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THE BOUNDARY BETWEEN THE MIDDLE EOCENE BRUSSEL SAND AND THE LEDE SAND FORMATIONS IN THE ZAVENTEM-NEDEROKKERZEEL AREA (NORTHEAST OF BRUSSELS, BELGIUM)

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(6 figures, 5 plates)

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ABSTRACT. In the Zaventem airport railway cutting, to the north-east of Brussels, the upper part of the Brussel Sand Formation consists of two major units, both attributable to calcareous nannofossil zone NP14a. The lower predominantly sandy unit ZB1 (including subunits A, B and C, belonging to NP14a1) is built up of sparsely glauconitic, relatively coarse tidal current deposits with nodule levels cemented by carbonate and silica, of which one shows slumping structures and is interpreted as a seismite. The uppermost unit ZB2 (also labelled D, belonging to NP14a2), composed of alternating thin fine sandstone bands and silty marls, represents the fill of a large channel. In the Berg-Nederokkerzeel sandpit the carbonate-rich Brussel Sand Formation is finer grained and more homogeneous. Here, the basal sand (unit A) is attributable to NP14a3 and consequently, younger than the section exposed at Zaventem. It is incised at its the top by a rather narrow erosive gully, filled in with well-sorted fine sand rich in washed-in molluscs (unit B), some of which seem to point to a brackish influence. The extreme top is made up of half a meter of sand with abundant *Callianassa* burrows and echinid fragments (unit C). From the nannofossil data it appears that, east of Brussels, at least two generations of tidal channel systems seem to have occurred within the Brussel Sand Formation, followed by a partial emersion at the end of the filling of the uppermost channel (Nederokkerzeel B). This was succeeded by a relative sea-level rise, as shown by unit C and the remains of a completely eroded fully marine deposit, reworked in the base of the overlying Lede Sand Formation. The lowest relative sea level, with at least partial emergence of the Brussels area, occurred during middle to late Biochron NP14b. In both outcrops the Lede Sand Formation displays its characteristic pale grey relatively fine-grained homogeneous nature with a stone layer near its base. It can be concluded that, at the beginning of the "Lede transgression", an erosion of older deposits, containing already lithified stone layers, occurred. This was, apparently, at least locally, caused by storms, which could redistribute, imbricate and turn over the stones, explaining their bio-perforation on both sides. Afterwards the stones have been above water for a relatively long time, enough to allow the dissolution of the perforating organisms and consequently an important oxidation of their surfaces. These stones have subsequently been colonised by a new marine fauna. Part of the shark teeth and calcareous nannofossil assemblages found in the coarse base of the Lede Sand is definitely older than the taxa normally found in the Lede Sand Formation. These fossils are the remains of a sediment package, believed to represent the formerly "Laekenian" stage.

KEYWORDS: Brussel Sand/Lede Sand boundary, Middle Eocene, Belgium, calcareous nannofossils.

RESUME. La limite entre les Formations de Bruxelles et de Lede (Eocène moyen) dans la région de Zaventem-Nederokkerzeel (au nord-est de Bruxelles, Belgique). Dans la tranchée du terminal *TGV* à l'aéroport national de Zaventem, au nord est de Bruxelles, la partie supérieure de la Formation des Sables de Bruxelles comprend deux unités principales attribuables par leurs nannofossiles calcaires à la zone NP14a. L'importante unité inférieure ZB1, subdivisées en sous-unités A, B, C et appartenant au NP14a1, est constituée de dépôts sableux fins et légèrement glauconifères dus à des courants intertidaux relativement puissants. Elle contient des niveaux à nodules dont le ciment est gréso-carbonaté. Un de ces niveaux présente des structures marquées de slumping et peut être qualifié de séismite. L'unité supérieure ZB2 (ou sous-unité D), appartient à la zone NP14a2. Elle consiste en alternances de fines bandes gréseuses et marno-silteuses et représente la phase de comblement progressif d'un large chenal. Dans la Sablière de Berg-Nederokkerzeel, la Formation des Sables de Bruxelles est composée de sables très carbonatés, plus fins et plus homogènes. En cet endroit, la partie basale sableuse (unité A) est attribuable à la zone NP14a3 et est donc postérieure à la section observée à Zaventem. Son sommet est incisé par un réseau de chenaux érosifs relativement étroits, remplis par un sable fin bien classé et particulièrement riche en coquilles de mollusques (unité B). La faune malacologique de sa partie supérieure révèle localement une influence saumâtre. La partie sommitale du chenal est représentée par un demi-mètre de sable fin où abondent terriers de *Callianassa* et fragments de tests d'échinides irréguliers (unité C). Les nannofossiles calcaires permettent de démontrer qu'au moins deux systèmes de chenaux intertidaux se sont succédés dans la partie supérieure de la Formation des Sables de Bruxelles. Une émersion partielle s'opéra après le comblement final des derniers chenaux (Nedderokkerzeel B). Y succéda un retour aux conditions marines franches démontré par l'unité C et par les restes de dépôts marins antérieurs entièrement érodés, déplacés et remaniés à la base de la Formation des Sables de Lede sus-jacente tant à Zaventem qu'à Nederokkerzeel. Le niveau marin le plus bas, associé à l'émersion partielle de la zone de Bruxelles, se produisit au cours des phases moyenne et terminale de la zone NP14b. Dans les deux sites, les Sables de Lede présentent leurs sables mi-fins, relativement homogènes, de teinte gris pâle accompagnés d'un puissant niveau grésifié très proche sinon au contact même de leur base. Il peut en être déduit qu'au début de la "transgression lédienne", se produisit une intense érosion et un puissant remaniement de divers dépôts antérieurs contenant des horizons déjà lithifiés. Ceci fut le résultat de tempêtes plus ou moins locales ayant provoqué redistribution, imbrication et renversement des blocs lithifiés, rendant possible les intenses perforations sur toutes leurs faces. Par la suite, ces pierres se trouvèrent émergées un temps suffisamment long pour permettre la dissolution complète des organismes perforants et encroûtants et devenir porteurs de traces d'oxydation marquées. Ces pierres météoriquement nettoyées et oxydées se sont vues réimmergées et recolonisées par une nouvelle faune marine. Certains assemblages faunistiques de nannoplancton et d'élasmobranches recueillis dans la base sableuse grossière des Sables de Lede sont indubitablement plus anciens que ceux qui se récoltent dans la Formation des Sables de Lede proprement dite. Ces fossiles sont les reliques d'un paquet sédimentaire disparu et supposé représenter l'ancien "Laekenien".

MOTS-CLES: Limite Sables de Bruxelles/Sables de Lede, Eocène moyen, Belgique, nannofossiles calcaires.

1. Introduction

The Middle Eocene Brussel Sand Formation is widely distributed in central Belgium, in the area between Brussels – Tienen – Namur (Fig. 1), reaching a thickness of more than 80 m (Houthuys, 1990; Damblon & Steurbaut, 2000). East of Brussels, it is about 40 m thick and known to underlie the Middle Eocene Lede Sand Formation (Rutot, 1888; Leriche, 1912; Gulinck & Hacquaert, 1954; Kaasschieter, 1961), although the nature of the junction has been poorly understood up to now. In 1995, during the construction of the railway access to the Zaventem airport, NE of Brussels, a large outcrop exposed the transition between both formations (Figs. 2 & 3). As the lithological context of this contact appeared to be much more complex than initially thought, it was decided to carry out some additional investigations in the Berg-Nederokkerzeel sandpit, North of the airport, where the same succession has been quarried for decades (Figs. 5 & 6).

Although the Brussel Sand Formation and the overlying Lede Sand Formation consist of similar lithologies, it is generally accepted that both are separated by a considerable break in sedimentation. This is witnessed by the regional geometric position of the Lede Sand overlying different lithostratigraphic units (Vandenberghe *et al.*, 1998), in the reworking of Brussel Sand calcareous sandstone concretions (Leriche, 1912; Fobe, 1988, 1990) and fossils (Leriche, 1912, 1921, 1939) in the base of the Lede Sand Formation, and in the composition of the calcareous nannofossil assemblages. Steurbaut (1988) assumed that the hiatus between both formations might correspond to the upper part of calcareous nannofossil zone NP 14 (subzone XIV of Steurbaut, internationally labeled NP14b). However, as the biostratigraphy of the Brussel Sand - Lede Sand boundary interval was not systematically studied, the importance of the hiatus remained questionable. In addition, the exact physical nature of the boundary events also remained unclear, especially in the light of the non-confirmed presence of an additional unit between the Brussel Sand Formation and the Lede Sand Formation, known as the « Laekenien » (Dumont, 1851). This local stage name, figuring on the official 1/40 000 geological map of Belgium (in the Legends of 1903 and 1909), has been considered obsolete since Leriche (1912) and was deleted from the stratigraphical register of 1929 ("Conseil Géologique").

