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The composite Kortrijk section (W Belgium): a key reference for mid-Ypresian (Early Eocene) stratigraphy in the southern North Sea Basin

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[2†] *Chris King sadly passed away while this paper was in its final stage. It is dedicated to his memory, in recognition of his lifetime achievements in stratigraphy and biostratigraphy and to his great love and fascination for the Ypresian strata of Belgium.*

ABSTRACT. The upper part of the Kortrijk Clay Formation (the Roubaix Clay and Aalbeke Clay Members of mid-Ypresian age) has been exposed in road and canal cuttings and clay quarries in the Kortrijk area (western Belgium), and penetrated by several cored boreholes. It is overlain disconformably by the Mont-Panisel Sand Member of the Hyon Sand Formation (upper middle Ypresian). The Roubaix Clay Member contains diverse and well-preserved calcareous nannofossils, dinoflagellate cysts, foraminifera, ostracods and other calcitic microfossils, and less well-preserved mollusc assemblages, while the Aalbeke Clay Member is secondarily decalcified. The calcareous nannofossil subdivision of upper NP11 and lower NP12 has been recognised in the Kortrijk area, and calibrated with the NW European mid-Ypresian dinoflagellate cyst, ostracod and planktonic foraminiferal zones and datums (e.g. *Subbotina* influx). Several medium-scale depositional sequences, with an estimated duration of 400 kyr or less, have been recorded. Their respective boundaries coincide with the resistivity maxima identified on the majority of the wireline log profiles of the Belgian Ypresian. Integrated biostratigraphic, magnetostratigraphic and sequence stratigraphic analysis enables correlation with other areas in Belgium, with the London Clay Formation of southern England, and with the standard chronostratigraphic scale. A marine erosion surface has been identified at the base of Unit 20 in the Kortrijk area (mid-Ypresian, early Biochron NP12, middle C24n.1n, ~ 52.8 Ma), corresponding to the first occurrence of estuarine channel-fill units in southern England. This indicates a brief but profound sea-level fall, either eustatically or tectonically controlled. The composite Kortrijk section is proposed as a reference section for the middle Ypresian in the southern North Sea Basin, and for similar settings in mid- to high-latitudes of the Northern Hemisphere (e.g. Kazakhstan and Crimea).

KEYWORDS: Integrated stratigraphy, microfossils, mid-Ypresian, key reference, southern North Sea Basin.

1. Introduction

Since the early days of stratigraphy (Lyell, 1852), the Kortrijk area in western Belgium has been renowned for its numerous clay exploitations for brick and tile manufacture. These clay layers, for which Lyell (op. cit.) introduced the name Kortrijk clay, have been formally defined as the Kortrijk Clay Formation (Maréchal, 1994: introduction of name; Steurbaut, 1998: full description with designation of stratotype). It is a dominantly argillaceous unit of Early Eocene (mid-Ypresian) age, forming the lower part of the Ieper Group (formerly Ieper [Ypres] Formation). The Kortrijk Clay Formation was deposited in marine, inner to mid-neritic environments and crops out extensively in western Belgium. It is part of a sheet of neritic marine argillaceous sediments of similar facies, overlain and underlain by shallower marine coarser-grained sediments, which extend through the southern margin of the North Sea Basin (Fig. 1), from southern England (London Clay Formation) through northernmost France, Belgium, the Netherlands and west Germany (King, 1981, 2006, 2016; Vinken et al., 1988; Steurbaut, 2006, 2011), into the southern North Sea.

These fine-grained sediments were deposited in response to relatively high eustatic sea levels during the mid-Ypresian (Haq et al., 1988), and include the deepest marine environments seen in the Eocene in these areas. The Kortrijk Clay Formation grades laterally southwards and eastwards in SW Belgium and northern France into inner neritic sand-dominated sediments, including a lower still unnamed sand body (Steurbaut et al., work in progress) and the upper Mons-en-Pévèle Formation (Steurbaut & Nolf, 1986; King, 1991b; Steurbaut & King, 1994) (Fig. 2). To the north it grades into clays deposited in bathyal environments.

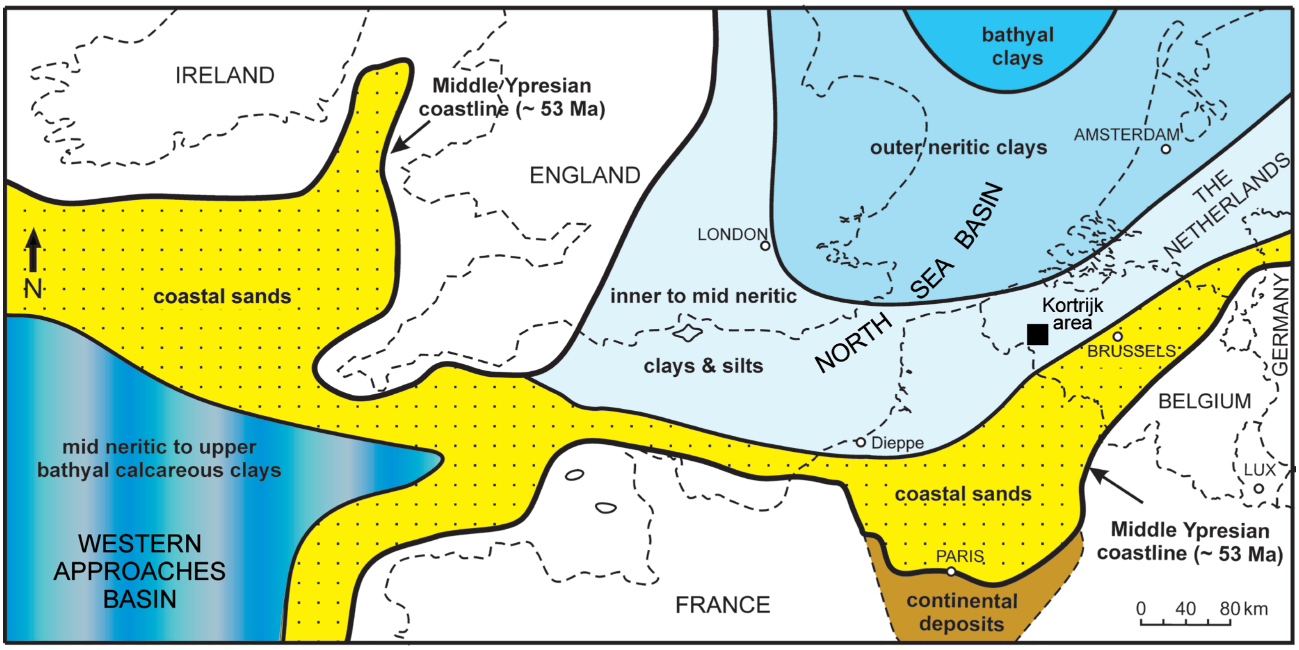

Figure 1. Lithofacies map of the southern North Sea Basin – Western Approaches Basin during middle Ypresian times (~53 Ma) and location of the Kortrijk area (after Steurbaut, 2011, based on King, 2006 and Steurbaut, 2006).

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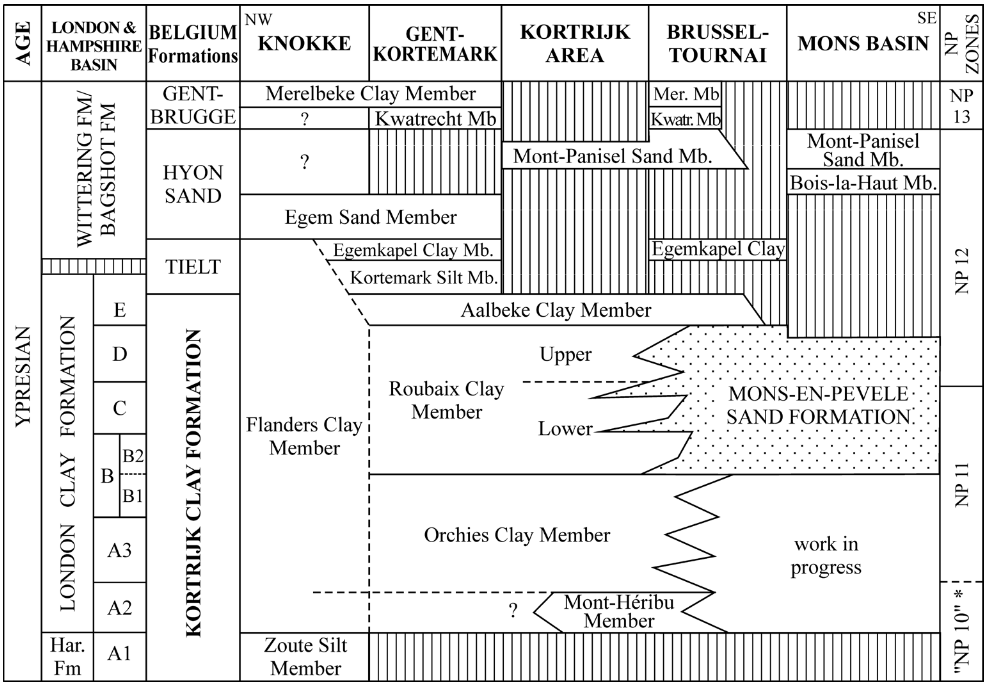


Figure 2. Lithostratigraphic classification of the early and middle Ypresian in western Belgium, and correlation with the succession in southern England. Abbreviations used: Har. Fm = Harwich Formation; * = not identified, but extrapolated.

Detailed investigation of the biostratigraphy, lithostratigraphy and magnetostratigraphy of the Ypresian in Belgium and northern France over the last decades (Willems, 1982; Steurbaut & Nolf, 1986; Steurbaut, 1988, 1998, 2006, 2011; King, 1990; Dupuis et al., 1991; Ali et al., 1993; Steurbaut & King, 1994; Vandenberghe et al., 1998; Steurbaut et al., 2003) has greatly improved knowledge of this previously poorly documented interval. Several exposures in the Kortrijk area (West Flanders), close to the France/Belgium border, have been included in these studies, but only brief lithological and palaeontological details have been published.

Reviews of the development of the stratigraphic terminology of the Ypresian of Belgium (and northern France) are given by Steurbaut & Nolf (1986), King (1991b) and Steurbaut (2006). The evolution of the stratigraphic classification of the Kortrijk Formation in the Kortrijk area is summarised in Fig. 3. It should be emphasised that the use of Saint-Maur and Moen as member names of the Kortrijk Formation, as suggested by Maréchal (1994) and adopted in the most recent mapping of the Kortrijk area (Jacobs et al., 1997), is regarded as incorrect by the National Commission for Stratigraphy of Belgium (see update of the lithostratigraphy of the Ieper Group, Steurbaut et al., 2016b). This means that the use of the original member names (the Orchies Clay and the Roubaix Clay respectively), as recommended by Steurbaut (1998, 2006), has been restored. The present investigation of the biostratigraphy and lithostratigraphy of the upper Kortrijk Clay Formation in the Kortrijk area is based on all exposures seen during the period 1975 - 2000, together with information from cored boreholes. Abundant and diverse microfaunal and nannofloral assemblages are present through much of this interval, permitting both local and inter-regional biostratigraphic correlations to be established. Systems tracts and sequence boundaries have been identified, and correlated with depositional sequences identified elsewhere in Belgium and southern England. The calibration of biostratigraphy, magnetostratigraphy and sequence stratigraphy in the Kortrijk area provides a framework for the interpretation of basin evolution during the middle Ypresian on the southern margin of the North Sea Basin. The exposures are proposed as a reference section for the middle Ypresian in this area.

2. The Kortrijk Clay Formation in the Kortrijk area

2.1. General comments and subdivisions

Exposures of Early Eocene clays in quarries near Kortrijk (Courtrai) were described already by Lyell (1852), who recorded the occurrence of the foraminiferid *Nummulites planulatus*. Brick and tile manufacture has continued to the present day in this area, mainly exploiting a unit of non-calcareous 'heavy' (stiff) clay with few fossils. This unit was attributed on the geological map (Anonymous, 1892) to the basal 'Paniselien' (P1m). It was correlated with the lithologically similar unit mapped as P1m in the Gent area of northern Flanders. Underlying sands and clays, more sandy and highly fossiliferous, but less frequently exposed, were assigned to the Ypresian 'Sables à *Nummulites planulatus*' (Yd) and the 'Argile de Roubaix' (part of Yc) respectively (Leriche, 1927). This interpretation was maintained by Kaasschieter (1961) and was accepted until the 1980s.

Recent re-interpretation of this succession (Steurbaut & Nolf, 1986; King, 1991b; Steurbaut, 1998, 2006), has resulted in the recognition that the 'heavy clay' unit of the Kortrijk area lies within the middle of the Ieper Formation (now Group), and does not correlate, as previously supposed, with the much younger 'Paniselien' clays (P1m) of northern Flanders (now the Merelbeke Clay Member) (see Fig. 2). It has been renamed the Aalbeke Clay Member. The underlying sandy clays were designated the Roubaix Member by Steurbaut & Nolf (1986), with a type section in the Kortrijk area.

Steurbaut & Nolf (1986) gave brief details of the lithology and calcareous nannofossils of several sections in the Kortrijk area. King (1991b) outlined the lithostratigraphy and microfauna of the Lauwe (A17) roadcut (cited as 'Marke roadcut'), and part of the Kortrijk - Bossuit (Moen) canal cut. Both publications gave biostratigraphic and lithostratigraphic correlations with other sections in Belgium. Steurbaut (1998, fig. 7) carried out a more detailed study of the lithostratigraphy of the Koekelberg quarry at Marke.

The magnetostratigraphy of the Bois Fichau (Moeskroen) quarry, Koekelberg (Marke) quarry, Kortrijk - Bossuit (Moen) cutting and Kwadestraat (Heestert) quarry was analysed by Ali (1989), and is summarised in Ali et al. (1993) and Steurbaut (1998).

