in Belgium with a river drainage system developing to the NNE in a normal consequent direction. One or several rivers draining to the North Sea had their mouth near the present-day Belgian-Dutch boundary. The continental relief was low and so was the sediment load of the river system.

7.2. Step 2 : sea-level fall and forced regression (Fig. 18A)

A relatively outstanding sea-level fall occurred. The global sea-level fall labelled “Yp10” in Hardenbol et al. (1998), situated at 50.0 Ma, is a logical candidate (Vandenberghe et al., 1998, 2004). The shore retreated further North and the rivers draining into the North Sea started to cut an incised valley. Correcting Fig. 2 back for tectonic tilt, it is estimated that the vertical incision and thus the sea level fall was in the range of 30-50 m. The related river incision (erosion component 1) extended from the shoreline gradually landward. Part of the Brabant Massif was denudated. North of the Brabant Massif, an incised valley system was cut into the former highstand deposits. Sediments must have been carried offshore, but no sediment body related with this lowstand, erosional stage has been identified.

7.3. Step 3 : sea-level rise and tidal ravinement (Fig. 18B)

The post-Yp10 sea-level rise made the North Sea enter the valley system turning it into an estuary system. Probably, some wave erosion occurred, especially over the former interfluvia. It is supposed that at some time, the basin dimensions were favourable for tidal resonance to set in. This phenomenon resulted in macrotidal ranges and strong tidal currents with erosive power. In this stage, the drowned topography was partly refashioned due to tidal ravinement (erosion component 2). Any continental deposits were removed and/or reworked. No preserved sediments are related to this the sea-level rise. Instead, sediments were pushed inland and newly arriving sediment from the continent remained in the river mouth’s area.

7.4. Step 4 : highstand lateral progradation from West to East (Fig. 18C, D)

Near the end of the sea-level rise, a wide area extending beyond the present-day limits of the Brussels Basin was inundated (Fig. 17A, 18C). The margins of the area most probably showed wide intertidal flats and marshlands, which is compatible with some macroscopic botanic finds. The tide going in and out twice a day caused important water movements through the Brussels Basin, which was then transformed into a tidal embayment. The main water movement direction was NNE-SSW (flood) and,