2. Characteristics of the Brussel Sand Formation in the different settings studied

2.1. The Zaventem airport railway cutting

The total exposed thickness of the Brussel Sand Formation, calculated from different sections along the excavation front, is about 7 m, although, vertically, along the outcrop, it only spans about 4 m. This is due to the presence of a wide, gently inclining channel, cutting the normal succession over several m (Figs. 2 & 3, Pl. 1.2). The channel-fill, defined here as unit ZB2 (Zaventem – Brussel Sand 2) also labelled D on Fig. 2, is characterised by an alternation of silty to chalky marls and thin fine sandstones. The deposits below the channel, com-

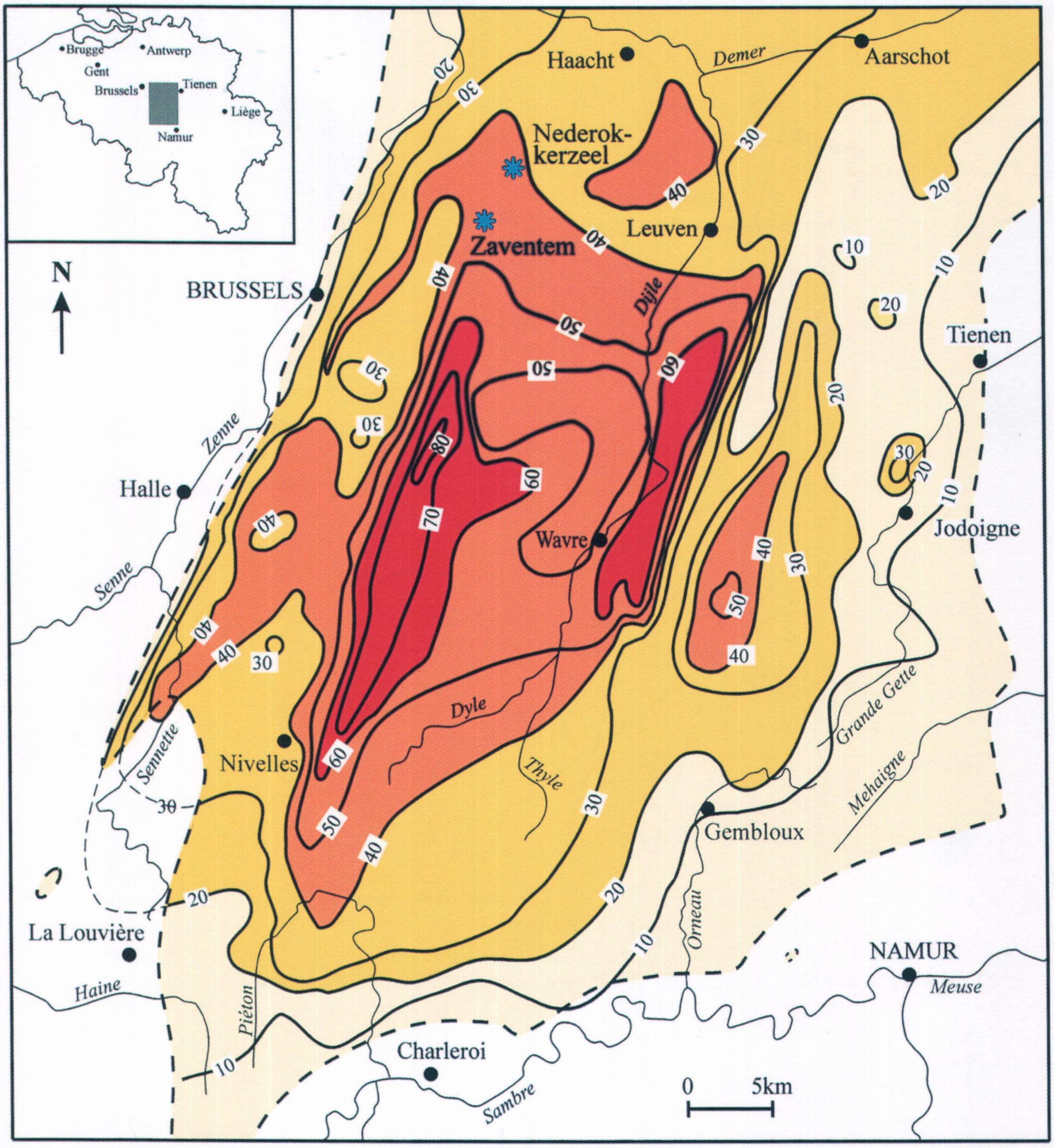

Figure 1. Distribution and thickness of the Brussel Sand Formation in Central Belgium with location of the sections studied (after Damblon & Steurbaut, 2000, based on Houthuys, 1990).

posing unit ZB1 (subdivided into subunits A, B and C in Fig. 2) are much sandier and coarser than those in the channel. At their base they contain mm to cm scale horizontal laminations of alternating fine pale grey, slightly glauconitic sand and pale yellowish marly sand and marl. Several types of silicified sandstone concretions of different dimensions occur in this sand. These, generally several tens of cms large concretions are platy, rounded and somewhat irregular with rounded components («grès fistuleux » sensu Rutot, 1874, 1875) (Pl. 1.4). Inside several of the irregular concretions, isolated shells of *Cubitostrea cymbula* (Pl. 2.6) occur, pointing to a very shallow depositional water depth. The concretions are formed by transport of dissolved biogenic silica along the most permeable laminae towards the nucleation sites. It can be observed in the field that the shape of the concretions is controlled by the permeability structure in the sand. Very few bioturbations occur in this sand facies.

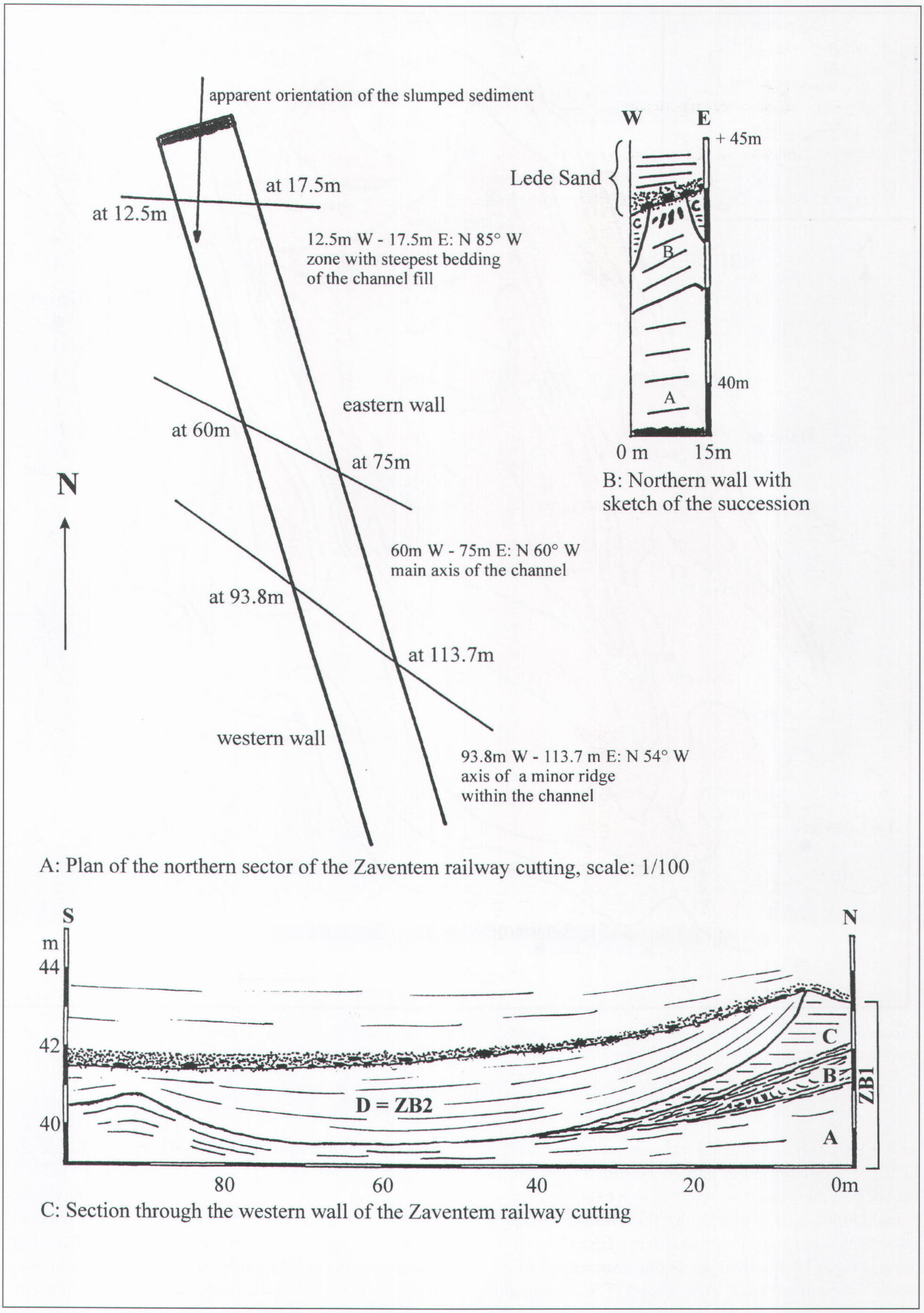

Figure 2. Situation map of the Zaventem Airport cutting with the geological succession in the W-wall of the excavation.