The Kortrijk Clay Formation in the Kortrijk area is divided into four successive members, in ascending order the Mont-Héribu Member, the Orchies Clay Member, the Roubaix Clay Member and the Aalbeke Clay Member, essentially following Steurbaut & Nolf (1986) and Steurbaut (1998). This subdivision is adopted in the recent update of the lithostratigraphy of the Ieper Group by the National Commission for Stratigraphy of Belgium (Steurbaut et al., 2016b). This update also includes a review of the lateral distribution and the boundaries of the successive members of the Kortrijk Clay Formation, mainly based on wireline

Geological Survey 1892		Gosselet (1874, 1883)		Kaasschieter (1961)		Steurbaut & Nolf (1986)		King (1991)		Maréchal (1994)		Steurbaut (1998)		Laga, Louwye & Geets (2001)		this paper			
PANISELIAN	P1a,b	YPRESIEN	?	PANISEL FM. (part)	?	IEPER FM.	Panisel Sand Mbr.	?	"Unnamed Sand Mbr"		?	HYON FM.	Mont-Panisel Sand Mbr.	?		HYON FM.	Mont-Panisel Sand Mbr.		YPRESIAN
	P1m		Argile de Roncq		Clays of Roncq		Aalbeke Clay Mbr.	IEPER FM.	Aalbeke Mbr.	KORTRIJK FM.	Aalbeke Mbr.	KORTRIJK CLAY FM.	Aalbeke Clay Mbr.	KORTRIJK FM.	Aalbeke Mbr.	KORTRIJK CLAY FM.	Aalbeke Clay Mbr.		
YPRESIAN	Yc		Argile de Roubaix	IEPER FM.	Clays of Roubaix		Roubaix Clay Mbr.		Bailleul Mbr.		Moen Mbr.		Roubaix Clay Mbr.		Roubaix Mbr.		Roubaix Clay Mbr.	upper	
									Wardrecques Mbr.									lower	
	Yc		Argile d'Orchies		Clays of Ieper		Orchies Clay Mbr.				St.-Maur Mbr.		Orchies Clay Mbr.		Orchies Mbr.		Orchies Clay Mbr.		
	Ya,b						Mt.-Héribu Bed		Mt.-Héribu Mbr.		Mt.-Héribu Mbr.		Mt. Héribu Clay Mbr.		Mt. Héribu Mbr.		Mt.-Héribu Mbr.		

Figure 3. Lithostratigraphic classification of the Ypresian succession in the Kortrijk area over the last 125 years.

logs. The upward shift of the lower boundary of the Roubaix Clay Member (*sensu* Steurbaut, 1998) to a level marked by a major increase in resistivity and a major decrease in gamma-ray intensity (base of layer 6 in the update of 2016) is accepted here (Fig. 2). This level approximately corresponds to the position of the lower boundary of the Roubaix Clay in Steurbaut (1991) and to the base of the Moen Member in Welkenhuysen & De Ceukelaire (2009). It is also proposed here to differentiate a 'Lower' and an 'Upper' Roubaix Clay Member, separated by omission surface F at the base of Unit 20 (see below).

2.1.1. Mont-Heribu Member

This was originally differentiated by Cornet (1874) and formally named and described by De Coninck et al. (1983). It was downgraded to Bed status by Steurbaut & Nolf (1986), but reinstated by King (1991b), Maréchal (1994) and Steurbaut (1998) (Fig. 3). It is a very heterogeneous unit, composed of poorly sorted sandy clays with diffuse beds of sandy silt, silty clay and fine sand and marked by a glauconitic base. This unit has been penetrated by boreholes in the Kortrijk area (e.g. the Ooigem borehole), but does not outcrop in this area.

2.1.2. Orchies Clay Member

The long-established subdivision of the Ieper Clay in this region into the (lower) Orchies Clay (stiff and relatively homogenous non-calcareous clays) and the (upper) Roubaix Clay (silty and sandy calcareous fossiliferous clay) was formalised by Steurbaut & Nolf (1986). The contact between these units was identified only in boreholes, as the Orchies Clay does not outcrop in the Kortrijk area.

The difficulty in defining the boundary between these units was commented on by King (1991b). Subsequently Steurbaut (1998) suggested that the boundary between the Orchies Member and the Roubaix Member should be drawn at the contact between the non-calcareous clays and overlying calcareous siltier clays, corresponding to a turning point in the resistivity (highest value) and gamma-ray (lowest value) curves, (Steurbaut, 1998, figs 4, 10), and which is interpreted as a third order sequence boundary, separating sequences Y-B and Y-C of Steurbaut (1998). The National Commission for Stratigraphy of Belgium (Steurbaut et al., 2016b) recently agreed upon a proposal to move the lower boundary of the Roubaix Clay upward to a level with a much more conspicuous increase in resistivity and decrease in gamma-ray intensity, which can be perfectly traced in boreholes throughout western Belgium (base of layer 6 in the lithostratigraphical update of 2016). It corresponds to the base of subsequence Y-C3 of Steurbaut (1998).

In the Wardrecques quarry (Pas de Calais, France) (King 1991b, fig. 9), which is the only accessible exposure of the middle of the Kortrijk Clay Formation, the newly defined Orchies Clay/Roubaix Clay contact is marked by the change from largely non-calcareous clays with dispersed phosphatic nodules and a dominantly agglutinating foraminiferid assemblage to overlying calcareous clays with abundant benthic and planktonic calcareous microfossils. This event corresponds to biostratigraphic event I1 of King (1991b, fig. 9). The same microfaunal event can be identified in the Ooigem borehole (King, 1991b, fig. 6), and also in the Kallo borehole (King, 1991b, fig. 4), at a minor break in lithology. This biostratigraphic event can be identified even in more distal areas where no obvious lithological break occurs, as in the Knokke borehole (King, 1990).

2.1.3. Roubaix Clay Member

The Roubaix Clay Member comprises calcareous clays and silts with subordinate very fine sands. The stratotype was selected by Steurbaut & Nolf (1986) as the Moen section (Kortrijk - Bossuit canal), but as neither base or top of the Member are exposed here, it was redefined by Steurbaut (1998) through boundary stratotypes, in the Kallo borehole and Kobbe quarry (Aalbeke) respectively. Its lower boundary stratotype, as redefined in Steurbaut et al., 2016b (base of layer 6), is designated here in the recently drilled ON-Kallo-1 borehole (14E355) at 355 m below surface. This boundary is

c. 40 m above the base of the Kortrijk Clay Formation in the Kortrijk area.

The Lower Roubaix Clay Member comprises dominantly silty, somewhat calcareous clays, with several thin glauconite-rich beds in the upper half. Only the upper part is exposed in the Kortrijk area. The Upper Roubaix Clay Member comprises mainly silty and sandy clays, often shelly, with beds of very fine sand and thin shell beds. Some thin and often nodular calcareous and siliceous sandstone beds are present. There is a thin basal highly glauconitic bed, and macroscopic glauconite occurs commonly in the lower part of this interval. The sediments are more differentiated and heterogeneous than those of the Lower Roubaix Member, and macrofossils (mainly molluscs) are much more abundant, both dispersed and concentrated into thin shell beds.

2.1.4. Aalbeke Clay Member

The Aalbeke Member is defined identically by Steurbaut & Nolf (1986) and King (1991b). Its basal boundary stratotype is defined in the Kobbe quarry, Aalbeke (Steurbaut, 1998). It is a non-calcareous (secondarily decalcified) silty clay with a thin sandy silt bed at about the middle. This unit was formerly correlated with the basal 'Paniselian' clay unit outcropping in northern Belgium (former P1m of the Geological Survey), but its correct stratigraphic position was identified by Steurbaut & Nolf (1986) and King (1991b) (Fig. 3). In the Kortrijk area the base of the Aalbeke Clay Member is c. 80 m above the base of the Ieper Group (King, 1991b, fig. 9; Welkenhuysen & De Ceukelaire, 2009, fig. 20).

2.1.5. Hyon Sand Formation (Mont-Panisel Sand Member)

The Aalbeke Clay Member is overlain by a bioturbated non-calcareous glauconitic sand (maximum recorded thickness 4 m). The contact is a sharply defined and interburrowed omission surface. It is correlated by Steurbaut and Nolf (1986) with the Panisel Sand Member (Fig. 2). This correlation is supported by the occurrence of common siliceous sponge spicules, which are characteristic of the Mont-Panisel Sand Member. This is the highest Eocene unit preserved in the area.

2.2. Regional context

The members discussed above are recognisable mainly in a strip trending SW-NE through northern France and Belgium, from the Wardrecques-Bailleul area, through Kortrijk to the Antwerp area (see Steurbaut & Nolf, 1986, fig. 12; King, 1991b, fig. 13; Steurbaut et al., 2016b, compendum). To the northwest of this area, in more distal depositional environments, the Mont-Heribu and Roubaix Members pass laterally into homogenous clay facies, mostly non-calcareous, and cannot really be diffentiated lithologically from the Orchies and Aalbeke Members. Without high-resolution wireline logs (as those presented in Steurbaut et al., 2016b), the Kortrijk Clay Formation cannot be lithologically subdivided in this area. This homogenous clay facies was designated 'undifferentiated' Ieper Formation by Steurbaut & Nolf (1986), and formally named the Flanders Member (from the Argile de Flandres of Ortlieb & Chellonneix, 1870) by King (1991b). The alternative option, to assign the entire Kortrijk Clay Formation in this area to the Orchies Member (as implied by Maréchal, 1994) would in the opinion of the present writers extend its application too widely.

In the predominantly more proximal depositional environments in eastern and southern Belgium, for instance in the Kester borehole, the Orchies Member is replaced by sandy and silty equivalents (Steurbaut et al., unpublished data). The Roubaix Member passes rapidly to the east and south-east into the sand-dominated facies of the Mons-en-Pévèle Formation (Fig. 2).

Steurbaut & King (1994) proposed to elevate the Mons-en-Pévèle and Panisel Sand Members of Steurbaut & Nolf (1986) to formation rank within the Ieper Group (as Mons-en-Pévèle Formation and Hyon Sand Formation). This proposal was not initially adopted by the National Commission for Stratigraphy of Belgium (Maréchal, 1994; Laga et al., 2001), but was recently restored by this commission (Steurbaut et al., 2016b).

In the following text, the lithological qualifiers of the Formation and Member names (e.g. Kortrijk Clay Formation) are omitted for brevity.

3. Sections studied

3.1. Exposures

Most of the exposures are in two areas, the Marke to Moeskroen area SW of Kortrijk, comprising the Aalbeke, Lauwe, Marke, Moeskroen and Markesteert sites, and the Moen area, SE of Kortrijk, comprising the Heestert and Moen sites (Fig. 4). These areas are only 12 km apart, but the sections differ significantly in lithology at some levels (Figs 5-9). A composite section for each area has been established, referred to here for brevity as the Marke section and Moen section respectively (Fig. 11). The Zwevegem section is between these areas. The stratigraphical and geographical relationships of these sections are summarised in Figs 10-11.

The studied exposures are discussed here in ascending stratigraphic order. Locations are shown on Fig. 4. Position is given in Lambert and in GPS coordinates. Correlation of the studied sections is discussed below.

3.1.1. Dottignies (A17 autoroute cutting): point 12 on Fig. 4

x = 74.150, y = 157.650; 50°43'29.30" N, 3°17'48.06" E. Lower Roubaix Member (King 1991b). A shallow cutting exposed during road construction in 1979. This lies stratigraphically below the other sections in this area, but is referred to briefly in chapter 4.1.1.

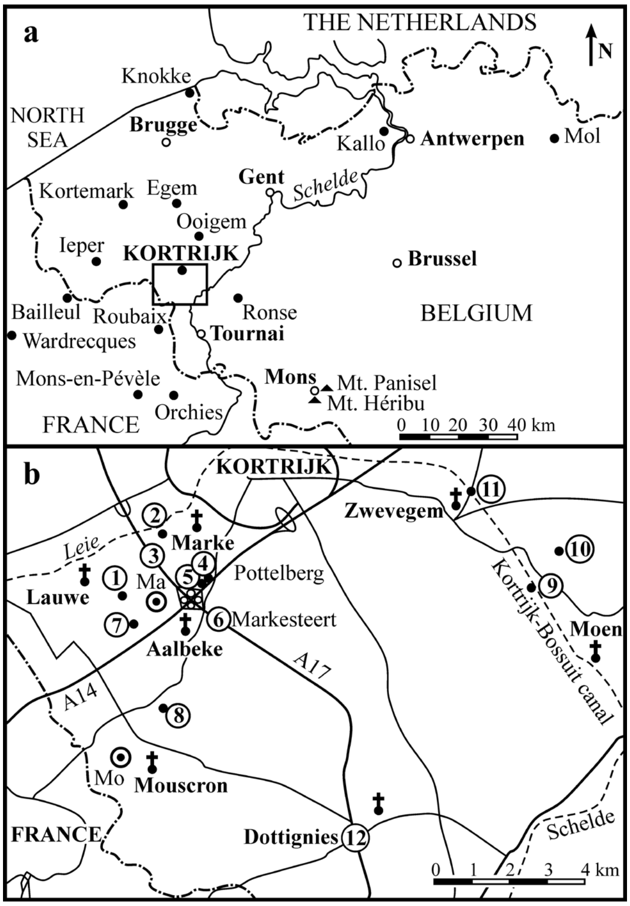


Figure 4a. Western Belgium and adjacent areas of France, with localities referred to in the text. 4b. The Kortrijk area, with location of sites studied. - 1. Lauwe quarry. - 2. Koekelberg quarry, Marke. - 3. A17 motorway cutting, Lauwe. - 4. Pottelberg quarry, Marke. - 5. Pottelberg A14 road cutting, Marke. - 6. A17 motorway cutting, Markesteert. - 7. Kobbe quarry, Aalbeke. - 8. Bois Fichau quarry, Mouscron (Moeskroen). - 9. Kortrijk - Bossuit canal cutting, Moen. 10. Kwadestraat quarry, Heestert. - 11. Zwevegem sluice. - 12. A17 motorway cutting, Dottignies. - Ma: Marke borehole. - Mo: Mouscron borehole.