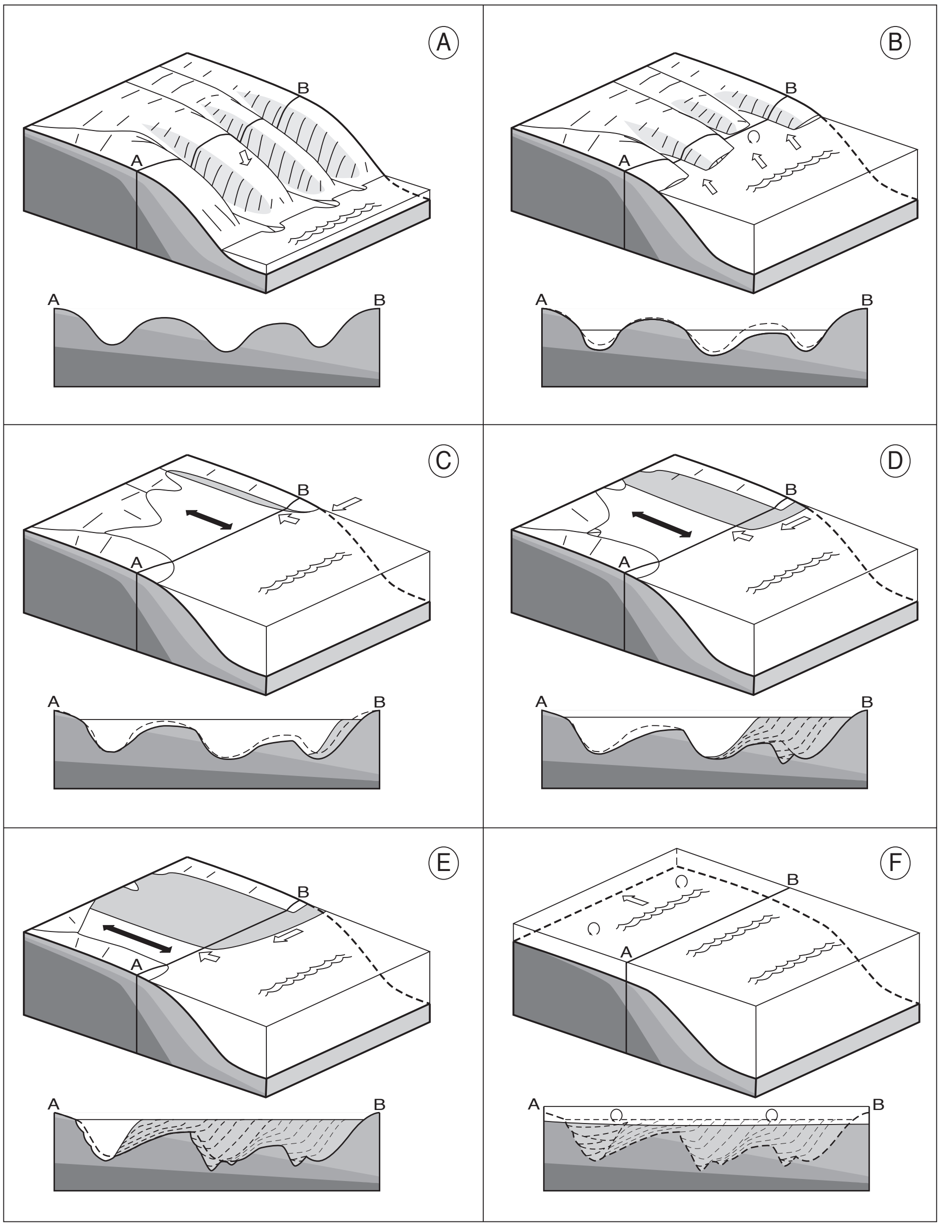

Figure 18. Sedimentary model for the Brussels Sands. The area represented is approximately the present-day Brussels Sands occurrence area, such as depicted in Fig. 1. The dimensions are schematic and not to scale. The view of the block diagrams is from NE. White arrows indicate net sediment transport, full arrows represent the tidal currents. The cross sections are East-West. In the cross sections, thick dashed lines represent the basin base at the previous step. A : consequent rivers drain into the North Sea. The sea-level fall Yp10 causes a forced regression and the rivers start to incise, creating a valley-and-interfluvium relief cut in the topographic slope near the shoreline. B : sea-level rises again. The sea enters the incised valleys, turning them into estuaries. Tidal erosion, probably assisted by wave erosion over the previous interfluvia, reworks the topography, pushing sediments inland and creating an estuary in the former incised valley area. C : near highstand, a tidal embayment is installed at the former incised valleys' location. Tidal currents continue to refashion the inherited morphology. Meanwhile, an important West-East sand transport path sets in under littoral drift at the North Sea shore west of the Brussels embayment. This path brings in a continuous supply of sand that is trapped inside the embayment and starts to build the westerly lateral accretion. D: sea level remains high and the embayment fills relatively quickly under continuing littoral-drift sediment supply. E : several times, inherited, now-submerged valley slopes are met by the sedimentation front advancing from the West. Each time, local flow-section restriction occurs, resulting in localized erosion soon followed by deposition of thick cross beds. F : the successive Lu1 transgressive cycle passes over the Brussels Basin and erodes at least the top 10-20 m of the Brussels Sands together with all of the surrounding intertidal flats. Now, the Paris Basin is invaded by the sea.

subdominantly, SSW-NNE (ebb). The southern North Sea coast was an approximately west-east shore connecting the English Channel with the North Sea mouth of the Brussels Basin. The high sea level probably re-established the seaway link with the Atlantic through the English Channel, claimed by Gramann & Kockel, 1988. An eastward coastal drift along the southern North Sea coastline is thought to have transported sand by coastal processes feeding the Brussels Basin via its northern mouth at the west side. This sand was trapped inside the embayment and contributed to building the western shore of the embayment. Coarse sand penetrated the basin at the level of the intertidal zone; finer sand was deposited near the base of the shoreface and in the centre of the embayment. Continued sand supply made the western bank relatively steep and many times, breaching events occurred conveying coarse sand to the foot of the bank face. Sedimentation continued all the time, causing the westerly lateral accretion to gradually fill the embayment (Fig. 18D).