Higher up in the section, a horizon of deformed sediment occurs (Pl. 1.3 & 1.4). At this level the sand displays an oblique stratification pattern. The deformation of the sediment is expressed by the steep position of the fine marl and sand laminae at a single level. The synsedimentary nature of the deformation is apparent from the regular sediment development above the deformed layer. The early deformation is also demonstrated by the silicification of the deformed sediment. The geometry of the already deformed laminae controls the silicification, through its permeability structure, leading to nodule formation. Therefore, the deformation is prior to the nodule formation. The nodule formation itself must have started almost immediately after the sedimentation as the opaline biogenic sediment particles created immediately after burial an oversaturation with respect to chalcedony, the major component of the nodules. Besides, nodules from the Brussel Sand have been reported as pebbles at the base of the overlying Lede Sand (Leriche, 1912), although it must be admitted that these reported concretions were calcareous (Fobe, 1988). The geometry of the deformed laminae is best explained by a gliding of the sediment at the bottom of the sea. The glided sediment might represent a seismite documenting the uplift of the Brabant Massif and the Artois Anticline, which towards the end of the Early Eocene and in the Middle Eocene led to the separation of the Paris basin from the North Sea

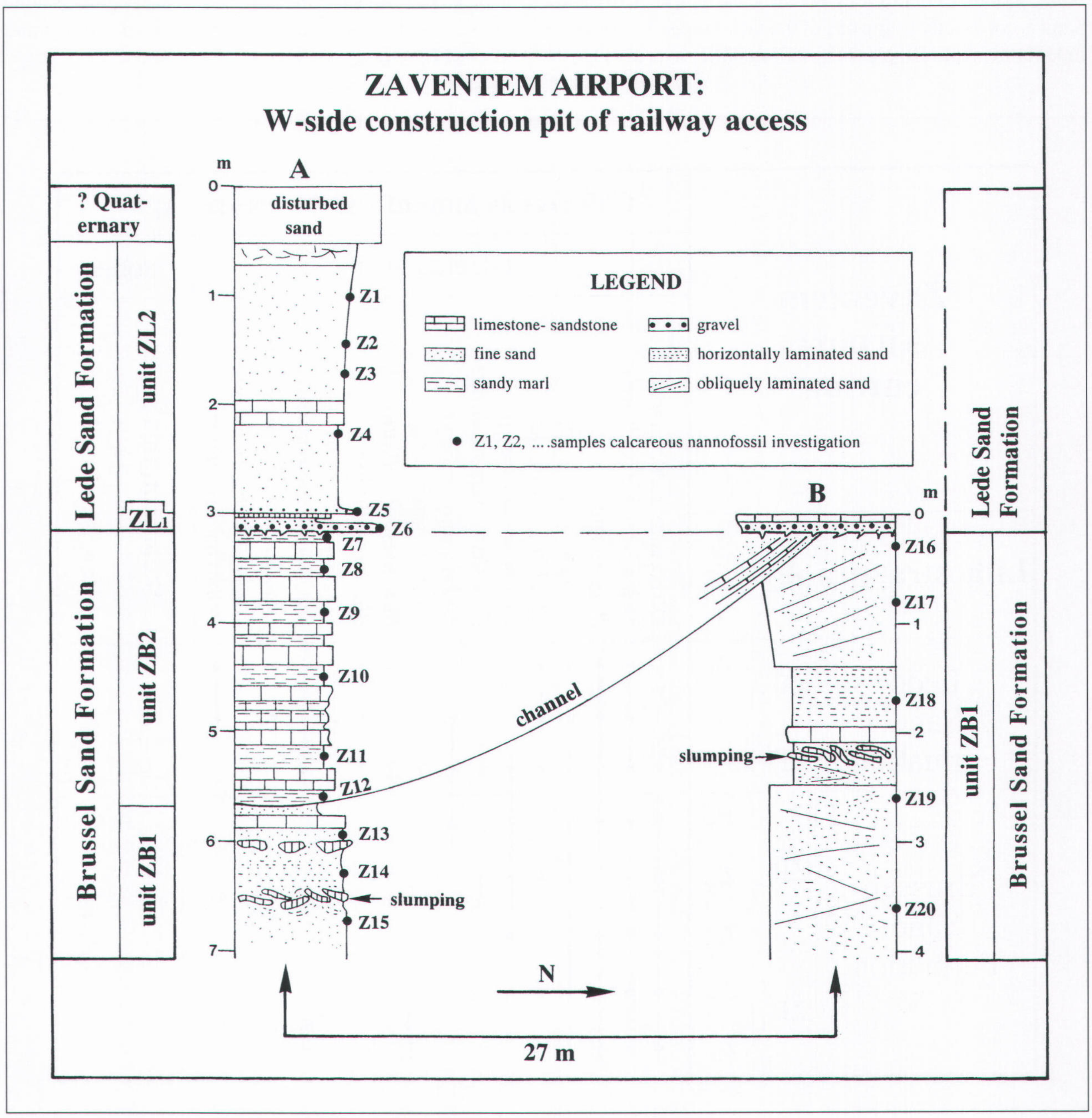

Figure 3. Lithological sections along the W-wall of the Zaventem airport cutting with location of the calcareous nannofossil samples.

basin. This tectonic uplift is also thought to be documented by the incised nature at the base of the different sequences of the late Early to early Middle Eocene in the area (Vandenberghe *et al.*, 1998), the detection of a seismite in the Egem Sand Member of early Late Ypresian age (Willems, 1995) and a fault controlling the deposition of the base of the Brussel Sands near Hoegaarden (Sintubin *et al.*, this volume) and even a small fault observed within the Brussel Sand Formation itself in the Zaventem exposure.

Above the deformed horizon and the oblique stratifications, the sand is again horizontally laminated (Pl. 1.3 & 1.4), but with less fine particles in general and only a few marl laminae in particular. Some small, cm scale, globular concretions occur. This type of Brussel Sand is not exactly fitting one of the facies types described in Houthuys' (1990) classical sedimentological work on the Brussel Sand Formation, although it resembles most his HB facies. The calcareous quartz sand facies corresponds to what has been predicted in the facies map by Gulinck (1963).

Unit ZB1, including the fine to medium-grained sands below the channel, are marked by poorly preserved, moderately diverse calcareous nannofossil assemblages (between 15 and 20 species/sample and 6 specimens/ mm^2 glass-slide), dominated by *Pemma* spp. and *Micrantholithus* spp. (together representing 50% of the total number of specimens). These, together with the regular occurrence of discoasters, indicate tropical, normal saline coastal surface waters. The presence of *Discoaster sublodoensis*, in association with the absence of *Blackites inflatus*, indicates the lowest part of zone NP 14, labelled NP 14a in Berggren *et al.* (1995) and NP14a1 here (Fig. 4).

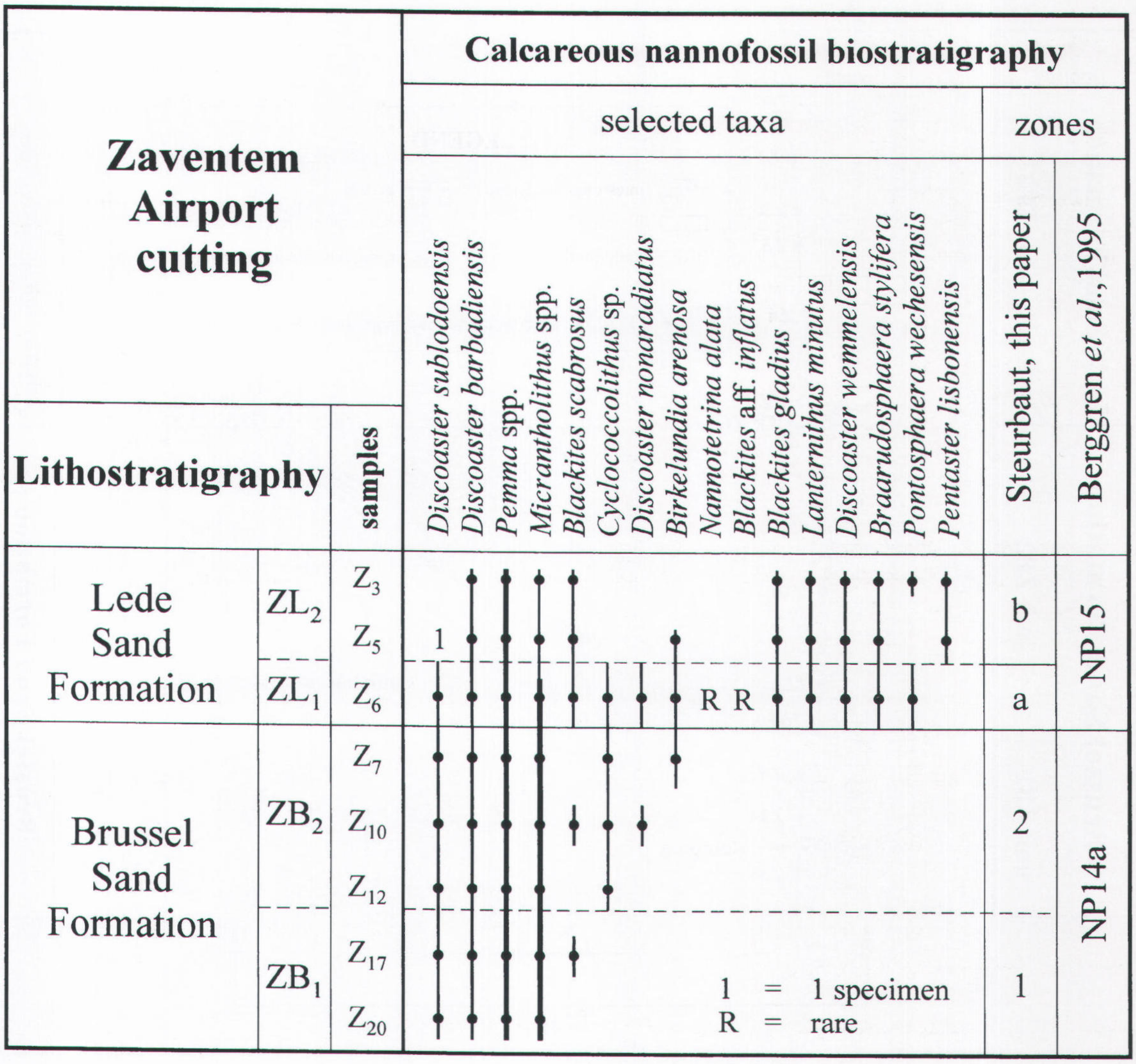

Figure 4. Calcareous nannofossil zonation and distribution of selected taxa in the Zaventem Airport cutting.