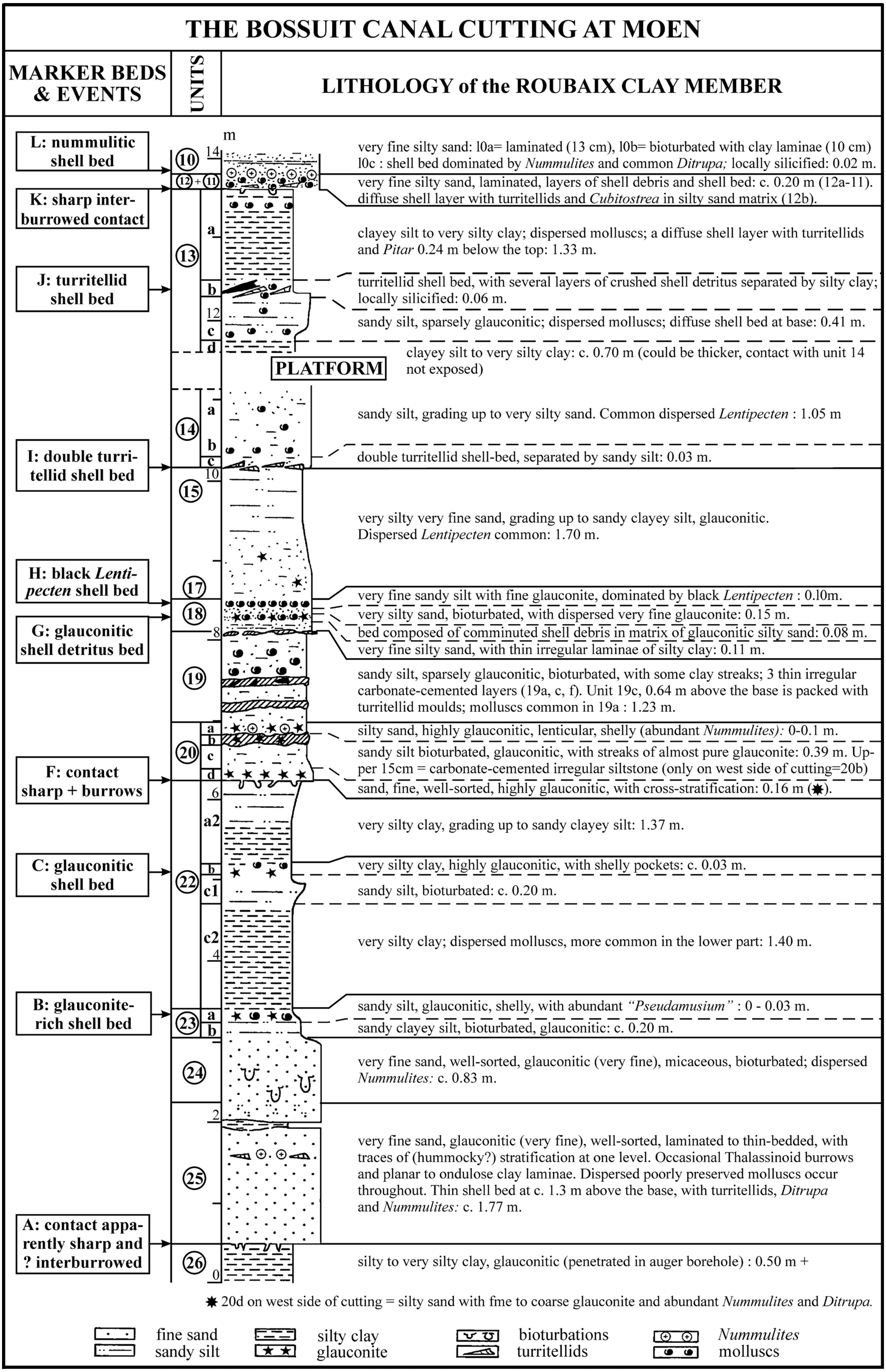
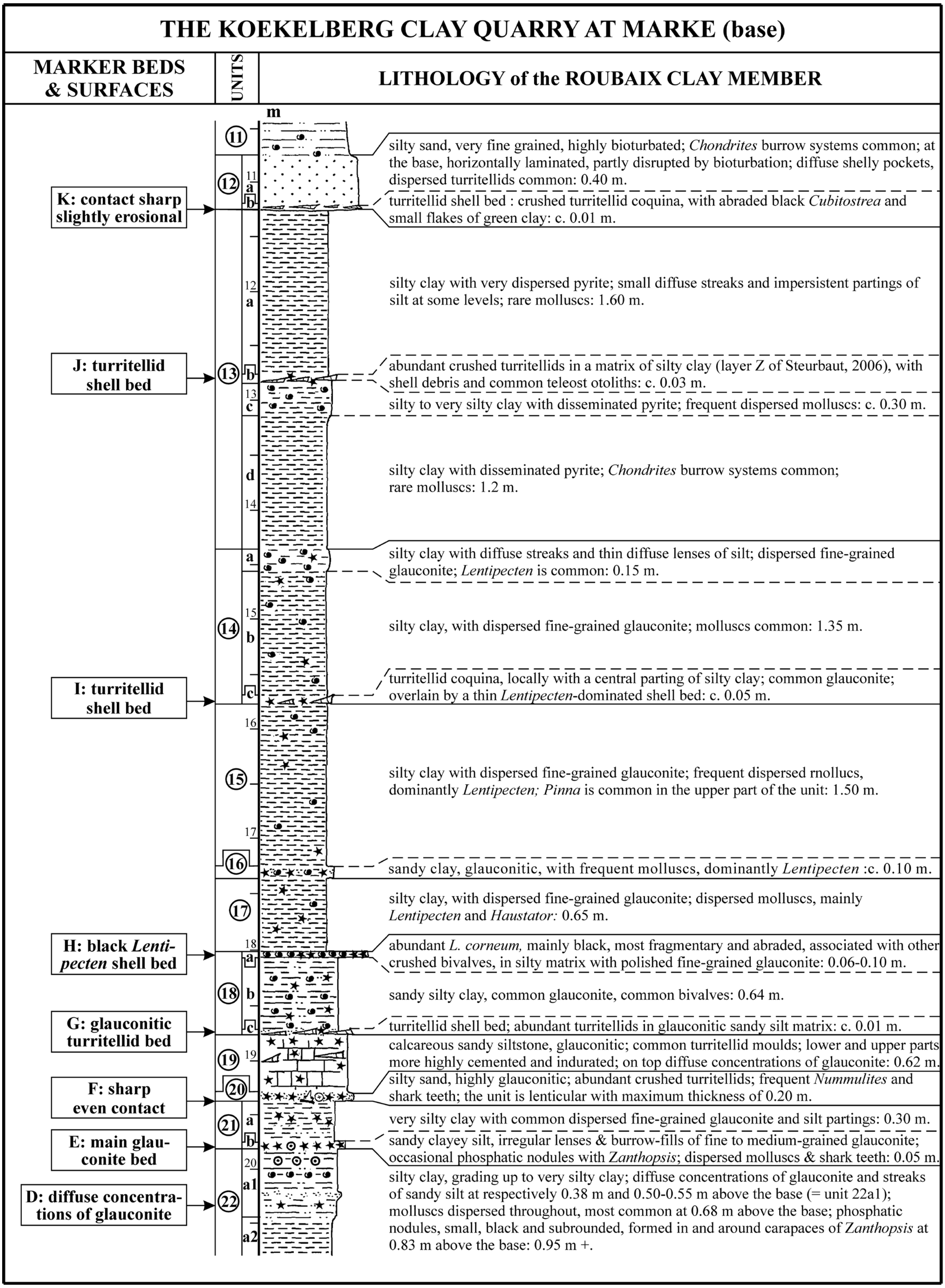


Figure 5. Lithology and stratigraphic interpretation of the Kortrijk-Bossuit Canal cutting at Moen.



silty sand, very fine grained, highly bioturbated; *Chondrites* burrow systems common; at the base, horizontally laminated, partly disrupted by bioturbation; diffuse shelly pockets, dispersed turritellids common: 0.40 m.

turritellid shell bed : crushed turritellid coquina, with abraded black *Cubitostrea* and small flakes of green clay: c. 0.01 m.

silty clay with very dispersed pyrite; small diffuse streaks and impersistent partings of silt at some levels; rare molluscs: 1.60 m.

abundant crushed turritellids in a matrix of silty clay (layer Z of Steurbaut, 2006), with shell debris and common teleost otoliths: c. 0.03 m.

silty to very silty clay with disseminated pyrite; frequent dispersed molluscs: c. 0.30 m.

silty clay with disseminated pyrite; *Chondrites* burrow systems common; rare molluscs: 1.2 m.

silty clay with diffuse streaks and thin diffuse lenses of silt; dispersed fine-grained glauconite; *Lentipecten* is common: 0.15 m.

silty clay, with dispersed fine-grained glauconite; molluscs common: 1.35 m.

turritellid coquina, locally with a central parting of silty clay; common glauconite; overlain by a thin *Lentipecten*-dominated shell bed: c. 0.05 m.

silty clay with dispersed fine-grained glauconite; frequent dispersed rnollucs, dominantly *Lentipecten; Pinna* is common in the upper part of the unit: 1.50 m.

sandy clay, glauconitic, with frequent molluscs, dominantly *Lentipecten* :c. 0.10 m.

silty clay, with dispersed fine-grained glauconite; dispersed molluscs, mainly *Lentipecten* and *Haustator:* 0.65 m.

abundant *L. corneum,* mainly black, most fragmentary and abraded, associated with other crushed bivalves, in silty matrix with polished fine-grained glauconite: 0.06-0.10 m.

sandy silty clay, common glauconite, common bivalves: 0.64 m.

turritellid shell bed; abundant turritellids in glauconitic sandy silt matrix: c. 0.01 m.

calcareous sandy siltstone, glauconitic; common turritellid moulds; lower and upper parts more highly cemented and indurated; on top diffuse concentrations of glauconite: 0.62 m.

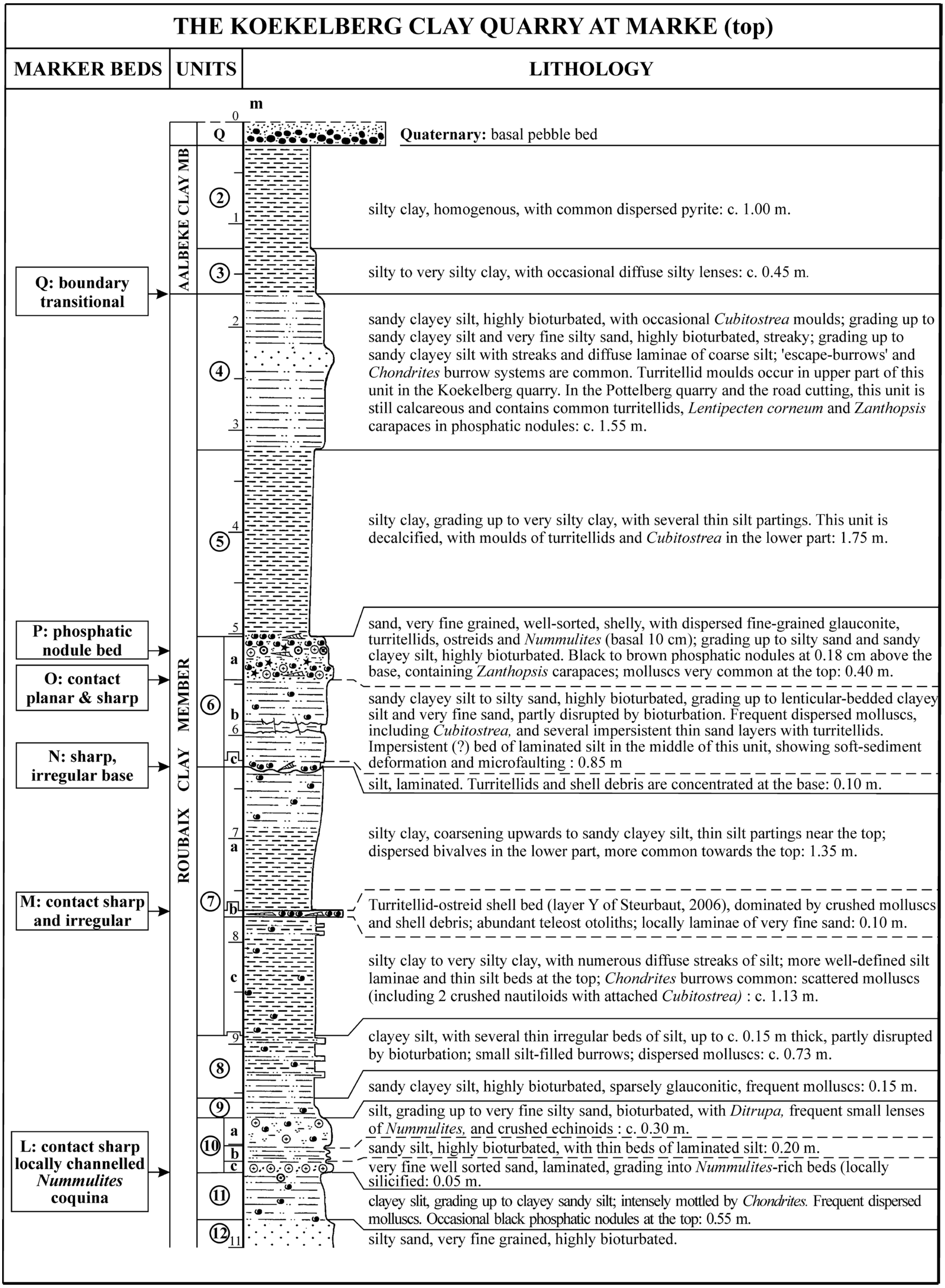
silty sand, highly glauconitic; abundant crushed turritellids; frequent *Nummulites* and shark teeth; the unit is lenticular with maximum thickness of 0.20 m.

very silty clay with common dispersed fine-grained glauconite and silt partings: 0.30 m.

sandy clayey silt, irregular lenses & burrow-fills of fine to medium-grained glauconite; occasional phosphatic nodules with *Zanthopsis*; dispersed molluscs & shark teeth: 0.05 m.

silty clay, grading up to very silty clay; diffuse concentrations of glauconite and streaks of sandy silt at respectively 0.38 m and 0.50-0.55 m above the base (= unit 22a1); molluscs dispersed throughout, most common at 0.68 m above the base; phosphatic nodules, small, black and subrounded, formed in and around carapaces of *Zanthopsis* at 0.83 m above the base: 0.95 m +.