7.5. Step 5 : increasing hydraulic flow-section restriction (Fig. 18D, E)

Topographic highs in the Brussels Basin floor together with the eastward advancing sedimentation front caused local channelized flow producing localized units of subaqueous dune cross-bedding. As the embayment narrowed due to the overall West to East sedimentary progradation (Fig. 17B), channel-like conditions near topographic high features became more frequent. The overall westerly lateral accretion caused flow section restriction. The related stronger flow eroded the east flank of the channels (erosion component 3a), but sediment supply outpaced the creation of supplementary accommodation space and the channels, despite their high-current regime, choked and were filled in a short time with thick cross beds (Fig. 16, step 2; Fig. 18D). At some points, free lateral channel shift was impeded when the east slope, cut into older, compacted deposits, was of considerable height, and a major flow-section restriction occurred. In such cases, the current flow was enhanced drastically and vertical scour pits were formed, some tens of metres deep, cutting through previously deposited facies Bm-Bf sediments and then through the formation base into the underlying deposits (erosion component 3b). Also in these cases, sediment supply outpaced accommodation creation and the scour pits were filled quickly with thick cross beds (Fig. 16, step 4; Fig. 18E). All the while, the westerly lateral accretion continued to function and rolled each time over the section-restriction related thick cross beds.

7.6. Step 6 : closure and subsequent coastal ravinement (Fig. 18F)

The last sediments of the Brussels Sands were deposited near the east side of the embayment and were of the narrow-channel type (thick cross beds attesting fast sedimentation). When the last channels were closed and the embayment was filled, actually a normal regression took place. A sedimentary hiatus followed, during which continental erosion may have occurred. The next transgression is thought to be related to the following sea-level cycle (i.e. the one following lowstand Lu1 situated at 48.1 Ma of Hardenbol et al., 1998) and to have brought open marine conditions over Belgium (Fig. 18F). The southern North Sea coast passed over the country from North to South and entered into the Paris Basin. This transgression may represent the onset of the Lutetian series in the Paris Basin, which was invaded from the North, at around 48 Ma. The marine ravinement related to this transgression is thought to have taken away the top part of the Brussels Sands, truncating them by at least 10 to 20 metres. All intertidal deposits inferred to have been present around the confined Brussels Basin must have been removed during the transgressive ravinement. The “Brussels Sands” outliers of Cassel and some NW Belgium boreholes may be deposits of this cycle, which is also the lowermost sedimentation cycle in the Paris Basin. Also, some fragments of concretions found in the present-day plateau area between the Brussels and the Paris Basin, may be relics of sediments of this cycle. The coarse glauconitic facies of the east margins of the Brussels Basin may well have been a source for the Glauconie Grossière, as the coastal drift in the Paris Basin after the first transgression has been identified to be directed from NE (Belgium) to SW (Gély, 2008).The Lu1 marine ravinement surface covering the Brussels Basin is thought to have been reworked in turn when later still, the Lede Sands marine transgression, situated after Lu2 at 46.0 Ma, created a new marine ravinement which is preserved as the Lede Sands base gravel. This scenario conforms with the observation that an entire marine transgression cycle is missing between the Brussels Sands’ top and the Lede Sands’ base in Central Belgium (Vandenberghe, 1998, 2004), and the presumed removal of minimally 10 to 20 m of the original Brussels Sands’ top is then the joint result of two marine transgressive ravinements.

8. Discussion and open questions

8.1. What’s new in this model ?

The present model differs from an earlier version (Houthuys, 1990) on the following points :