Locally, between the Brussel Sand Formation and the overlying Lede Sand Formation, occurs an extra unit (unit D = unit ZB2), filling in a gently inclining channel (Fig. 2). This channel is about 100 m wide and almost symmetrical with a maximal depth of 3.5 m. The sediments at the rims of the channel are dipping 10 to 15° towards the centre of the channel. The axis of the channel has a NWW-SEE orientation (around 295° N). This orientation is almost perpendicular to the major NE trend marking the base morphology and the internal sand structuring of the Brussel Sand Formation, as observed by Houthuys (1990). The channel-fill is composed of an alternation of cm to dm thick fine sandy and marly laminae (Pl. 1.2). The marly laminae are in some places eroded and marl rip up clasts occur in the sand. The silicification in the sands leads to several levels of platy concretions. Fissures in these silicified plates are covered with diagenetic spots of fine pyrolusite and limonite, while some are cemented by opal. No macrofossils have been observed in the channel-fill sediments, but some bioturbations occur in the top of the sands. Microfossils, such as ostracods and foraminiferids, and abundant well preserved irregular echinoid radioles occur at the top and the bottom of the platy silicified concretions.

The nannofossil associations from the silty to chalky marls of unit ZB2 are also dominated by *Pemma* and *Micrantholithus* (40 to 50 % of the association). Except for their higher frequencies towards the top (30 specimens/mm2 glass-slide) and the larger number of *Sphenolithus* spp., they are similar to these from the underlying unit ZB1, reflecting almost identical surface water temperature and salinity. The only major biostratigraphical difference is that unit ZB2, already from its base on, contains *Cyclococcolithus* sp., a taxon that is known to reappear in the middle of the Brussel Sand Formation (Steurbaut, 1990 and unpublished).

2.2. The Berg-Nederokkerzeel sandpit

Although the mollusc fauna from the Nederokkerzeel area has been known for more than a century (Burtin, 1784; Vincent, 1887; Glibert, 1933), little was understood about its stratigraphy till the re-examination of the Berg-Nederokkerzeel sandpit in 1994 by the present authors. Detailed investigation of this pit by the first author (JH) has shown that the Brussel Sand Formation consists of three major units (Fig. 5). The lowermost unit A is a fine pale grey sand, homogeneously bioturbated and containing near the base of the sandpit a concretion level consisting of large calcareous and silicified sandstone nodules. The only fossil specimens found in the sand are a few oyster shells (*C. cymbula)* and part of the rostrum of the spade fish *Cylindracanthus*. This facies is similar to facies B of Houthuys (1990). Fobe (1986) reported an increase in coarse quartz grains towards the top of this unit. The latter is cut by a more than two meter deep narrow channel, filled in with alternating layers of shelly sand and less fossiliferous sand, forming unit B (Pl. 2.1). The southern border of the channel is very steep, indicating a rapid cutting and filling of the channel. The fossiliferous layer at the base of the channel (bed 2 on Pl. 2.1) contains the highest fossil concentration: transported mollusc shells, elasmobranch teeth and some rare ellipsoidal concretions formed around large fossils, very different from the regular concretions present in the Brussel Sands (Pl. 2.2). Note the chaotic mixture of the shells on Pl. 2.2, pointing to a very rapid deposition of the transported shells. In the overlying fossiliferous layer (bed 3 on Pl . 2.1) the shells are also deposited without any preferential orientation (Pl. 2.3). In the same fossiliferous horizon some 30 cm to 90 cm large clusters of fossils, cemented by silica occur. They were transported into the channel indicating that some silicification was very early in the diagenetic history of the Brussel Sand Formation (Pl. 2.5). Sporadically smaller and still soft concretions are found at this level. This observation suggests that cementation of the stone layers in the Brussel Sand was underway at the time of the formation of the tidal gully under discussion. Indeed, the silicification did not precede the gully cut because otherwise several of these concretions would have been found at its base, and on the other hand, they are known to have been formed before the formation of the basal gravel of the overlying Lede Sand Formation, as they occur as reworked pebbles in this gravel. The uppermost shelly sands (bed 4 on Pl. 2.1) are dominated by *Divaricella* and *Eumargarita. Bullinella* and *C. cymbula* are present too. The small solitary corals *Turbinolia* and *Sphenotrochus* are very abundant (Glibert, 1930). The shells are smaller than in the other units. Rapid deposition is demonstrated by numerous shells with the concave side upwards (Pl. 2.4).

The elasmobranch remains in each fossiliferous layer of unit B are similar to the classical Brussel Sand elasmobranch fauna. Almost all the teeth are fully grown specimens. Among the additional vertebrate remains are numerous turtle fragments, some rare snake fragments and even, although very rarely, bird bones. In the upper fossiliferous layers occur possibly brackish water fossils, such as the abundant *Rhinoclavis (Semivertagus) unisulcatus* (Lamarck, 1804). Almost all the specimens are perforated by a naticiform type of gastropod. This is surprising as the mollusc *Rhinoclavis* is very mobile and could easily have escaped the predators. This suggests that the bottom of the channel was alternatively emerged and covered by water. Under these conditions they were temporarily caught into some isolated tidal pools from where they could not escape the boring gastropods.

The channel fill sands are overlain by a well-sorted homogeneous fine sand layer of about 50 cm thickness (unit C). This layer contains abundant radioles and fragments of irregular echinids and numerous callianassid type burrows (Fig. 5). As it covers the underlying facies it represents a new marine pulse, submerging the tidal flat area. Some teleostean remains are found in this layer, together with very rare teeth of small sharks. At the top of the Brussel Sand Formation occur palm trunks presumably stranded on a beach flat. These trunks are exceptionally silicified. In the specimen shown on Pl. 3.4 the burrows of the perforating Teredinid molluscs are even silicified. Over most of the area this level is directly overlain by the coarse base of the Lede Sand Formation (Pl. 3.1).

The lowermost unit A at Nederokkerzeel contains moderately rich, but highly diverse nannofossil associations (around 30 species/sample and 10 specimens/mm2), which are marked by the abundance of *Pemma* spp. and *Micrantholithus* spp. They are furthermore characterised by the co-occurrence of *Discoaster sublodoensis*, *D. praebifax*, *D. wemmelensis, Blackites perlongus*, *Cyclococcolithus* sp. and *Toweius* sp. throughout the section, and by *Lanternithus minutus* in the topmost meter. This, together with the absence of *Blackites inflatus* indicates the higher parts of nannofossil zone NP14a, labelled here NP14a3. The well-sorted coarser units B and C are too poor in nannofossils to be precisely dated.