Figure 6a. Lithology and stratigraphic interpretation of the Koekelberg Clay quarry at Marke: base of the quarry.



Quaternary: basal pebble bed

silty clay, homogenous, with common dispersed pyrite: c. 1.00 m.

silty to very silty clay, with occasional diffuse silty lenses: c. 0.45 m.

sandy clayey silt, highly bioturbated, with occasional *Cubitostrea* moulds; grading up to sandy clayey silt and very fine silty sand, highly bioturbated, streaky; grading up to sandy clayey silt with streaks and diffuse laminae of coarse silt; 'escape-burrows' and *Chondrites* burrow systems are common. Turritellid moulds occur in upper part of this unit in the Koekelberg quarry. In the Pottelberg quarry and the road cutting, this unit is still calcareous and contains common turritellids, *Lentipecten corneum* and *Zanthopsis* carapaces in phosphatic nodules: c. 1.55 m.

silty clay, grading up to very silty clay, with several thin silt partings. This unit is decalcified, with moulds of turritellids and *Cubitostrea* in the lower part: 1.75 m.

sand, very fine grained, well-sorted, shelly, with dispersed fine-grained glauconite, turritellids, ostreids and *Nummulites* (basal 10 cm); grading up to silty sand and sandy clayey silt, highly bioturbated. Black to brown phosphatic nodules at 0.18 cm above the base, containing *Zanthopsis* carapaces; molluscs very common at the top: 0.40 m.

sandy clayey silt to silty sand, highly bioturbated, grading up to lenticular-bedded clayey silt and very fine sand, partly disrupted by bioturbation. Frequent dispersed molluscs, including *Cubitostrea,* and several impersistent thin sand layers with turritellids. Impersistent (?) bed of laminated silt in the middle of this unit, showing soft-sediment deformation and microfaulting : 0.85 m

silt, laminated. Turritellids and shell debris are concentrated at the base: 0.10 m.

silty clay, coarsening upwards to sandy clayey silt, thin silt partings near the top; dispersed bivalves in the lower part, more common towards the top: 1.35 m.

Turritellid-ostreid shell bed (layer Y of Steurbaut, 2006), dominated by crushed molluscs and shell debris; abundant teleost otoliths; locally laminae of very fine sand: 0.10 m.

silty clay to very silty clay, with numerous diffuse streaks of silt; more well-defined silt laminae and thin silt beds at the top; *Chondrites* burrows common: scattered molluscs (including 2 crushed nautiloids with attached *Cubitostrea)* : c. 1.13 m.

clayey silt, with several thin irregular beds of silt, up to c. 0.15 m thick, partly disrupted by bioturbation; small silt-filled burrows; dispersed molluscs: c. 0.73 m.

sandy clayey silt, highly bioturbated, sparsely glauconitic, frequent molluscs: 0.15 m.

silt, grading up to very fine silty sand, bioturbated, with *Ditrupa,* frequent small lenses of *Nummulites,* and crushed echinoids : c. 0.30 m.

sandy silt, highly bioturbated, with thin beds of laminated silt: 0.20 m.

very fine well sorted sand, laminated, grading into *Nummulites*-rich beds (locally silicified: 0.05 m.

clayey slit, grading up to clayey sandy silt; intensely mottled by *Chondrites.* Frequent dispersed molluscs. Occasional black phosphatic nodules at the top: 0.55 m.

silty sand, very fine grained, highly bioturbated.

Figure 6b. Lithology and stratigraphic interpretation of the Koekelberg Clay quarry at Marke: top of the quarry.

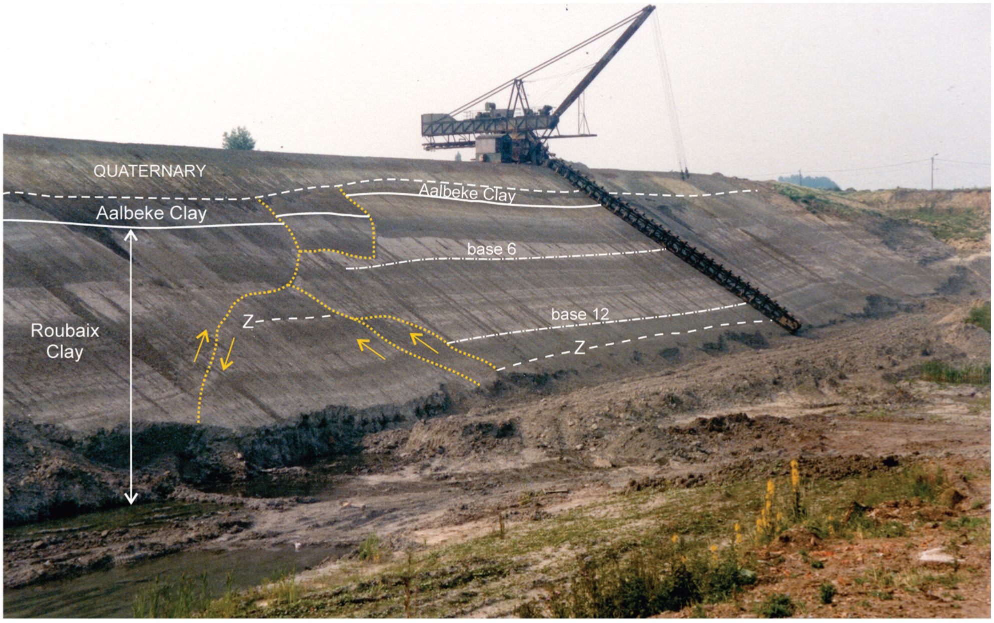


Figure 6c. Lithology and stratigraphic interpretation of the Koekelberg Clay quarry at Marke: photograph of the quarry face, anno 1997.

3.1.2. Moen (Kortrijk - Bossuit canal cutting): point 9 on Fig. 4

x = 79.775, y = 164.725; 50°47'17.39" N, 3°22'21.85" E. Roubaix Member (Steurbaut & Nolf, 1986; King, 1991b; Ali et al., 1993) (Fig. 5). This cutting was excavated in the 1970s, and is now strongly overgrown. Exposures are (were) visible on both the west and east sides of the canal; the best sections are in gullies cut by rainwater on the west side of the canal, but these now require excavation to be adequately studied. The section is cut by several minor faults, which can complicate interpretation of the scattered exposures.

3.1.3. Marke (Koekelberg quarry): point 2 on Fig. 4

Ex-Koramic S.A. brick and tile company: x = 69.000, y = 166.800; 50°48'17.94" N, 3°13'06.48" E. Roubaix Member and lowest Aalbeke Member (Steurbaut & Nolf, 1986; Ali et al., 1993; Steurbaut 1998) (Figs 6a, b, c). This large quarry was opened in the 1980s and abandoned c. 1998. It provided the best sections seen in the Kortrijk area, but is now completely flooded. The sediments dip steeply and are cut by several minor faults. The lowest 7m of the section recorded here (Units 14 - 23) was exposed in an upfaulted block, which was subsequently removed by quarrying. Parts of this interval are partially visible on the quarry floor. The repeated alternations of silty clays, thin sandy beds and shell beds, together with minor faulting, can cause difficulties in identifying individual units. A map of the quarry face has been published by Steurbaut (1998, fig. 7). This quarry face was subsequently photographed (Steurbaut, 2015, fig. 3.15) and is refigured here (Fig. 6c). The uppermost part of the Roubaix Member is decalcified in this quarry, and was misidentified by King (1991b, fig. 7) and Ali et al. (1993) as the basal Aalbeke Member. Detailed studies of the clay tectonics in this quarry have been carried out by Verschuren (1992) and, to a lesser extent, by Vandycke (1992).

3.1.4. Lauwe quarry: point 1 on Fig. 4

'Ceramiques et Briqueteries du Littoral': x = 67.975, y = 165.140; 50°47'30.05" N, 3°12'27.76" E. Upper Roubaix Member (De Coninck, 1976b; Steurbaut & Nolf, 1986, p.139). This quarry was abandoned and flooded in the 1970s. It was not logged in detail, but exposed a section closely similar to that in the nearby Koekelberg quarry at Marke.

3.1.5. Lauwe (A17 autoroute cutting) (formerly E117 road): point 3 on Fig. 4

x = 68.700, y = 166.100; 50°47'58.95" N, 3°12'56.86" E. Upper Roubaix Member. A temporary section recorded during road construction in 1975 (recorded as 'Marke roadcut' by King, 1991b, fig. 7). The Kortrijk Formation dips northwards and is cut by several minor faults, as in the adjacent Koekelberg quarry.

3.1.6. Zwevegem (sluice): point 11 on Fig. 4

x = 78.450, y = 167.700; 50°49'21.85" N, 3°20'46.17" E. A section exposed by excavations in 1998 for a new sluice on the Kortrijk - Bossuit canal. Roubaix Member (Fig. 7).

3.1.7. Marke (Pottelberg quarry): point 4 on Fig. 4

Ex-Koramic S.A. brick and tile company: x = 70.475, y = 165.575; 50°47'43.04" N, 3°14'25.65" E. Topmost Roubaix Member and lower Aalbeke Member. This section was studied in 1979. The quarry is now abandoned and infilled.

3.1.8. Marke (Pottelberg A14 motorway cutting): point 5 on Fig. 4

x = 70.350, y = 165.500; 50°47'39.72" N, 3°14'19.83" E. Topmost Roubaix Member and lower Aalbeke Member. A temporary section recorded during road widening in 1976, close to the Pottelberg quarry.

3.1.9. Marke (Markesteert A17 motorway cutting): point 6 on Fig. 4

x = 70.750, y = 164.050; 50°46'53.67" N, 3°14'41.65" E. Topmost Roubaix Member and Aalbeke Member. A temporary section recorded during road construction in 1979.

3.1.10. Heestert (Kwadestraat quarry): point 10 on Fig. 4

Ex-Koramic S.A. brick and tile company: x = 80.550, y = 165.550; 50°47'46.45" N, 3°22'59.20" E. Topmost Roubaix Member, Aalbeke Member and Mont-Panisel Member (Steurbaut & Nolf, 1986; Ali et al., 1993) (Fig. 8). This quarry was abandoned in the late 1980s and is now infilled. A new larger quarry was opened 100m further south in 1992, but soon infilled. Excavation of the Aalbeke Member resumed in 2009 about 250 m S of the quarry we sampled in the mid-1980s.

3.1.11. Aalbeke (Kobbe quarry): point 7 on Fig. 4

Ex-Koramic S.A. brick and tile company: x = 68.450, y = 164.300; 50°46'57.12" N, 3°12'39.72" E. Topmost Roubaix Member and lower Aalbeke Member (Steurbaut and Nolf, 1986). Excavation ceased here in 1992. In the mid-1990s the quarry was partially flooded and is now infilled. From 2009 excavation of the Aalbeke Member resumed, although intermittently, about 400 m NNW of the old quarry.

3.1.12. Mouscron (Moeskroen) (Bois Fichau quarry): point 8 on Fig. 4

Ex-Koramic S.A. brick and tile company: x = 68.575, y = 161.850; 50°45'35.92" N, 3°12'54.43" E. Topmost Roubaix Member, Aalbeke Member and Mont-Panisel Member (Steurbaut & Nolf, 1986; Ali et al., 1993) (Fig. 9). This quarry, which worked only intermittently over the last decades, is now abandoned. The upper part of the section is still accessible.