1. the basal surface of the Brussels Sands in their type area in Central Belgium is a composite ravinement surface that (1) stems from a continental incised valley relief, (2) was transformed during transgression into a tidal ravinement surface, and (3) was locally widened into asymmetrical channel flanks and deepened into troughs during intraformational scour episodes induced by hydraulic flow-section restriction;
2. no or very few transgressive deposits are thought to be present in the Brussels Sands. The fragmentary gravel may partly be related to the transgression, and partly be intraformational, related to local scour events associated with flow-section restriction;
3. the bulk of the formation is a highstand deposit, with inclined beds prograding from WNW to ESE thus filling up the basin, which is interpreted to be a marine tidal embayment. The fine carbonate-rich bioturbated facies are basin floor deposits while small-scale cross beds and bioturbated medium to coarse sand are related to the western shore environment of the embayment. The lateral progradation of this system created a coarsening-upwards sequence;
4. the westerly lateral accretion arrangement of beds of mostly medium-sized, well-rounded quartz grains implies a coastal transport path at the southern shore of the North Sea bringing in the material from the West to the north entrance of the Brussels Basin embayment;
5. repeated breachings conveyed relatively coarse sand into the deeper basin producing massive sand packages intercalated in the westerly lateral accretion deposits and local fining-upwards profiles;
6. thick cross beds are related to restricted hydraulic flow sections. Flow-section restriction events were more frequent in the eastern half of the basin, which was the last to sand up;
7. the formation must have contained an upper, intertidal shore and shoreface environment, which has been truncated entirely during later transgressions.

8.2. The breaching deposits

Breaching deposits are known in fine-grained sand deposits (van den Berg et al., 2002). In this paper, the breaching mechanism is proposed to explain the geometry and structures of the M facies. This is a relatively coarse-grained deposit built in the westerly lateral accretion arrangement whose bedding planes were not exceptionally steep. Slope angles of the embayment's bank are thought not to have much exceeded 10-12 %. Further research on sand-flow deposits in medium to coarse sand will clarify the proposed mechanism. Anyhow, from the Brussels Sands' sedimentary record, it is believed that breaching is an important sedimentary agent and many shallow marine nearshore to embayment sandy deposits, containing similar massive intercalations, throughout the geological record, will turn out to be breach failure-like deposits.

8.3. One or several filling stages ?

The lack of a deposit that could be attached to a successive sedimentary cycle made Vandenberghe et al. (1998) wonder if the Brussels Sands did not conceal two sedimentary transgression-regression cycles.

The uniformity in sedimentary facies and facies arrangements found throughout the Brussels Sands basin, related to one mechanism of continuous sedimentation, is a strong argument for only one, uninterrupted depositional cycle. This paper therefore favours the view that the Brussels Sands represent the deposits of a single depositional cycle.

8.4. Regional fine-scale stratigraphy

Our model may help to clarify the position of the Brussels Sands in the regional temporal and spatial context. Some implications can already be given here.

The global sea-level fall Yp10 (Hardenbol et al., 1998) was originally estimated to be some 110 m (Haq et al., 1987), but more recent reports state all amplitudes are probably lower by a factor of two or more (Miller, 2009). A suitably low sea level, the lowest of its age, is found on Miller's (2009) Fig. S7 at 50.1 Ma. The associated global sea lowering is only some 25 m. Reading the Brussels Sands' base incision map (Fig. 2), allowing for the tectonic tilt, and taking into account that only erosion component 1 was related to river incision, we now infer a pre-Brussels Sands sea level drop by 30-50 m, which approaches Miller's (2009) amplitude values.

If the correlation with the 50.0 (50.1) Ma lowstand is correct, this might place the Brussels Sands in the top of the Lower Eocene.

The (pene)contemporaneous Vlierzele Member and Aalter Formation (Laga et al., 2001) may belong to the same depositional cycle as the Brussels Sands (Vandenberghe, 1998), and may represent slightly earlier deposits (as the sedimentation proceeded from West to East) and/or contemporaneous nearshore deposits.

New detailed paleontological research and absolute datings will help to settle the exact time-space relationship with these lateral deposits, and with the Paris Basin.

8.5. Why is the glaucony facies so localized ?

The glauconitic sands have a puzzling, geographically limited occurrence, such as summarized by Houthuys (1990), his Fig. 4.28. Most striking is the absolute absence of coarse glauconite west of the line Charleroi – Haacht (Fig. 2). East of this line, glauconitic sands are found at the base of the formation, either in cross-bedded facies, but mostly in bioturbated facies. However, at the east flanks of the Archennes and Hoegaarden channels, the entire formation is made up of stacked thick cross beds showing a glaucony facies, with locally up to 50 % glauconite grains. These glaucony sand bodies do not extend to the southern margin of the basin.

Glauconite is also a prominent component of the (nearly) age-equivalent Vlierzele Sands and the Aalter Formation.