3. The base of the Lede Sand Formation in the area NE of Brussels

In the Zaventem railway cutting several remarkable observations can be made in the basal layer of the Lede Sand Formation. Most of the characteristic features recorded there can also be observed in the Berg-Nederokkerzeel sandpit. The base of the Lede Sand is dominated by abundant rounded, perforated and transported concretions (Pl. 1.1). A coarse gravelly quartz sand occurs between the nodules, containing sparse dark pebbles and very typically elongated rice-grain quartz (4 to 7mm length over 1 to 2 mm cross-dimension). Some of these quartz grains are yellowish, orange to blood red. Some of the coarse rounded quartz grains appear to be amethyst (Pl. 4.1). Hyaline quartz grains are also present (Pl. 3.2). Originally the concretions must have been rather flat (see also Pl. 1.2) and some of these concretions have the internal sedimentary laminations preserved resembling the concretions in the underlying Brussel Sand Formation (see also Pl. 1.5). However, shell moulds as present in these basal concretions are not observed in the Brussel Sand below. Some concretions were broken up into smaller fragments before they were rounded (Pl. 4.2). Transport is also indicated by the imbrication and the stacking of the concretions (Pl. 1.1). The current strength must have been very high seen the size of the concretions involved and high enough to turn over the concretions as is proven by the bio-perforation of the concretions on all sides (Pl. 4.2 & 4.3). If the concretions become inbedded or moved upside down, true boring molluscs, sessile sponges or worms are unable to survive. After having been turned over the blocks can be recolonised again by new generations of these organisms. The perforations have diameters of up to a centimeter and are a few centimeters deep. Some of these can also be attributed to regular echinoids. Shells of boring molluscs are never preserved, as is the case for all the first colonisers of the nodules. Several mollusc moulds are present on the concretions and the dissolution of the shells requires the emersion of the nodules. The dissolved moulds are covered by a limonite film which is generally occurring around the whole concretion, also pointing to an emersion phase after the perforation. Some parts of the concretions are also covered by a dark greenish varnish, probably a glauconitic precipitation as shown on Pl. 3.3, on which it can be observed that the limonite staining is younger than the glauconite staining. This glauconite varnish is also present on some internal moulds. Logically, glauconitisation would require a submersion by a relatively deep water sheet of at least 15 meters (Giresse & Odin, 1973). This renewed submersion is documented by the colonisation of the concretions and perforation holes in it. Very typically, the first recoloniser was the foraminiferid *Bdelloidina* (Pl. 4.7). Also serpulid tubes (Pl. 5.3), calcareous sponges (Pl. 5.2) and oysters occur on top of the concretions. Some of the molluscs in the coarse basal layer are reworked from the Brussel Sand Formation but also younger fauna elements are present. Similarly, the shark teeth in the coarse basal layer are partly reworked, including well-preserved teeth derived from the underlying Brussel Sand, but also indigenous taxa which are definitely older than the classical Lede Sand teeth assemblage. This age relationship of the basal layer with respect to the classical Lede Sand Formation is also found in the calcareous nannofossil assemblage. The co-occurrence of *Blackites gladius, Blackites* aff. *inflatus* (very few and less inflated than the type material), *D. sublodoensis* and *Nannotetrina alata* (never recorded in Belgium up to now) in sample Z6 indicates the base of zone NP15, tentatively labelled here NP15-1 (Fig. 4). This subdivision has only local significance, and differs from the standard subdivision of NP 15 as defined in Berggren *et al.* (1995). It also indicates that the base of the Lede Sand Formation at Zaventem is slightly older than in all other nannofossil bearing Lede Sand sections studied.

Remarkably, the rounded and perforated concretions occur generally below but also above an almost continuous non-perforated platy concretion level (see also Pl. 1.2). This situation requires sedimentation above the basal layer with the formation of a concretion level inside the newly deposited sediment. The newly deposited sand was subsequently eroded, just leaving the sandstone concretion level as a lag deposit, and bringing some of the earlier rounded and perforated concretions above this concretion level. Only after this history starts the deposition of the currently preserved Lede Sand Formation. Its base undulates over the underlying Brussel Sand Formation (Pl. 1.2) while the internal sandstone layer higher up in the Lede Sand remains subhorizontal. Apparently the repeated strong currents and turbulence at the base of the Lede Sand Formation have left a slight relief in the underlying sediments which was only blanketed out during the later deposition of the transgressive Lede Sand.

In the Berg-Nederokkerzeel sandpit most of the characteristic features described above can also be observed. In this sandpit rounded and perforated concretions, as well as some fossils are sometimes cemented to the overlying thick concretion sandstone layer in the Lede Sand. In the coarse sediment between the rounded concretions occur reworked *Nummulites* with a glauconite varnish (Pl. 4.4), reworked asteroid ossicles (Pl. 4.5) and reworked brachiopod fragments (Pl. 4.6). Some of the reworked fragments, including *Nummulites laevigatus*, are apparently derived from higher non-preserved parts of the Brussel Sand Formation. Certain molluscs are very well preserved, including pectinids (Pl. 5.6 & 5.10) and oysters (Pl. 5.5, 5.7 & 5.9). Well preserved shark teeth, hydrozoa, bryozoa, small bivalves and small brachiopods, often with both valves joined, are documenting the original fauna at the time of the final deposition of the coarse sediment. The shark teeth fauna is slightly different from both the classical Brussel Sand Formation and the classical Lede Sand Formation.

4. The Lede Sand Formation

The Lede Sands s.s. (excluding the basal conglomerate) are pale grey to yellowish coloured, fine to very fine sands, slightly calcareous and marly, homogenised by bioturbation, with partially decalcified mollusc shells. In the Zaventem railway cutting, among the recognisable fossils are Nuculidae, Cardiidae and Myidae and some well-preserved *Ditrupa* specimens. In this section a 20 cm thick concretion sandstone layer is present about one meter above the basal layer of the formation. In the Berg-Nederokkerzeel sandpit the Lede Sand Formation has a similar aspect. A thick sandstone concretion horizon is cemented directly to the basal layer and a similar additional sandstone concretion level is present about 50 cm higher in the section. Mollusc shell traces can be identified in the concretions. The nannofossil associations, only studied at Zaventem (samples Z3 and Z5, see Fig. 4), are marked by *Blackites gladius*, frequent *Lanternithus minutus* and *Discoaster wemmelensis*, and by the first consistent occurrence of *Pentaster lisbonensis*. They belong to a higher part of zone NP15, labelled here NP15-2.

5. Discussion

The Brussel Sand facies present in the vicinity of the Zaventem airport is a fine grained calcareous and only slightly glauconiferous sediment, deposited in very shallow water of only a few meters depth, influenced by tidal currents causing the pattern of alternating muddy and sandy layers. Finally the water became shallow enough for strong currents to incise broad channels of only a few meters deep into the underlying sand, probably on a tidal flat. They are filled with tidal sands and mud layers. From the nannofossil associations it is clear that the totality of the exposed Brussel Sand Formation at Nederokkerzeel is younger than the top of the Brussel Sand Formation (unit ZB2 = unit D of Fig. 2) at Zaventem, implicating that the channel cut at Nederokkerzeel is posterior to the one observed at Zaventem. This means that shallow water conditions with strong tidal currents persisted over a considerable long period in the Brussels area. The differences in channel structure (a steep and narrow channel at Nederokkerzeel versus a broad channel at Zaventem) and in composition of the channel-fill (silty marls at Zaventem versus much coarser shelly sand at Nederokkerzeel) point to certain palaeoenvironmental changes during the deposition of the Brussel Sand Formation (e.g. in sediment supply and in orientation of current systems). The fossil associations indicate a partial emersion at the end of the channel filling at Nederokkerzeel, followed again at the very top by a complete submersion.

A much thicker package of Brussel Sand was originally deposited in the area, as demonstrated by the many reworked fossils at the base of the Lede Sand, in particular by the reworked concretions from within the Brussel Sand. Information about the duration of the hiatus can be gained from the nannofossil data. These indicate that sediments belonging to subzone NP14b, whose duration is estimated at 1.2 m.y. (Berggren *et al.*, 1995) are now entirely missing in the Brussels area. However, the presence of a few reworked *Blackites* aff. *inflatus* in the base of the Lede Sands suggests that sediments pertaining to this subzone had been deposited in the area. In the same basal layer occur two types of reworked *Nummulites laevigatus* and two types of reworked asteroid ossicles and brachiopod valves (Pl. 4.5 & 4.6). Some of the *N. laevigatus* are silicified and seem to be rather well preserved, but most of them are abraded and rounded, even with glauconite formation in the pores (Pl. 4.4), apparently having undergone considerable physical and chemical weathering. This observation confirms earlier descriptions by Van den Broeck (1902). The silicified *N. laevigatus* come from silicified rolled blocks derived from a southern uplifted area, while the calcareous less solid and more abraded ones are probably originating from erosion of a local source. In situ records of *N. laevigatus* are known from several sites east of the line Tienen –