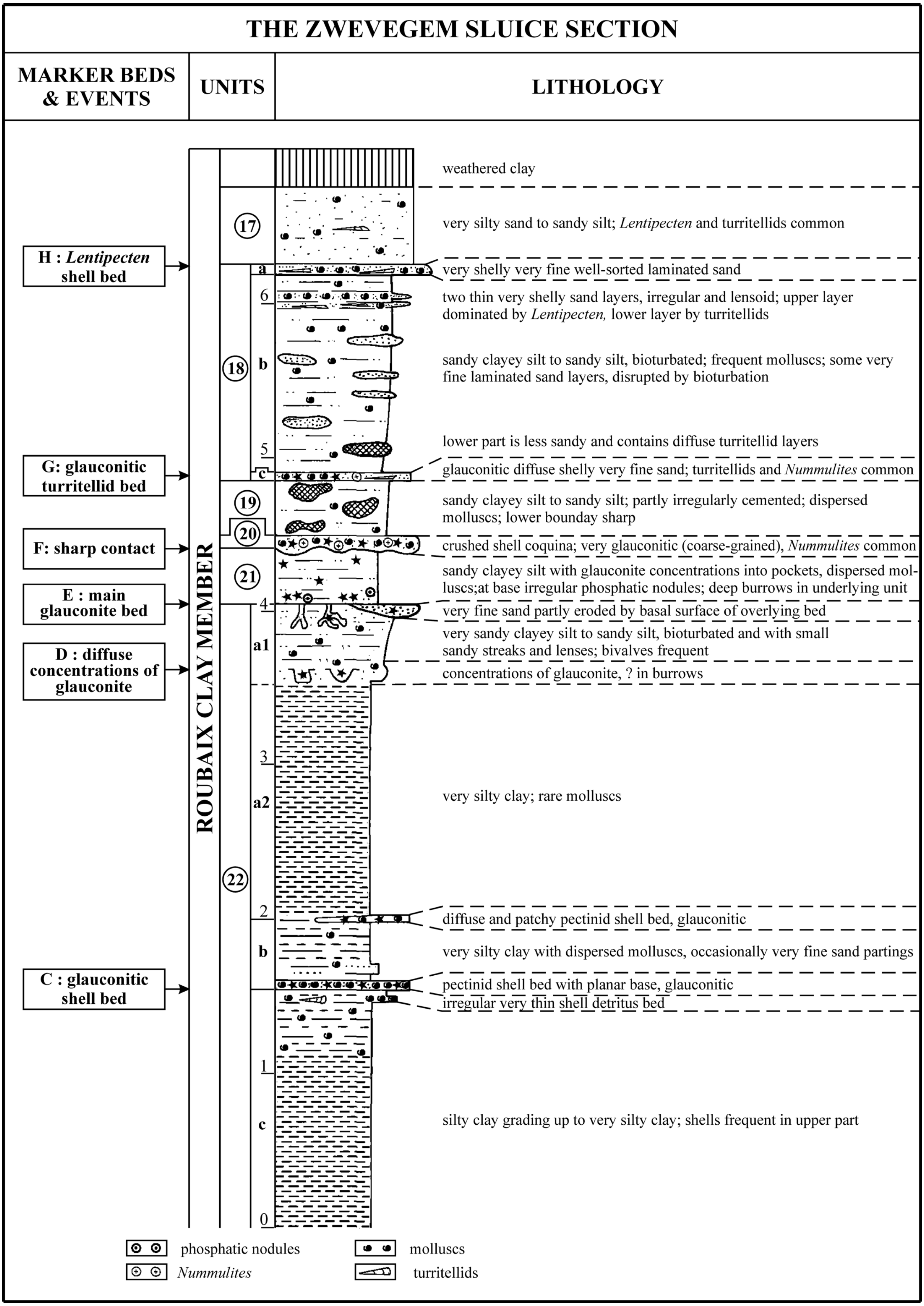
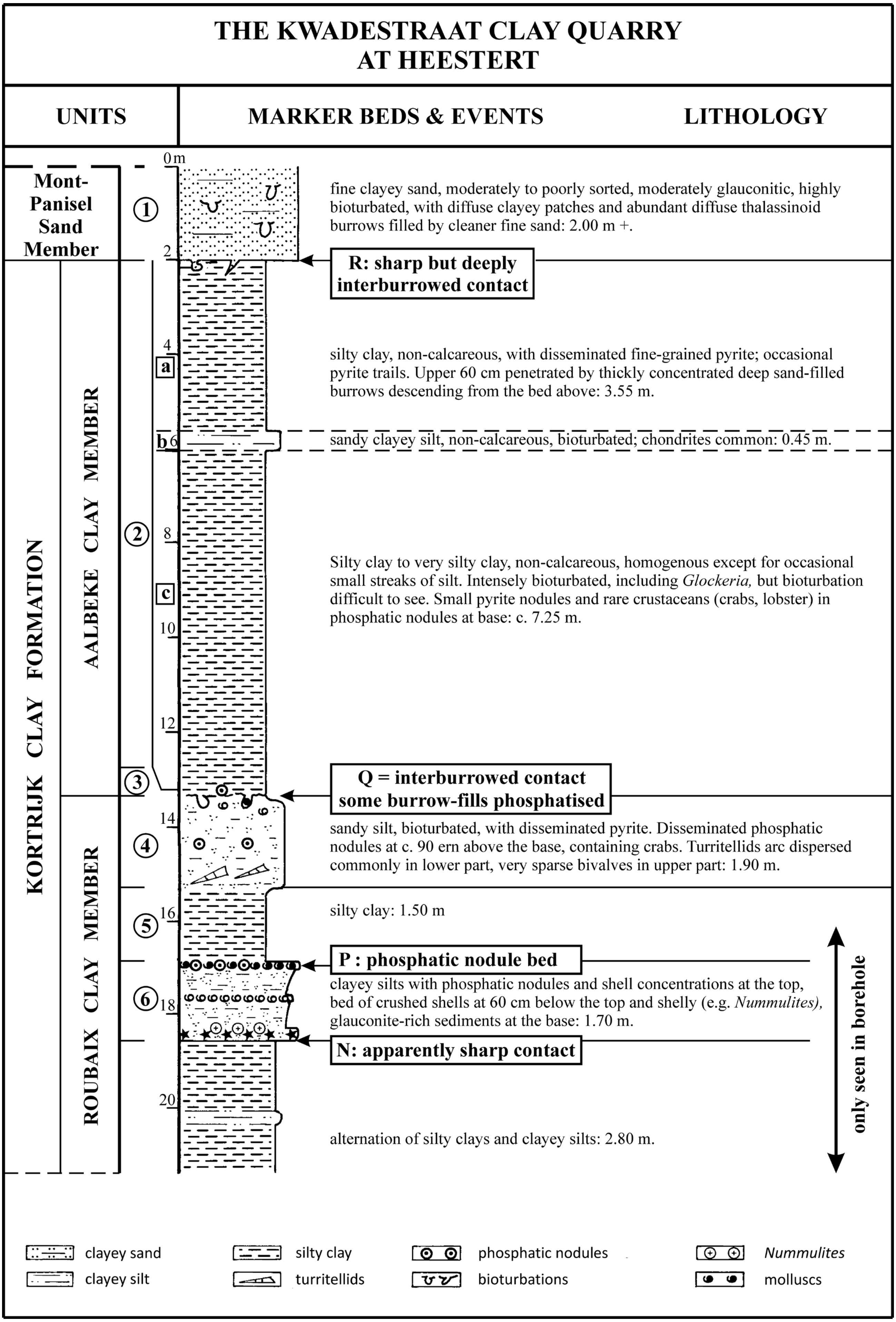


Figure 7. Lithology and stratigraphic interpretation of the Zwevegem sluice section.



fine clayey sand, moderately to poorly sorted, moderately glauconitic, highly bioturbated, with diffuse clayey patches and abundant diffuse thalassinoid burrows filled by cleaner fine sand: 2.00 m +.

silty clay, non-calcareous, with disseminated fine-grained pyrite; occasional pyrite trails. Upper 60 cm penetrated by thickly concentrated deep sand-filled burrows descending from the bed above: 3.55 m.

sandy clayey silt, non-calcareous, bioturbated; chondrites common: 0.45 m.

Silty clay to very silty clay, non-calcareous, homogenous except for occasional small streaks of silt. Intensely bioturbated, including *Glockeria,* but bioturbation difficult to see. Small pyrite nodules and rare crustaceans (crabs, lobster) in phosphatic nodules at base: c. 7.25 m.

sandy silt, bioturbated, with disseminated pyrite. Disseminated phosphatic nodules at c. 90 ern above the base, containing crabs. Turritellids arc dispersed commonly in lower part, very sparse bivalves in upper part: 1.90 m.

silty clay: 1.50 m

clayey silts with phosphatic nodules and shell concentrations at the top, bed of crushed shells at 60 cm below the top and shelly (e.g. *Nummulites),* glauconite-rich sediments at the base: 1.70 m.

alternation of silty clays and clayey silts: 2.80 m.

Figure 8. Lithology and stratigraphic interpretation of the Kwadestraat clay quarry at Heestert.

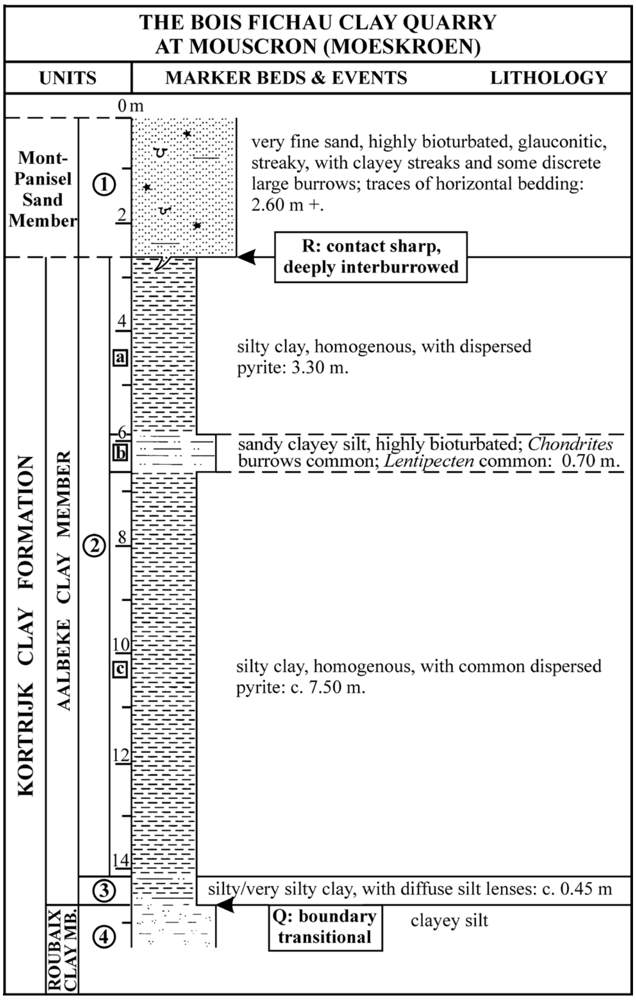


Figure 9. Lithology and stratigraphic interpretation of the Bois Fichau clay quarry at Mouscron (Moeskroen).

3.2. Boreholes

The data available from these boreholes is less detailed than for the exposures, but it is possible to correlate them with the outcrop sections (Fig. 10), as previously demonstrated by King (1991b).

3.2.1. Marke borehole

x = 68.775, y = 164.900; 50°47'22.84" N, 3°13'03.72" E. A 40 m-deep cored borehole drilled by the University of Gent in 1963 close to motorway E17, at about 2 km south of the Koekelberg quarry. It is known as the Marke borehole, although situated in the NW of the municipality of Aalbeke. This borehole penetrated the section exposed in the Koekelberg quarry, and also deeper parts of the Roubaix Member. Only a grain-size log has been published (Steurbaut, 1988, fig. 4, 1998, fig. 4).

3.2.2. Mouscron (Moeskroen) borehole

This cored borehole, very close to the French border, approximately 10 km SW of Kortrijk (x = 67.440, y = 160.274; 50°44'49.19" N, 3°11'57.63" E), penetrated the lower 95 m of the Ieper Group. Brief lithological and microfaunal details are given by Feugueur (1951), Feugueur & Le Calvez (1956) and Feugueur (1963, p. 433-434), and the information included here is derived from these publications (see also King, 1991b). The borehole is recorded as penetrating 'Paniselien' between 1.80 m and 12.50 m, overlying 'Ypresien' with its base at 95.5 m. The Mont-Panisel Sand Member is represented by beds 4 and 5 of Feugueur, described as 'sable glauconifère' overlying 'sable fin, argileux' (1.80 - 4.0 m). Bed 6 ('argile grise', 4.0 - 12.50 m) represents the Aalbeke Member. The Roubaix Member is represented by alternating clays, sandy clays and clayey sands. The contact between the 'Argile de Roubaix' and 'Argile d'Orchies' was arbitrarily placed by Feugueur at the lowest record of *Nummulites planulatus* at 54.0 m. This is believed to be slightly above the newly adopted lower boundary of the Roubaix Clay Member (see above; also Steurbaut et al., 2016b).

3.2.3. Ooigem borehole 83E - 407

x = 76.050, y = 177.200; 50°54'00.37" N, 3°19'01.60" E. A cored borehole through the lower 90 m of the Ieper Group, 7 km NE of Kortrijk, drilled by the Geological Survey of Belgium (Gulinck, 1967). The lithostratigraphy and biostratigraphy of the upper part of the section was summarised by King (1991b, figs 6 and 10). A few samples were analysed for foraminifera by Willems (1980). Calcareous nannofossils from the interval between 20.70 - 47.50 m were studied by Steurbaut (1991, table 4). Only short sections of core collected at approximately 1m intervals were available for analysis. Comparison of the gamma-ray log (Vandenberghe et al., 1998, fig. 7), lithology and biostratigraphy has enabled identification of the base of the Aalbeke Member at c. 13 m and the base of the Roubaix Member at c. 51 m.

4. Lithostratigraphy

Detailed descriptions of the Marke and Moen sections are given in Figs 5 and 6, summarised and correlated in Fig. 10. The sections are divided into lithostratigraphic units (beds or bedsets: Units 1 - 26). This numbering scheme is based on that used for the Koekelberg (Marke) quarry (Steurbaut, 1998, fig. 7). Although unorthodox (numbered from the top down), it is a logical concept, allowing further numbering, as each pit could be deepened at any moment, exposing additional older beds. It is retained here and applied to the other sections in the area, and continued downwards to include the lower part of the Moen section, which includes beds lower than those seen at Marke. Some units are further subdivided (as 18a etc.). The correlation of these sections (Figs 10, 11) is based on recognition of distinctive lithological units, supported by the biostratigraphic data. The Moen canal cutting exposures are mostly small gullies cut by rainwater runoff on the slopes. Minor details are therefore less easily recognisable than in the large exposures visible at Marke (Koekelberg quarry). Correlation is possible at unit level between the Marke and Moen sections (Fig. 11), but lateral lithological changes at some levels require different sub-units.

Unit 1 was applied originally to Pleistocene sediments overlying the Aalbeke Member in the Koekelberg (Marke) quarry. It is here re-allocated to the highest Eocene unit outcropping in the area, the Mont-Panisel Sand Member.

The following text is complementary to the figures, and intended to clarify details or to indicate reasons for correlation. It should be noted that all units are intensely bioturbated (homogenised), and all bed boundaries are transitional, unless described otherwise.

The major breaks in sedimentation, characterised by major omission surfaces, as well as the shell beds or glauconite beds with high correlation potential, which together represent the major events in the depositional history of the Kortrijk Formation, were given a letter code. Eighteen major marker beds or surfaces (ascending from A to R) have been identified. Their position, nature and significance are detailed on Figs 5-10.

4.1. Roubaix Member

The total thickness of the Roubaix Member is c. 42 m in the Mouscron borehole, and c. 38 m in the Ooigem borehole.

4.1.1. Lower Roubaix Member

This unit reaches a thickness of c. 21.5 m in the Moescron borehole and c. 20 m in the Ooigem borehole. The lowest part of this interval does not outcrop in the area. In the Mouscron and Ooigem boreholes, it comprises relatively homogenous calcareous silty clays.