In some transition areas inside the Brussels Sands' basin, a West-East gradient in glauconite content appears to be present.

The significance of the localized glauconitic sands in our new model for the deposition of the Brussels Sands remains to be clarified. Some outcrops clearly prove glauconitic and non-glauconitic facies were present near each other in the same sedimentary environment, with the glauconite sands there taking in lower positions. Coarse glauconite sands were undoubtedly associated with strong current flow such as occurred at flow-section closure stages. But strong-current deposits devoid of coarse glauconite are found as well.

9. Conclusion

The Eocene marine Brussels Sands fill a 40 km wide, 120 km long, complex erosional valley in Central Belgium, the long axis of which is oriented SSW-NNE.

This paper proposes a new model to explain the sedimentary fill style of the Brussels Basin. The model starts from observations made in the 1980s (Houthuys, 1990) and integrates new sedimentological and sequence stratigraphic insights and new observations made in large outcrops.

The systematic large-scale buildup of the formation arranged in inclined planes prograding from WNW to ESE, called here the "westerly lateral accretion", is the essential feature of the depositional history. All major sedimentological characteristics fit in the paleogeographical picture constructed from this key observation.

The Brussels Basin is interpreted as a tidal embayment, the western shore of which consisted of a beach-like environment (truncated during a later marine transgression), an upper shoreface with abundant benthic life (also truncated), a middle shoreface with subaqueous small dunes (facies Xb) grading to a lower shoreface with slower and smaller dunes and an increasing amount of benthic life (facies Bx, Bc, Bm). The lowest part of the shoreface and the embayment floor was filled with fine, carbonate-rich sand, which was completely bioturbated (Bf). Frequent breach failures conveyed relatively coarse sand from the shallow into the deeper environment, producing the M facies intercalations. Due to the continuing progradation from WNW to ESE, the flow section was repeatedly reduced locally (near intraformational relief and inherited paleorelief highs) and regionally (when major parts of the embayment were sanded up). Each time, the flow was enhanced and during a brief interval, eastward lateral erosion and sometimes vertical erosion tried to create new accommodation space. The erosion rates were outpaced by the westerly accretion and large dunes rapidly filled the eroded space, creating the cross-bedded facies X. As long as the tidal embayment was not completely filled, the westerly lateral accretion each time prograded over local "easterly closure" events (Fig. 16).

The direct implications of the new model are :

- the oldest sediments in the Brussels Basin are present in the West and the younging direction is from WNW to ESE;

- a coastal sediment pathway along the southern shore of the North Sea, connecting the English Channel with the mouth of the Brussels Sands embayment, is inferred to have carried in most of the well-rounded quartz grains that characterize the Brussels Sands;

- the erosional surface of the Brussels Sands base is complex. The origin is an incised valley morphology formed during the Yp10 lowstand (50.0 Ma, Hardenbol et al., 1998). The valley was refashioned and enlarged during sea-level rise and transgression, under tidal currents, into an estuary which further developed into a tidal embayment. Some local, deep scour pits in the Brussels Sands' base are intraformational scours produced under local paleorelief-induced enhanced flow conditions;

- the westerly lateral accretion implies a constant, relatively high sea level. The entire Brussels Sands Formation is thus derived to be a highstand systems tract in terms of sequence stratigraphy;

- the top part (at least 10 to 20 m) of the Brussels Sands has been removed by subsequent erosion, probably mostly associated with a successive marine ravinement, following the Lu1 (48.1 Ma) lowstand. This first full-Lutetian transgression invaded the Paris Basin over Belgium, but apart from the mentioned marine ravinement removing the top of the Brussels Sands, and possibly the western "Brussels Sands" outliers of Cassel and some boreholes, left no traces in the Middle-Belgium sedimentary record, due to the pre-Lede Sands marine ravinement.

10. Acknowledgments

I thank the many sandpit and construction pit owners who granted access to their sites. I am grateful to Tucrail NV/SA and Tucrail geologist Hilde Dupont for informing me of important railway construction outcrops and for allowing me to do fieldwork there. This paper benefited greatly from fruitful discussions with Noël Vandenberghe and Marc De Batist.

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Manuscript received 03.10.2009, accepted for publication 21.06.2010, available on line 01.10.2010.