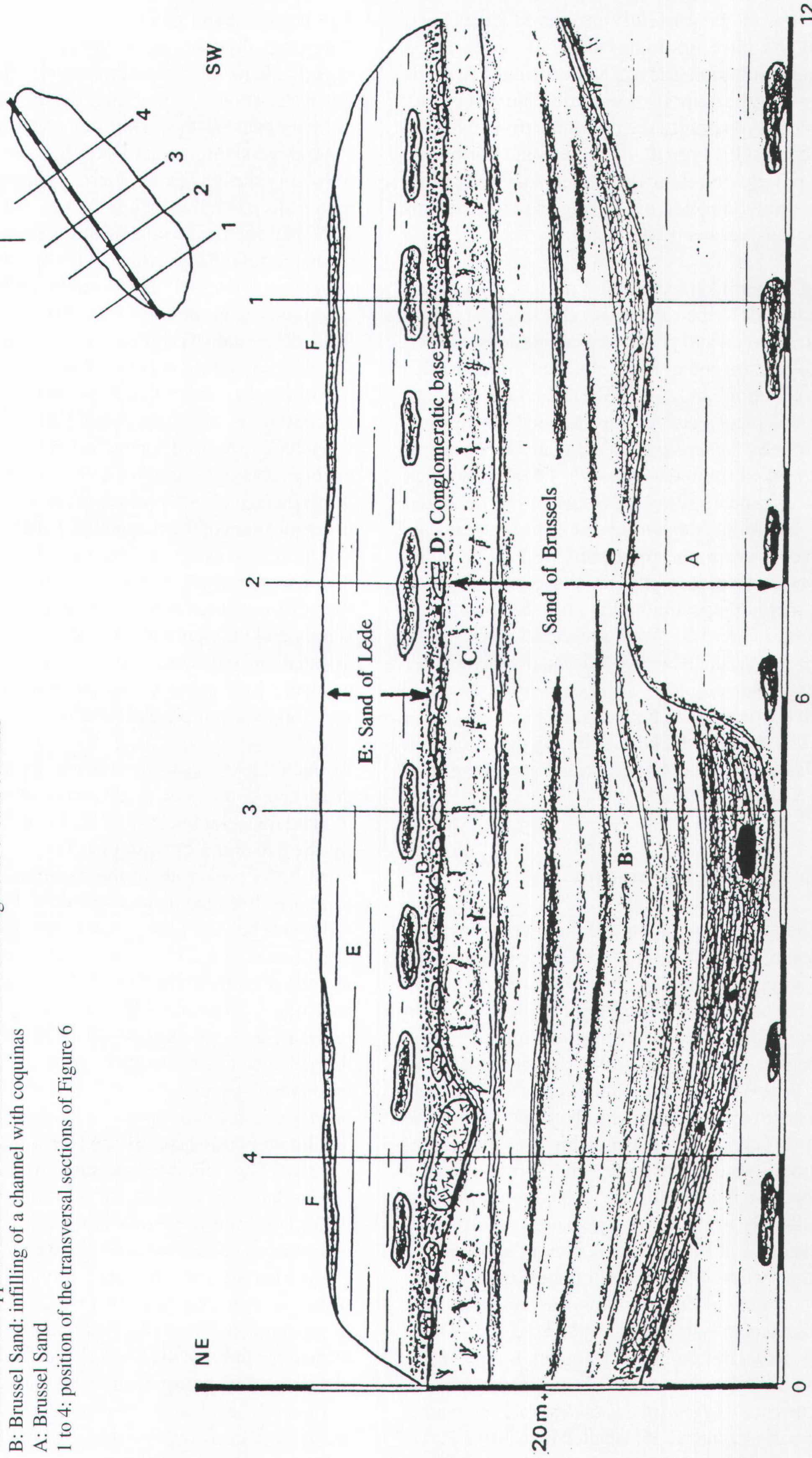

Figure 5. NE-SW section through the Berg-Nederokkerzeel sandpit (situation summer 1994).
F: Quaternary
E: Lede Sand
D: Conglomeratic base of the Lede sand
C: Brussel Sand: uppermost level with *Callianassa* burrows and fragments of sand echinids
B: Brussel Sand: infilling of a channel with coquinas
A: Brussel Sand
1 to 4: position of the transversal sections of Figure 6

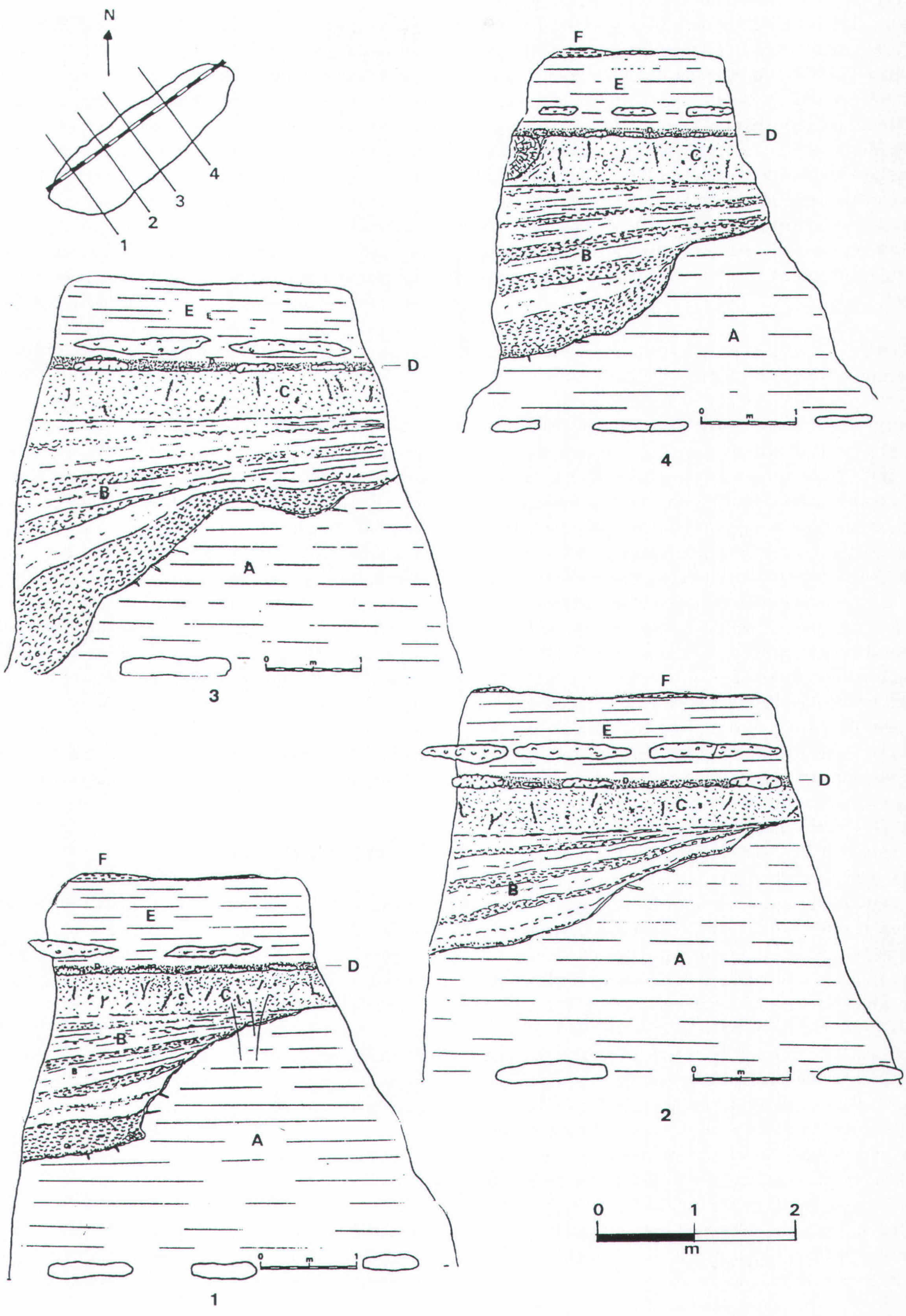

Figure 6. NW-SE sections through the Berg-Nederokkerzeel sandpit (see Figure 5 for legend).

Gembloux – Charleroi (Leriche, 1923; Blondeau, 1966) (see Fig.1). They are also known from the southeastern outskirts of Brussels (Van den Broeck, 1902; Leriche, 1927; Dartevelle, 1934), from the Zeebrugge area (Depret & Willems, 1983), the Knokke borehole (King, 1990) and the Mont des Cats, Mont Aigu (Leriche, 1921, 1923) and Mont-de Récollets in N France (Nolf & Steurbaut, 1990). Moreover, the presence of reworked Early Lutetian terrestrial mammal fragments at the base of the Lede Sand Formation in the southern part of Brussels (Rutot, 1881; Depéret, 1912; Misonne, 1958) suggests that, after the deposition of the *Nummulites* bearing levels, part of the area must have been emerged for a considerable period of time.

When the sea reached the area again, at the time of the deposition of the basal layer of the Lede Sand Formation, strong erosion must have occurred, producing a pile of broken and rounded concretions from the underlying Brussel Sand. Perforations by marine molluscs show that most of the concretions were turned over by the currents at this palaeo-shoreside. These perforating molluscs require a continuous submersion and the early glauconitic varnish suggests even at least temporary water depth of about 15 m. Afterwards, the sea must have retreated somewhat to allow a complete oxidation of the perforated and rounded concretions. The perforating mollusc shells were dissolved already before the oxidation (see Pl. 1.5). Colonising fossils on the oxidised concretions and in the perforated voids, together with the arrival of a new type of sediment consisting of differently coloured rice-grain quartz show the renewed submersion. The basal lag deposit also incorporates a sandstone concretion, newly formed similar to the ones occurring now in the Lede Sand. This means that some Lede type sand was deposited, cemented and eroded again, leaving the cemented blocks incorporated now in the basal layer. The turbulence and currents must once again have been very strong, not only in order to erode all the sand and leave only the sandstone concretion layer, but in particular to bring some of the rounded and perforated concretions above the newly formed sandstone concretion horizon. Some of the fossils, preserved in the basal layer, particularly the calcareous nannofossils and shark teeth, represent the biota at the time of the earliest fully marine conditions over the area. They are definitely older than the fossils normally found in the Lede Sand Formation. Probably, they form part of the fossil record used to define the 'Laekenien', a local stage, positioned just below the 'Ledien' stage (de Heinzelin & Glibert, 1957). The classical Lede Sand was deposited only after this erosion phase, during the subsequent installation of a higher relative sea level over the area.