The lowest interval seen at outcrop, in the Dottignies section, comprises 4 m of sandy clays and sandy silts, with frequent small oysters near the base. This 'oyster bed' has been

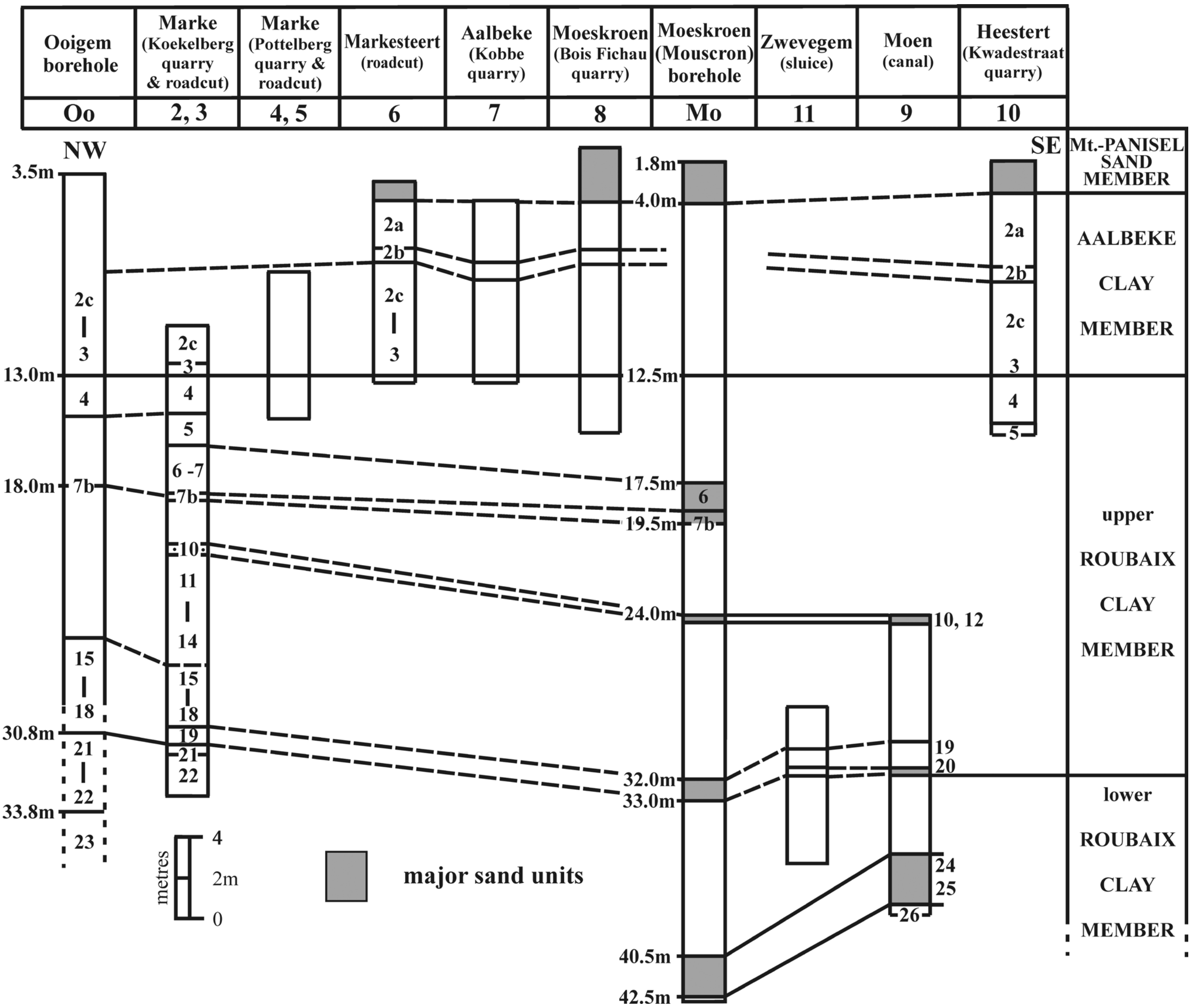


Figure 10. Exposures and boreholes in the Kortrijk area. Datum: base of the Aalbeke Clay Member. For unit numbers see other figures and text. Site numbers refer to Fig. 4b.

documented within the Lower Roubaix Member at outcrop and in boreholes throughout the area from Wardrecques eastwards to the Kester borehole in the Brussels area (King, 1991b, figs 10-11) and can also be recognised within the coeval Mons-en-Pévèle Formation further south (Steurbaut & King, 1994, fig. 3). In the Ooigem borehole it is probably represented by silty clays with *Crassostrea multicostata* at c. 37 - 39.5 m. It is estimated to be c. 3 - 5 m below the base of the section at Moen (Figs 10-11).

The composite continuous outcrop section begins with Unit 26 (silty clay, Fig. 5). Units 26 - 23 are exposed only at Moen.

Units 25 and 24. These together comprise the most coarse-grained glauconitic sand unit of the lower Roubaix Clay Member (representing resistivity maximum 5 or layer 5 in Steurbaut et al., 2016b; see also Fig. 22), comparable to the 'Mons-en-Pévèle Sand' facies . The lower part is laminated (bed 25); the upper part (bed 24) probably was also originally laminated, but has been reworked by bioturbation. It can also be recognised in the Mouscron borehole as 'sable très fin' with glauconitic beds in the lower part (beds 37 - 38 of Feugueur, 1963, p. 433-434, from 40.5 - 42.5 m). In the Marke-Aalbeke area (in the Marke borehole) it is represented by a 4 m thick package of silty sand (Steurbaut, 1988, fig. 4, from 32 - 36 m). In the Ooigem borehole this sand unit is not represented.

Units 23 - 21. This interval is represented at Marke by silty clays with several thin glauconitic beds. At Zwevegem and Moen, this interval is similar, but more silty, and the glauconitic beds are shelly, with abundant pectinid bivalves. At Zwevegem there is a very thin and apparently localised very fine sand with abundant *Venericor* at the top of Unit 22 (Fig. 7), not seen at other localities. The stratigraphic correlations within this interval can be refined using biostratigraphic criteria (detailed below in section 5). The upward increase in *Subbotina* from c. 60% to c. 100% of the planktonic foraminifera population, recorded at Moen in Unit 22b (Figs 20-21), occurs below the base of the Marke section. The *Subbotina 'patagonica'* to *S. 'triangularis'* population shift (see below, also Fig. 19: shift from P to T), occurring within Unit 22a2, is identified in both sections (c. 1.5 m below surface F at Marke and c. 1 m below F at Moen). Unit 21 is c. 0.35 m thick at Marke and clearly finer-grained (very silty clay) that the underlying (sandy very silty clay) and overlying (silty sand to sandy silt) units. Here there is an abrupt upward decrease of *Subbotina* from >90% to <20% of the planktonic foraminifera assemblage, occurring in the glauconite-rich layer at the base of Unit 21 (Unit 21b). This event is also recognisable at Zwevegem, where Unit 21, also finer grained that the underlying and overlying units, is 0.3 m thick. At both localities, 21b is highly glauconitic, including fine and medium grained glauconite (termed "main glauconite bed"), resting on an intensely interburrowed omission surface (surface E), and containing frequent shark teeth and small phosphatic concretions enclosing crab (*Zanthopsis*) carapaces. However, at Moen the beds across surface F are all rather coarse grained (sandy silt) and the decrease of *Subbotina* is coincident with the top of the Lower Roubaix Member, indicating that Unit 21 is absent at Moen. This is also evidenced by the absence of *Pontosphaera excelsa* in the Lower Roubaix Member at Moen, while it is present between surfaces E and F (marking Unit 21) at Marke (see section 5.4.).

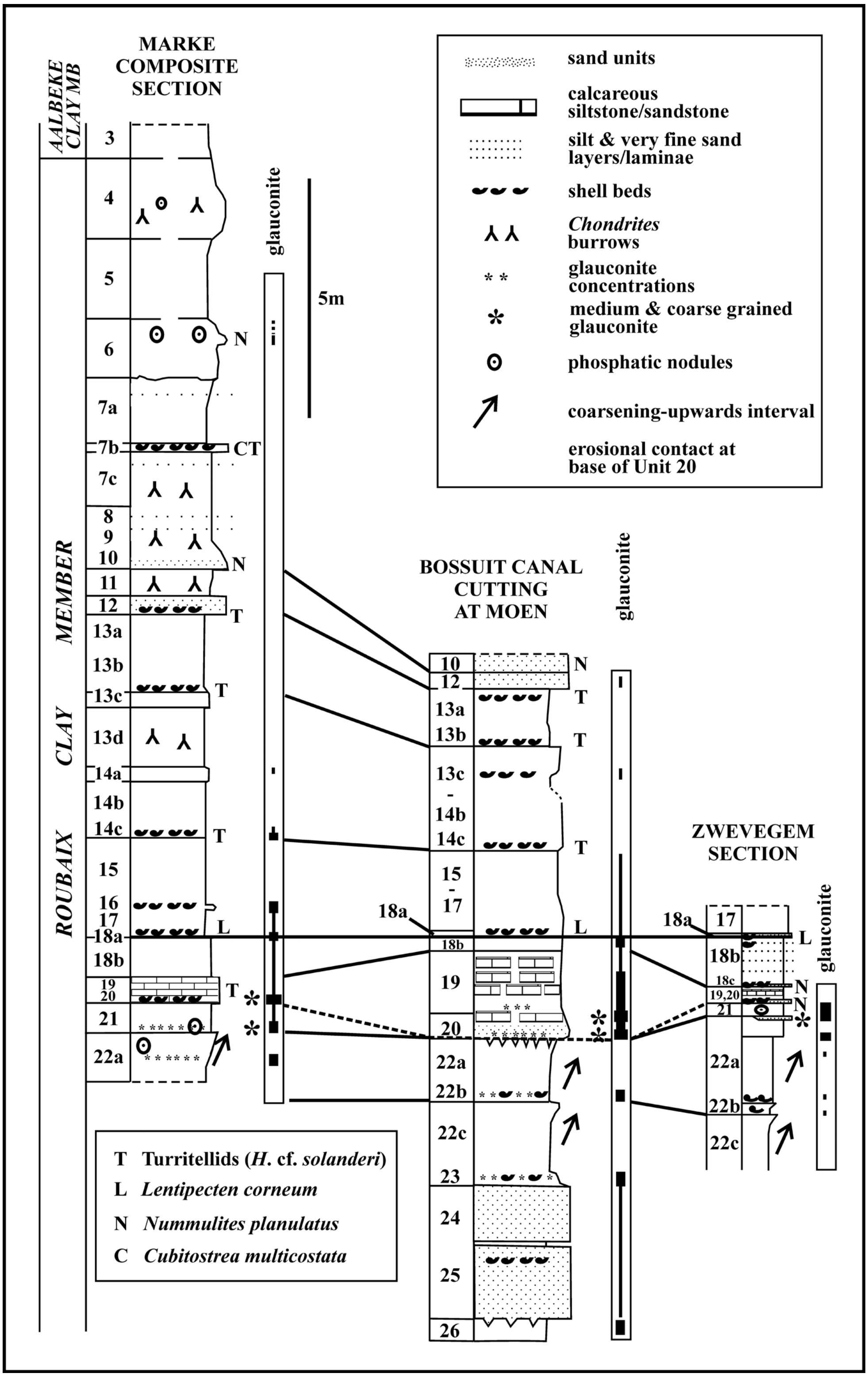


Figure 11. Correlation of the main sections in the Roubaix Clay Member. Horizontal datum is the base of shell bed 18a. Shell beds (T, L, N, and C, see below left side) are highlighted.

4.1.2. Upper Roubaix Member

The thickness of the Upper Roubaix Member is c. 18 m at Marke (Koekelberg), c. 20.5 m in the Mouscron borehole and c. 17.8 m in the Ooigem borehole. In the Moen area, the thickness is uncertain; c. 15.3 m was indicated by Steurbaut & Nolf (1986), but it is possible that the unit they identified as the Aalbeke Member (in a weathered part of the section) may be Unit 5 of the Roubaix Member.

Unit 20. This distinctive glauconite-rich bed, including fine to coarse-grained glauconite, and containing abundant *Nummulites* and serpulids (*Ditrupa, Rotularia*) forms the basal unit of the Upper Roubaix Member. It can be distinguished from the glauconitic-rich bed at the base of Unit 21 by the absence of phosphatic nodules and the presence of frequent *Nummulites*. At Marke Unit 20 comprises a thin sandy turritellid coquina with abundant coarse-grained glauconite and common *Ditrupa*. At Moen (Fig. 5) and to a lesser degree Zwevegem (Fig. 7), it is represented by two thin layers of shelly coarsely glauconitic sand separated by 0.40 m of finely glauconitic sandy silt to silty sand, partly irregularly calcite-cemented. The basal contact (F) is sharp and rather irregular at Marke and Zwevegem, but is an interburrowed omission surface at Moen. These burrows could however be from the base of Unit 21b, as seen at Marke and Moen, but with 21 otherwise absent, as noted above. The 'grès argileux calcarifère' in the Mouscron borehole (Feugueur 1963, p. 433-434, 32.0 - 33.0 m), with moulds of '*Turritella*' in the middle and coarse glauconite in the lower part, is equivalent to Units 19 (the turritellid siltstone) and 20. Coeval glauconitic turritellid-rich beds are known to occur in the Ooigem borehole (30.80 - 29.80 m).

Unit 19. At Marke this is a thin calcareous siltstone with turritellids (the 'turritellid siltstone' of Fig. 6a). It is represented at Moen and Zwevegem by a sandy silt with turritellid-rich beds and several irregular beds of calcareous siltstone.

Unit 18. This *Lentipecten*-rich unit is capped by a thin, very distinctive 'black *Lentipecten* shell bed' (bed H), which can be identified at Marke, Moen and Zwevegem.

Units 14c and 13b. These turritellid shell beds (respectively beds I and J; bed J is equal to layer Z in Steurbaut, 2015, fig. 3.15 and in Fig. 6c) can be identified at both Marke and Moen; correlation is confirmed by the characteristic 'doubling' of 14c, and by the highest occurrence of common *Lentipecten* at the top of Unit 14, at both sites.

Units 12a and 10. These two sand units, identified at Marke, appear to be amalgamated at Moen. A highly nummulitic bed (Unit 10c) can be identified at both sites; its identification is reinforced by its partial silicification at both localities. It can be identified in the Mouscron borehole as 'grès calcaire formée de *Nummulites planulatus*' (Feugueur, 1963, bed 20, 24.0 - 24.30 m).

Unit 7. A distinctive 'turritellid-ostreid coquina bed' occurs in the middle of the unit at Marke (Unit 7b, equal to layer Y in Steurbaut, 1998). It is probably represented in the Mousron borehole by bed 15 of Feugueur (1963, p. 433-434), 'lit calcaire pétri de Turritelles, d'*Ostrea* etc.' (c. 19.0 - 19.5 m).

Unit 6. The upper part of this slightly coarsening upward sandy unit is marked by very rich shell concentrations (6a), including numerous phosphatic nodules, enclosing crab (*Zanthopsis*) carapaces. It is represented in the Mouscron borehole by 'sable argileux' with *Nummulites planulatus* (17.5 - 19 m, Feugueur, 1963, p. 433-434).

Units 5 and 4. These, the highest units of the Roubaix Member, are almost identical lithologically in the Marke and Moen areas (Heestert). Their correlation is confirmed by the close similarity of the microfauna and macrofauna at both localities. The 'sable argileux' at 14 - 16.5 m in the Mouscron borehole probably corresponds to Unit 4 of the Kortrijk sections.

The Upper Roubaix Member is significantly finer grained in the Ooigem borehole, and individual units are not readily identifiable lithologically.

4.1.3. Regional lithological variation

There is a progressive N to S/SW increase in sand content of the clays and silts of the Upper Roubaix Member, from Ooigem through Marke to Moen and the Mouscron borehole, together with the appearance of individual sand beds of 'Mons-en-Pévèle' facies in the same direction (including Units 24/25, 12, 10 and 6). These are absent in the Ooigem borehole, and best developed at Moen and in the Mouscron borehole. This reflects the regional trends (Steurbaut & Nolf, 1986, fig. 11; King, 1991b, fig. 13), which show SE-NW trending facies belts, with progressive decrease in water depths to the S/SE. Moen and Mouscron lie only 10-15 km NW of the northern limit of the Mons-en-Pévèle Formation (Steurbaut & Nolf, 1986, fig. 11). The Kortrijk area sections demonstrate the beginning of the transition between the Roubaix Member and the Mons-en-Pévèle Formation, with interfingering of thin sand units within the dominantly argillaceous succession (Fig. 5).

4.2. Aalbeke Member

The basal contact of the Aalbeke Member appears transitional at most sites, but clear exposures at Heestert (Fig. 8) suggest that an originally sharp contact (omission surface) has been modified by intense interburrowing. The Aalbeke Member does not differ significantly in lithology from the silty clay units in the upper part of the Roubaix Member (e.g. Unit 5), but is almost always non-calcareous. This is probably an early diagenetic feature (see comments below). Where Unit 5 of the Roubaix Member is decalcified by near-surface groundwater-related weathering, as at Marke (Koekelberg quarry and Lauwe road cut) it can be mistaken for the Aalbeke Member in discontinuous sections.

A sandy clayey silt unit, c. 0.7 m thick (Unit 2b), has been identified in all sections within the middle of the Aalbeke Member. It weathers to a distinctive reddish brown colour.

The thickness of the Aalbeke Member in the area south of Kortrijk is relatively constant at c. 8.5 - 9.0 m. No significant lateral lithological variation has been identified.

4.3. Mont-Panisel Sand Member

The sharp and deeply interburrowed basal contact of the Mont-Panisel Sand Member is an omission surface which records a significant stratigraphic break. Only the lowest 2 - 3 m of the Mont-Panisel Sand Member are preserved beneath Quaternary sediments on hilltops in the Kortrijk area. In the Ronse area, 25 km E of Kortrijk, it is c. 20 m thick. Although originally believed to be a correlative of the Egem Sand Member (Steurbaut & Nolf, 1986, fig. 10), the Mont-Panisel Sand Member is now known to be slightly younger (Steurbaut & King, 1994; Steurbaut, 2006).

5. Biostratigraphy

5.1. Introduction

Well-preserved calcareous microfossils and nannofossils occur throughout the Roubaix Member in the Kortrijk area, except where near-surface weathering has taken place. Foraminifera and ostracods are very abundant at some levels, particularly in the upper part of the Lower Roubaix Member. Molluscs are also common at some levels, although aragonitic molluscs are partially decalcified and often deformed by compaction. Other fossil groups, including diatoms, serpulids, bryozoa, crustaceans, teleost fish otoliths and shark teeth, are briefly discussed below.

The Aalbeke Member is decalcified, but pyrite and limonite casts and moulds of calcareous benthic foraminifera, and clay moulds of molluscs, indicate the former presence of a low-diversity calcareous microfauna and macrofauna. Pyritised diatom moulds are frequent, and occasional crustacea are recorded, preserved in phosphatic nodules.

A comprehensive study of the dinoflagellate assemblages has not been carried out, but published and unpublished data relevant to this area is summarised here.

Taxonomic details of taxa included on the range charts (Figs 12 - 18) are included in Appendix.

5.2. Techniques

Closely spaced samples (generally with 0.3 - 1.0 m sample spacing) were collected for micropalaeontological and calcareous nannofossil analysis from the Roubaix Member, mainly from the Kortrijk - Bossuit canal section (Moen), the Koekelberg quarry (Marke), the Lauwe roadcut and the Kwadestraat quarry (Heestert). The samples were processed by standard techniques, as described in Steurbaut & King (1994). Macrofossils (mainly molluscs) were collected in the field. Core samples were processed at approximately 1m intervals from the Ooigem borehole.

5.3. Dinoflagellate cysts

De Coninck (1969, 1973, 1976a, 1991) studied the dinoflagellate cyst assemblages of a number of boreholes and outcrops in the Ieper Group, and proposed a dinoflagellate cyst zonation for the Ypresian of Belgium (1991). This zonal scheme, subsequently enhanced by additional dinocyst events in its lower part (De Coninck, 1999), differs significantly from others applied to the Early Eocene of the North Sea Basin, such as that of Costa & Downie (1976), as revised by Costa & Manum (1988). The dinoflagellate cysts of the Kortrijk area have not yet been studied in detail, but some samples from the Koekelberg quarry have been analysed by Dr. C. Heilmann-Clausen (University of Aarhus) who has kindly permitted the information to be published here. Published data from this area, and relevant data from other localities, is also summarised here.

The majority of the Roubaix Member falls within the *Eatonicysta ursulae* zone of De Coninck (1991). This zone corresponds to the upper part of the *Dracodinium simile*

[*Wetzeliella similis*] zone of Costa & Downie (1976) (Subzone D7a of Costa & Manum, 1988) (see Fig. 21). The base of the overlying *D. varielongitudum* zone of De Coninck is defined by the first (earliest) occurrence (FO) of *D. varielongitudum*. It corresponds to the lower part of the *D. varielongitudum* [*W. varielongituda*] zone of Costa & Downie (1976), Subzone D7b of Costa & Manum (1988). *D. varielongitudum* has its lowest occurrence between 303.9 m and 307 m in the Kallo borehole (De Coninck, 1991), subsequently pinpointed at 306.2 m by Vanhove & De Coninck (1992, p. 358). This interval lies between events **I**5 and **I**6 of King (1991b, fig. 40). Further precision is possible, as a sample at 306 m, on the basis of its nannofossil content (rare occurrence of *Discoaster lodoensis* and *Neochiastozygus rosenkrantzii*; absence of *Ellipsolithus macellus*), seems correlatable with the upper part of Unit 22 of the Kortrijk area, whereas the sample at 303.90 m can be correlated with Unit 21 (presence of nannofossil taxa *Neochiastozygus rosenkrantzii* and *Pontosphaera excelsa* in combination with the absence of *Ellipsolithus macellus*).

The dinoflagellate cyst assemblage of a sample from the Upper Roubaix Member of the Lauwe quarry (Lauwe a/11 m, De Coninck, 1976b) was stated to be intermediate between assemblages of the *E. ursulae* and *D. varielongitudum* zones (De Coninck, 1991, p. 293), but in the original description of the assemblage it is said to include *D. varielongitudum*. It must therefore be referable (by definition) to the *D. varielongitudum* zone. According to stratigraphic information supplied by Dr. T. Moorkens (pers. comm.), who collected the sample, it was taken c. 1.5 m below the base of Moorkens' level "P" (= Unit 6 here; different from event P in this paper), and thus probably within Unit 7a (Fig. 6b). This agrees well with the nannofossil data, as a sample from a '*Turritella*' bed within Unit 12, about 5 m below the dinocyst sample (Lauwe d/11 m) can be assigned to subzone IIIb2 (presence of *Micrantholithus mirabilis*, absence of *Chiphragmalithus barbatus*), and not to subzone IV, as formerly stated by Steurbaut & Nolf (1986).

A series of samples collected from the Koekelberg quarry, between Units 13 and 5, all contain *D. varielongitudum*; the highest sample contains *Charlesdowniea reticulata*, suggesting a location just below the FO of *C. coleothrypta* (C. Heilmann-Clausen, unpublished data).

Samples from 8 - 10 m below the top of the Mons-en-Pévèle Sand Formation at Ronse - Waaienberghe, 25 km SE of Kortrijk, must also be assigned to the *D. varielongitudum* zone, as the lower sample contains the zonal index species (Vanhove & De Coninck, 1992). De Coninck (1991, p. 294) assigned them to the *E. ursulae* zone, surely mistakenly. The nummulitic bed from which this lower sample was taken probably corresponds to Unit 10 of the Kortrijk area (cf. King, 1991b, fig. 10). This is in accordance with the nannofossil data, as this sample belongs to subzone IIIb2 (presence of *M. mirabilis*).

The lowest occurrence (LO) of *Charlesdowniea* [*Kisselovia*] *coleothrypta* (*K. clathrata,* sensu De Coninck) defines the base of the *K. [Wetzeliella] coleothrypta* zone of Costa & Downie (1976) (zone D8 of Costa & Manum, 1988). According to De Coninck (1991) this taxon appears together with *D. varielongitudum* in the Kallo borehole, although Vanhove & De Coninck (1992, p. 358) noted that at Kallo *K. coleothrypta-clathrata* has its LO above 305 m depth, slightly above the LO of *D. varielongitudum* (and just below event **I**6). However, the position of the LO of *C. coleothrypta* seems much too low, by comparison with the position of the same event in other areas of the southern North Sea Basin, including the Kortrijk area (no co-occurrence of both taxa at Waaienberghe and at Steenhuize - Wijnhuize, Vanhove & De Coninck, 1992, tab. 1) and may reflect contamination of certain Kallo core samples by caving from higher levels. Further study is necessary to resolve these problems.

Samples from the Aalbeke Member at Aalbeke and other localities are assigned to the *Ochetodinium romanum* zone (De Coninck, 1991). This corresponds to part of the *K. coleothrypta* zone of Costa & Downie. This implies that the FO of *C. coleothrypta* is probably in the highest Roubaix Member (Unit 4), as it is not yet present in Unit 5 (C. Heilmann-Clausen, unpublished information) or the basal Aalbeke Member. *Ochetodinium romanum* is now known to be an important index-species, widespread and restricted to a short interval within the *C. coleothrypta Zone* (*sensu* Heilmann-Clausen, 1988) (Iakovleva & Heilmann-Clausen, 2010; King et al., 2013).

5.4. Calcareous nannofossils

The stratigraphy of the Ypresian of Belgium has been unraveled in the late 1980's and early 1990's through a combined lithological and calcareous nannofossil investigation of a wide gamut of outcrop and borehole successions throughout the southern North Sea Basin (Steurbaut & Nolf, 1986; Steurbaut, 1991, 1998; synthesized and updated in Steurbaut, 2006). Martini's (1971) standard calcareous nannofossil zones NP11, NP12, NP13 and NP14 were recognized and zone NP11 was furthermore subdivided into 6 (Ia, Ib, Ic, II, IIIa1, IIIa2) and zone NP12 into 11 (IIIa3, IIIa4, IIIb1, IIIb2, IIIb3, IV, V, VI, VII, VIIIa, VIIIb) nannofossil units or subzones (Steurbaut, 1998). These subdivisions have been recognized beyond the North Sea Basin as far as NW Kazakhstan (Steurbaut, 2011; King et al., 2013), and have proved to be major keys for early and mid-Ypresian mid-latitude northern hemisphere high-resolution biostratigraphy. Several short-lived nannofossil species have been detected in zones NP13 and NP14 in the southern North Sea Basin (Steurbaut, 1990, 2011; Steurbaut & Nolf, 1989; Steurbaut et al., 2016a, fig. 4), which may lead to a further subdivision of these zones in that area.

A comprehensive study of the calcareous nannofossil assemblages from the Kortrijk area has not yet been carried out, although some data have been used to establish Steurbaut's 1998 high-resolution nannofossil zonation. The associations from the interval studied here (upper half of the Roubaix Member, the Aalbeke Member being entirely decalcified) are generally poor (less than 100 specimens/mm² glass-slide, generally around 35 specimens/mm²: this means generally less than 1 specimen per field of view at magnification 1000x), but well-diversified (generally between 20 and 30 species/sample) and fairly well preserved (Fig. 12). From the black *Lentipecten* shell bed (Unit 18a, event H) up to the top of the Roubaix Clay Member (Unit 4) the number of specimens remains constantly low, except within bed 10. The richest and most diversified associations occur in Units 26, 24 and 10. The quantitatively and qualitatively poorest assemblages occur in Unit 20, just above surface F. They are characterised by relatively high numbers and proportions of *Braarudosphaera bigelowii* (12% of the association).

The vertical changes in calcareous nannofossil abundance as registered in the Roubaix Member of the Kortrijk area are not yet well understood. Calcite dissolution seems to be strongest in the clayey intervals (Unit 22a2, Units 13-17), probably because of strong water mass density stratification with corrosive bottom waters. However, this does not explain all decreases in abundance and species diversity recorded here. The low nannofossil diversity in Unit 19 seems to be due to calcite remobilisation and redeposition in this unit (numerous overgrown unidentifiable nannofossils; calcite cementation of fine sands and silts), whereas the low nannofossil abundance and diversity, associated with the high percentages of *Braarudosphaera bigelowii* (up to 12%) at the base of Unit 20 are probably due to a too high sea-water turbulence (winnowing of the larger more solid nannoliths and selective loss of the tiny forms) and the presence of hyposaline conditions. The latter is believed to be due to a major shallowing of the deposition system, as the result of a prominent sea-level fall.