6. Conclusions

During the transition between the Brussel Sand Formation and the Lede Sand Formation a particular long period of strongly fluctuating relative sea-level regime existed over the area. The sediment structure and the fossils document an extreme shallowing with the development of at least two generations of tidal channel systems within the upper part of the Brussel Sand Formation and even emersion at the end of the uppermost channel-fill at Nederokkerzeel. This was followed again by a relative sea-level rise, as shown by unit C and the remains of a completely eroded fully marine deposit, reworked in the base of the overlying Lede Sand. The lowest relative sea level, with at least partial emergence of the Brussels area, occurred during middle to late Biochron NP14b. Two subsequent consecutive erosive pulses could be documented, leaving a lag deposit: the classical Lede basal gravel. In this lag deposit, relics are preserved, on the one hand, from the underlying Brussel Sand Formation, and, on the other hand, from the earliest overlying Lede Sand Formation. Some of the fossils in this basal gravel are older than these in the classical Lede Sand Formation. The overlying classical fine-grained Lede Sand represents the transgressive part of a new sedimentary sequence. It is suggested that this relatively long time of shoreline fluctuation in the area was caused, or at least influenced, by the rising of the Brabant Massif, which vertical tectonic movements were competing with a fluctuating sea level. The initial sediments, which became eroded soon after their deposition, and now concentrated in the basal lag deposit of the Lede Sand Formation are considered to represent the former "Laekenien" stage.

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PLATES
1-5

PLATE 1

FEATURES OF THE ZAVENTEM AIRPORT RAILWAY CUTTING

1.1. The basal conglomerate of the Lede Sand Formation, consisting of rounded, on all sides perforated and transported concretions, some of which are imbricated. The largest block on the photograph is about 80 cm in diameter. At the base occur large white fragments of a *Nautilus* shell.

1.2. Northwest part of the Zaventem railway cutting showing the rather homogeneous Lede Sand Formation overlying and eroding the laminated Brussel Sand Formation along a curved contact (white dots). Unit D (= unit ZB2 in Figs. 3 & 4) of the Brussel Sand represents the channel-fill as shown in Fig. 2. The different units are labelled as in Fig. 2. Note the flat lithified concretions along the contact and the silicifications along the strata in the Brussels Sand.

1.3 & 1.4. Slumped horizon with clear steep stratification in the Brussel Sand. The silicified nodules follow the detailed structures of the slumped strata as exemplified by the toes of the nodules. This indicates slumping before silicification. The horizon is interpreted as a seismite. The largest nodule is about 40 cm wide. In the top left corner of 1.4 figures a silicified sandstone nodule of the 'fistuleux' type, characterised by irregular outlines caused by differences in advection of silica resulting from the differences in permeability of the laminae. The irregular sediment at the base is slope rubble.

1.5. A completely silicified contact between the Brussel Sand and the Lede Sand. The sandstone at the base is a fractured Brussel Sand concretion, displaying the original sedimentary layering, perforated at its top, oxidised afterwards and later covered by the coarse base of the Lede Sand. This coarse base layer has been cemented to the underlying sandstone concretion and also to an overlying sandstone layer developed inside the Lede Sand, visible in the top of the photograph.


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PLATE 2

FEATURES OF THE BERG-NEDEROKKERZEEL SANDPIT

2.1. The shelly sand filling of the steep sided channel in the top of the Brussel Sand. The shell layers are labeled bed 2, bed 3 and bed 4 respectively displayed in plane view on 2.2, 2.3 and 2.4 (preparations and photographs by M. Vervoenen). Note the limonite concentration at the rim of the channel.

2.2. The basal fossiliferous layer bed 2 (2.1) in plane view showing a chaotic assemblage of different shells. The sand at the base of the channel is marked by a limonitic crust. The largest shell is about 3 cm.

2.3. Typical shell concentration in the median part of the channel-fill (bed 3 in 2.1). The fossils in these fossiliferous sands show no preferential orientations in plane section. The dimension of the largest shell is 5 cm.

2.4. Shell concentration near the top of the channel fill (bed 4 in 2.1). The shell dimensions are smaller than in the other fossiliferous layers (largest shell about 2 cm). The absence of double valved shells and the concave upwards position of a large number of pelecypods in plane section point to a sudden deposition from a turbulent current.

2.5. Part of a silicified chunk of fossils found in fossiliferous sediment in the middle of the channel-fill in the Brussel Sand of Nederokkerzeel. Note the internal silica filling of a large Naticid (4.8 cm diameter).

2.6. Sessile and opercular valves of *O. (C.) cymbula,* the typical oyster in the Brussel Sand Formation.

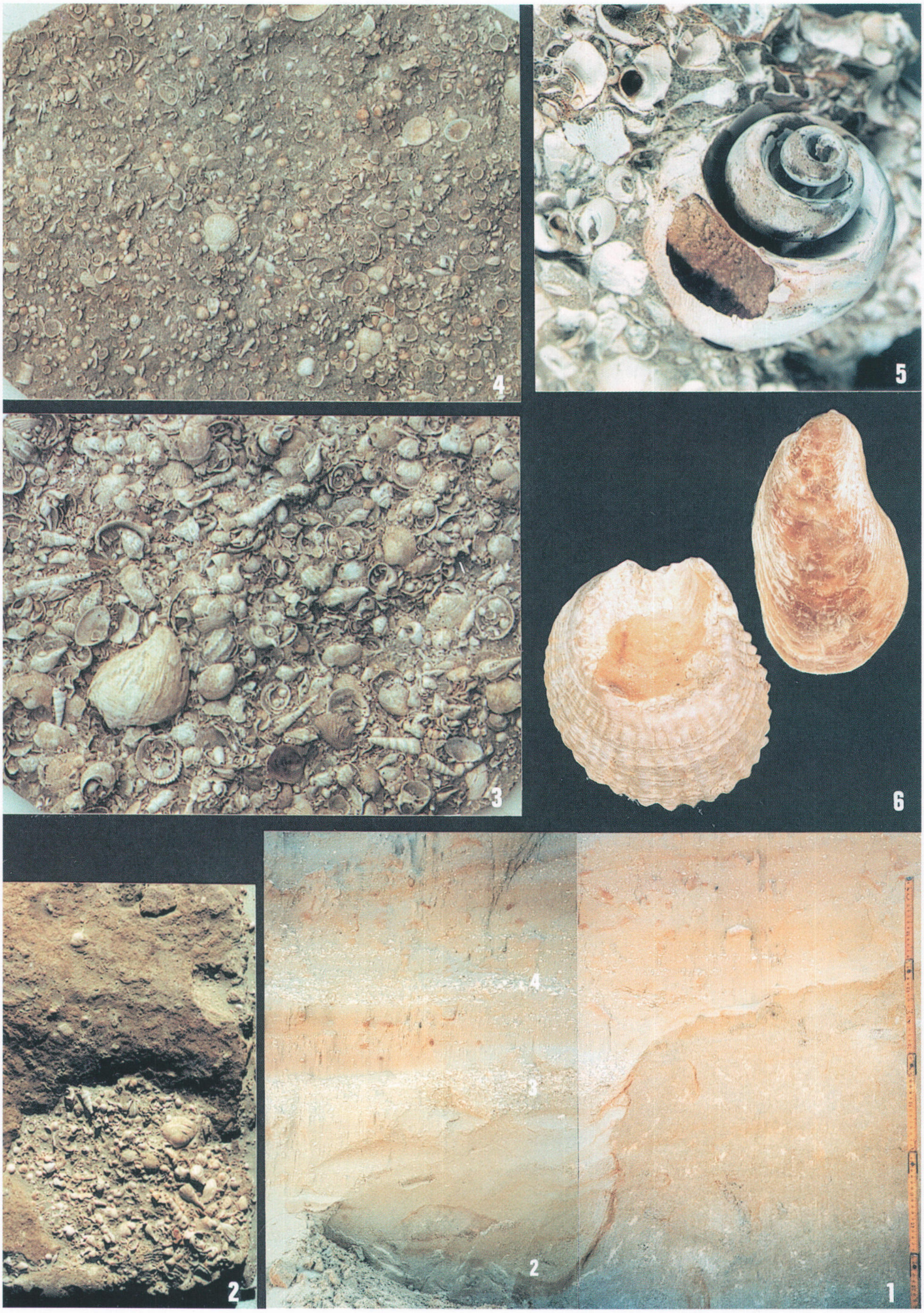
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PLATE 3

FEATURES OF THE BERG-NEDEROKKERZEEL SANDPIT

3.1. A fossil beach, stained by limonite, on top of the channel-fill in the Brussel Sand Formation as shown in Pl 2.1, on top of which occurs the ghost of a palm tree trunk. Inside, a network of cemented burrows by a *Calianassa* type organism can easily be distinguished. The trunk diameter is about 35 cm. Directly overlying the trunk occurs the coarse base layer of the Lede Sand Formation.

3.2. Fill-in of a perforation void by hyaline quartz grains in a silicified nodule at the base of the Lede Sand Formation.

3.3. Detail of the Brussel Sand /Lede Sand contact, with an empty perforated void in a Brussel Sand concretion, upward cemented to smaller also perforated rounded nodules from the Lede Sand Formation. The coarse cemented zone is stained with glauconite. The surface of the smaller cemented pebbles (top photograph) is markedly stained by limonite.

3.4. Detail of a palm tree trunk swept on the palaeo-beach on top Brussel Sand (Pl 3.1) containing abundant silicified tubes of Teredinid molluscs.

3.5. Cross-section of a gallery of the most typical, but unidentified, burrowing organism from both the Brussel Sand Formation and the Lede Sand Formation.


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PLATE 4

FEATURES OF THE ZAVENTEM AIRPORT RAILWAY CUTTING AND THE BERG-NEDEROKKERZEEL SANDPIT

4.1. Remarkable rice-grain shaped quartz and blood-red rounded quartz grains in a sieve residue of the basal coarse sand and gravel of the Lede Sand Formation in the Zaventem railway cutting. Identical quartz grain assemblages have been found at Nederokkerzeel.

4.2. Broken and rounded fragments of originally much larger concretions in the base of the Lede Sand Formation found at Nederokkerzeel.

4.3a & b. Two sides of a flat fragment found in the base of the Lede Sand Formation in the Zaventem Airport cutting. Both sides are intensely bioturbated. Sea-urchins colonised the rock fragment on one side (see 3a), whereas the other was predominantly colonised by perforating bivalves. The fragment has been stained by limonite after dissolution of the colonising organisms. After oxidation new colonising organisms can be observed such as bryozoa, serpulids, brachiopods and oysters (3b). The length of the fragment is about 15 cm.

4.4, 4.5 & 4.6. Selected fragments from the coarse base of the Lede Sand Formation at Zaventem: 1.2 cm wide *Nummulites laevigatus* with glauconite staining (4.4), rounded and broken sea star fragments, largest about 1.1 cm (4.5) and eroded brachiopod valves, largest about 1.8 cm (4.6).

4.7. Foraminiferal *Bdelloidina* specimens (around 0.7 cm diamater), colonising a fragment in the coarse base of the Lede Sand Formation.


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PLATE 5

CHARACTERISTIC FOSSILS COLLECTED IN THE BASE OF THE LEDE SAND FORMATION AT NEDEROKKERZEEL AND ZAVENTEM

All these fossils of sessile or free organisms are considered as sub-contemporaneous of the deposit. Their morphology, their dimensions, as well as their quantitative association, differ obviously from all that was discovered formerly in both Brussel Sands or Lede Sands *sensu stricto*.

5.1. Small (27 mm), thin (1 mm) and very brittle calcareous concretion supposed of algal origin. These are quite frequent on the top or lateral sides of some blocks of the conglomerate, but also on the slightly indurated sea bottom between large silicified concretions covering and partially cementing the top of the conglomerate.

5.2. A calcareous sponge of an undetermined species (18 mm long) showing its particularly large central osculum. This species is one of the relatively common recolonisator organisms found on the top of the derived blocks of the conglomerate. It may also occur as isolated fossil in the shelly mass deposits between the blocks of the basal conglomerate. This seems to be due to the dissolution of its original support. The osculum shows at least eight recognizable double rings, which could be interpreted as a growing process of eight years or eight monsoons.

5.3. Large (18 mm) spiral calcareous tube of a serpulid species. The tube of this species is always strongly keeled and more or less crested. This species is relatively abundant on the derived blocks of the conglomerate. As the spongid of photo 2, it may also occur as isolated fossil in the shelly mass of the basis of the Lede Sand, for the same reason.

5.4-5-6. Brachiopod of a *Crania*-like species (*Ancistocrania*?).

5.4. Profile of the sessile valve (15 mm) of an adult specimen with on its side a juvenile one in the first stage of growing. This shell shows at least seven growing phases.

5.5. Outer view of the opercular valve (17 mm) of an adult specimen.

5.6. Inner view of the opercular valve (17 mm) of the same specimen.
Numerous juvenile specimens were collected on top or sides of the derived blocks, some on shells of dead oysters. The greatest part of the adult or old individuals was found in the shelly mass.

5.7-8. *Ostrea (Pycnodonte) gigantica* (Solander, 1766). Outer (5.7) and inner view (5.8) of an opercular valve of umbono-ventral length of 55 mm. The largest specimen of this species collected during our campaigns is 108 mm in length.

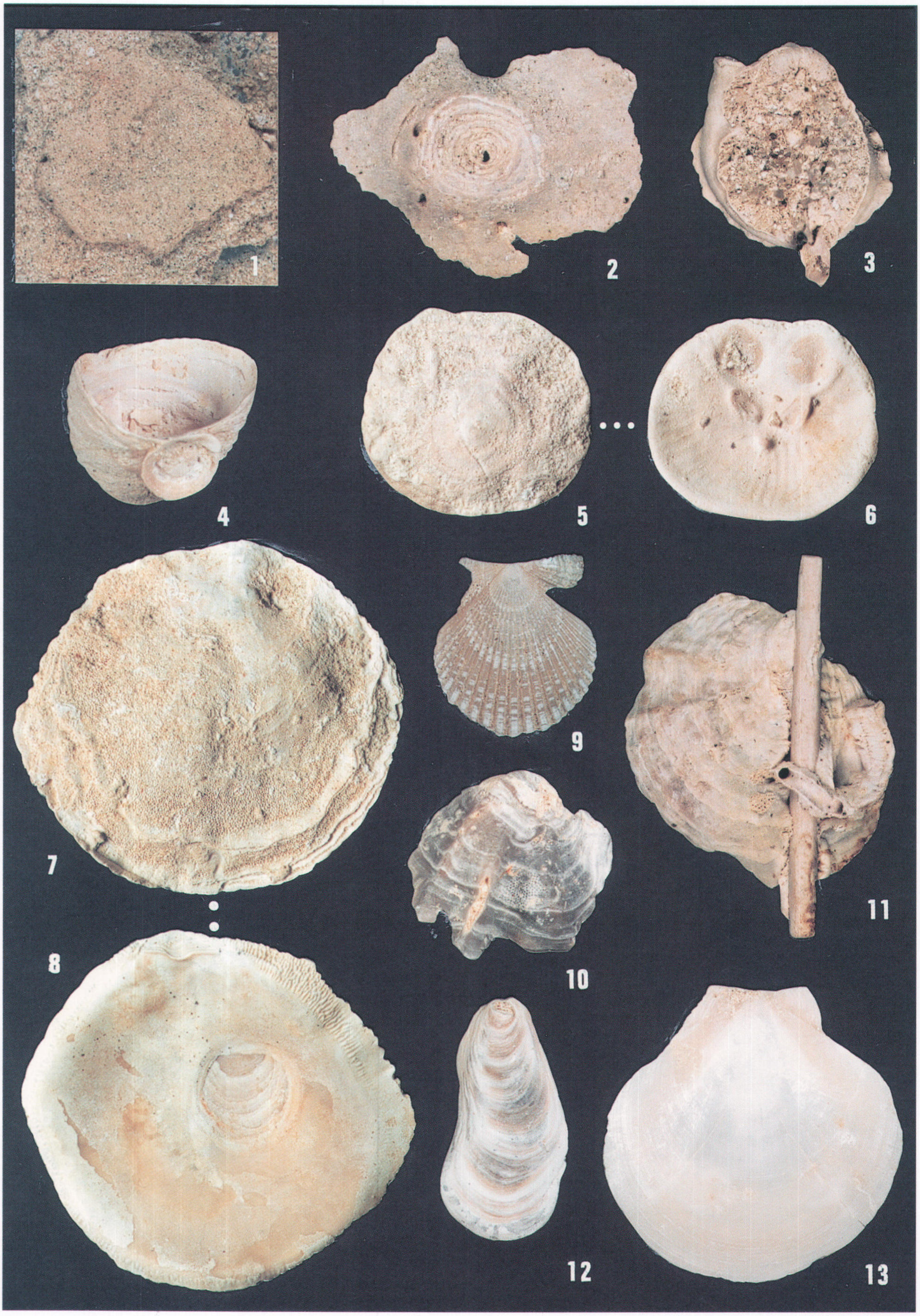
5.9. *Lyropecten (Aequipecten) walleri* Glibert, 1976 (Umbo-ventral length 18 mm). One of the most common pectinids of this level in which it is always associated with the following pectinids: *Lyropecten (Aequipecten) plebeius* (common), *Lentipecten corneus* (very common) and *Pseudamussium (Paliollum) nysti* (rare).

5.10. *Ostrea (Pycnodonte) gryphina* (Deshayes, 1832), umbo-ventral length 21 mm. This typical strongly costulated form is characteristic for this level and only for this level. In the Lede Sands *sensu stricto* the specimens of this species always show more globular shell without any costulation. According to a classic interpretation this is only due to the dynamics of the sedimentary environment. In the energetic environment they are relatively flat and costulated.

5.11. Other specimen of *O. (P.) gryphina,* chosing as growing support the stalk of a living plumatellid anthozoa. Here, it was accompanied by a young serpulid of the same species as illustrated in 5.3. Plumatellids were very common inhabitants of all the shallow sandy facies of both the Brussel and Lede Formations. The stalk fragment is 21 mm high.

5.12. *Vulsella deperdita* Lamarck, 1819 (umbo-ventral length 23 mm). Other typical and quite common component of the pelecypod fauna of this horizon. This species is quite unknown in the Brussel Sands and relatively uncommon in the true Lede Sands. The frequency of *V. deperdita*, associated with the costulated form of *O. (P.) gryphina* and *O. (P.) gigantica* is characteristic for this horizon.

5.13. *Lentipecten corneus* (Sowerby, 1818), umbo-ventral length 32 mm, a very well preserved specimen from the shelly mass.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