The composition of the calcareous nannofossil assemblages is quite similar throughout the studied interval, because of the dominance of *Toweius pertusus* and *Coccolithus pelagicus*, which together represent more than 70% of the number of specimens (Fig. 12). *Pontosphaera exilis* is also fairly common (between 5% and 10%, with a maximum of 15%). Fortunately, within the remaining 20% of the assemblages, nearly all of the lowest (LO) and highest (HO) occurrences of species figuring in Steurbaut's 1998 high-resolution biozonation are recorded, allowing the Roubaix Member of the Kortrijk area to be correlated with coeval deposits elsewhere in the southern North Sea Basin. Steurbaut (1991) produced a comprehensive

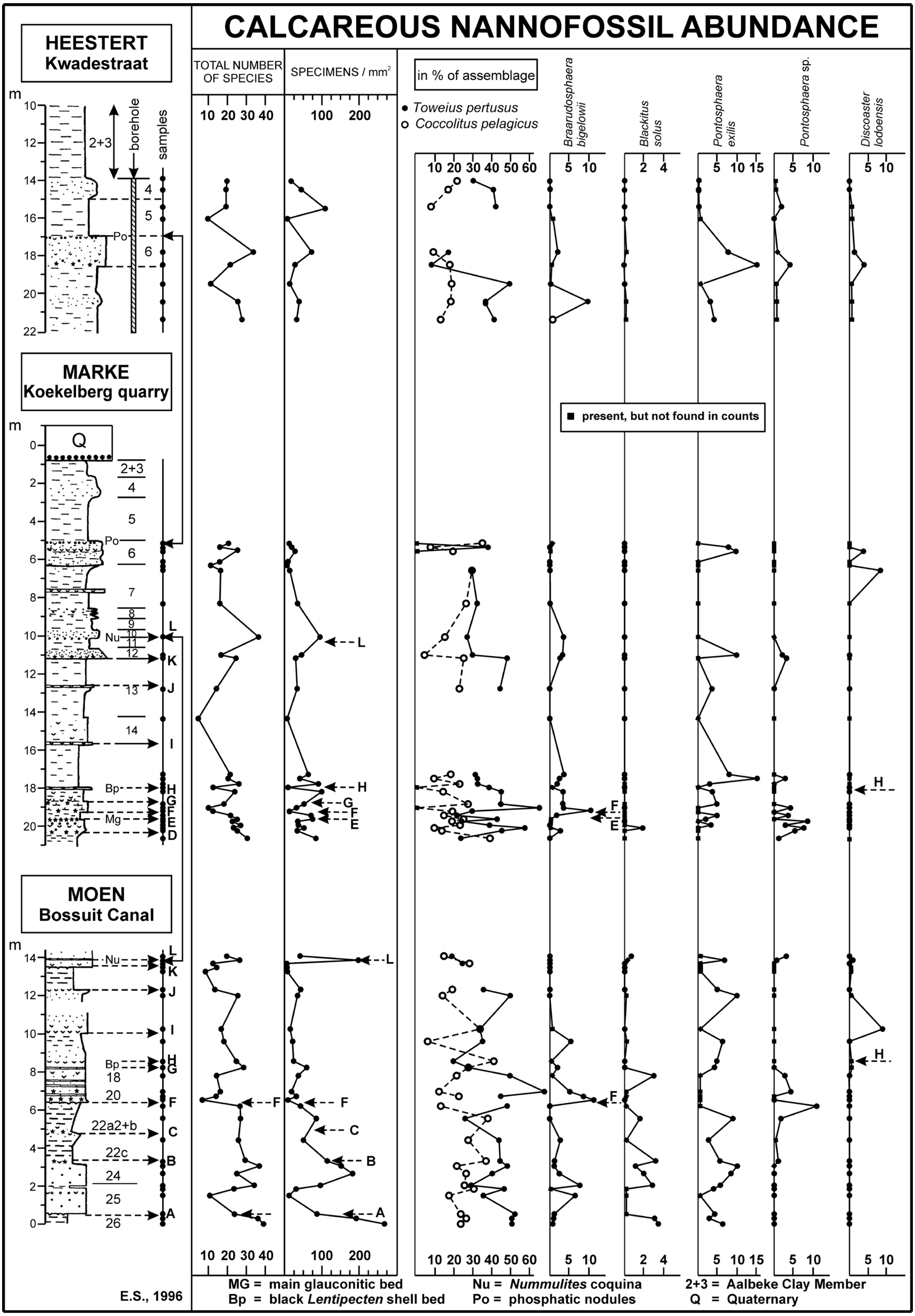


Figure 12. Quantitative distribution of selected calcareous nannofossil taxa through the Kortrijk Clay Formation in the Kortrijk area.

iconography of the Ypresian nannofossils of Belgium, including the marker species recorded in the Kortrijk area.

The LO of *Discoaster lodoensis*, defining the base of Martini's NP12, is difficult to pinpoint in the Kortrijk area, as elsewhere in the southern North Sea Basin. The start of its consistent occurrence has been recorded within Unit18 in the sections studied here. This event was shown to be synchronous throughout the southern North Sea Basin and was used to define the base of subzone IIIb (Steurbaut, 1998). However, this event does not correspond to the first occurrence of the species. A few specimens of *D. lodoensis* have been recorded up to now below the base of subzone IIIb in the Belgian Basin. These records, two from the Kortrijk area (Marke ~20.70 m, Zwevegem 2.60 m) and one in the Kallo borehole (306 m depth) are within the upper part of Unit 22a2. The LO of *D. lodoensis* is thus within subzone IIIa3 (see below).

Application of Steurbaut's nannofosil zonation to the Roubaix Member of the Kortrijk area allows the following to be concluded (Fig. 21):

Units 26-23b. The presence of *Chiphragmalithus calathus*, *Blackites dupuisii*, *Ellipsolithus macellus* and relatively frequent *Blackites solus* allows assignment to subzone IIIa1.

Unit 23a. This thin unit already belongs to subzone IIIa2, because of the disappearance of *Blackites dupuisii* just below its base.

Unit 22. The HO of *Ellipsolithus macellus*, defining the base of subzone IIIa3, is within the middle of Unit 22a2, indicating that the upper part of Unit 22a2 and Unit 22a1 belong to subzone IIIa3. The very first occurrence of *D. lodoensis* is positioned just above the HO of *E. macellus* (both species have never been found to co-occur in the North Sea Basin).

Unit 21. The co-occurrence of *Pontosphaera excelsa* and *Neochiastozygus rosenkrantzii* within this unit allows its assignment to subzone IIIa3. It is furthermore marked by the LOs of *Aubrysphaera deconinckii* and *Pentaster* sp.

The base of Unit 20. There is an abrupt increase in *Braarudosphaera bigelowii* (from ~1% to 12%) and in *Pentaster* sp. (from ~1% to ~13%) at the base of the unit. This event coincides with the disappearance of *N. rosenkrantzii*, marking the base of subzone IIIa4.

Unit 18. The lowest consistent occurrence of *D. lodoensis*, marking the base of subzone IIIb1, has been recorded just above marker bed G, within the middle of the unit (e.g. at Moen, but slightly higher at Marke).

Units 12-7. This interval is bracketed between the LO of *Micrantholithus mirabilis* at the base of Unit 12 and the LO of *Chiphragmalithus barbatus* at the top of Unit 7, indicating subzone IIIb2.

Unit 6. The lower and upper limits of this unit are marked respectively by the LO and HO of *Chiphragmalithus barbatus*, allowing this unit to be attributed to subzone IIIb3.

Unit 5-4. The HO of *Pontosphaera exilis*, marking the boundary between subzones IV and V is located around the top of Unit 5. The LO of *Chiasmolithus* aff. *expansus* is recorded slightly higher in the lower part of Unit 4.

5.5. Planktonic foraminifera

The taxonomy and biostratigraphy of planktonic foraminifera from the Ieper Group of Belgium have been studied by Kaasschieter (1961), Moorkens (1968), Berggren (1969), Willems (1980), Hooyberghs (1983, 1992) and Pardo et al. (1994), but a comprehensive regional study has not yet been carried out. The assemblages in the Kortrijk area have not yet been studied in detail, but are very similar to coeval asemblages in the corresponding stratigraphic interval in the Kallo borehole (Willems, 1980, 1991) and the Mol borehole (Hooyberghs, 1983).

During the present study, identifications have been carried out mainly to generic level only. Previous studies have indicated that most taxa occurring in the Early Eocene of the North Sea Basin are relatively long-ranging, and do not permit accurate calibration with the standard low latitude planktonic foraminiferal zonation. This zonation (e.g. Berggren & Pearson, 2005) is based mainly on species of *Morozovella,* which has a very limited geographic and stratigraphic distribution in the North Sea Basin (see Steurbaut & King, 1994). Spiegler (1986, 1989) defined regional planktonic foraminiferal zones in NW Germany, following detailed sampling of a thick Ypresian section in the Wursterheide borehole, and these can be applied to the sections studied here.

Assemblage changes (particularly the relative abundance of *Subbotina*), and quantitative assessment of the proportion of planktonic foraminifera in the total foraminiferal population (**P**% of King, 1991b), have been found to be valuable tools in correlation and environmental interpretation in the Early Eocene of the North Sea Basin (King, 1991b; Steurbaut & King, 1994; Schmitz et al., 1996). In Belgium, Willems (1982) noted several successive assemblage changes in the Kallo borehole. King (1990, 1991b) analysed the vertical distribution and quantitative abundance of planktonic foraminifera in the middle Ieper Group of western Belgium and northern France. Several events were found to be regionally recognisable, and were formalised by King (1991b) as events **I**1, **I**4, **I**5 and **I**6.

In the Roubaix Member, the planktonic foraminiferal assemblages are composed almost entirely of *Acarinina* and *Subbotina*. This type of assemblage is typical for the mid-Ypresian of the North Sea Basin, and similar assemblages occur at this level in southern England (King, 1989) and NW Germany (Spiegler, 1986, 1989). No specimens of the predominantly low to mid-latitude genus *Morozovella* have been recorded, although it occurs consistently in the coeval Mons-en-Pévèle Formation in eastern Belgium (Hooyberghs, 1983, 1992; King, 1990; Steurbaut & King, 1994).

The features of the assemblages which have been analysed in this study (Fig. 19) are the percentage of planktonic foraminiferal specimens in the total foraminiferal assemblage (**P**% of King, 1991b), the proportion of *Subbotina* in the planktonic foraminiferid assemblage (here designated **S**% for brevity), and the taxonomic composition of the *Subbotina* populations (see below).

The influx of *Subbotina* in the highest part of the lower Roubaix Clay Member (in this area through Units 23 and 22) is a very prominent event, forming between 60-90% of the planktonic foraminiferal population, compared to 10% or less at other levels. It was noted originally in Belgium by Willems (1982) (*Globigerina patagonica* acme zone), and used there as a biostratigraphic event by King (1990, 1991b). It has subsequently been identified in other areas of the North Sea Basin (King, 1989, 1991a; Spiegler, 1989; Schmitz et al., 1996), and has also been recently identified in western Kazakhstan (King et al., 2013) and the Crimea (King et al., 2017). The taxonomy of the *Subbotina* specimens in this interval has been variably interpreted in the past, generally as *S.* gr. *linaperta*, *S. patagonica* or *S. yeguaensis*. Olsson et al. (2006) referred them to a new species (*S. roesnaesensis*) on the basis of their distinctive wall texture. Spiegler (1986, 1989) however had noted that in NW Germany the earlier part of the *Subbotina* influx was dominated by a 3 1/2-4 chambered morphotype she identified as *S. patagonica* (Spiegler, 1986, pl. 7, figs 17, 18), and the later part by a 3-3 1/2 chambered morphotype with a large final chamber, identified as *S. triangularis* (Spiegler, 1986, pl. 8, figs 3, 4). *S. roesnaesensis*, as illustrated by Olsson et al. (2006, pl. 6.16) appears to include both morphotypes, although most are closer to the '*patagonica*' morphotype'. The same succession of morphotypes has been identified in the London Basin (King, unpublished data) and is here recognised in Belgium. Here they are differentiated as morphotypes A and B respectively. The main features of the planktonic foraminiferal assemblages are summerised below (see Figs 19-21).

5.5.1. Lower Roubaix Member

Unit 26. **P** is relatively high (30%). This indicates a position just above the planktonic influx event **I**4 of King (1991b).

Unit 25. **P** decreases to <15%.

Unit 23. A brief influx of planktonic foraminiferids occurs in this unit (**P** = 62% at Moen). This is the highest proportion of planktonics recorded in the Roubaix Member in the Kortrijk area. At this level, there is also an abrupt assemblage change, marked by an upward increase in **S** from 10-15% to >50%. This event defines event **I**5 of King (1991b), as revised here (see below). It marks the base of a sharply delimited *Subbotina*-dominated interval (Units 23 and 22).

Unit 22. At the base of Unit 22b there is an abrupt increase in **S** to >90%. There is an associated decrease in **P** to <5%. This high dominance of *Subbotina* continues to the top of Unit 22. Within Unit 22a there is a shift in the *Subbotina* population from dominantly morphotype A to morphotype B. This event is identified at both Moen and Marke, in (or close to the top of) Unit 22a2. It corresponds to the boundary between the *triangularis* and *patagonica* zones of Spiegler (1986, 1989).

Unit 21. There is an abrupt decrease in **S** to 20% or less at the base of Unit 21. It remains relatively low through the rest of the section.

5.5.2. Upper Roubaix Member

Units 18a-14b. There is an abrupt decrease in **P** at the base of 18a (to <3%). This is event **I**6 (King, 1991b).

Units 14b-6. **P** decreases to <1% in 14b and above. At Marke, very rare planktonic foraminifera persist to the top of Unit 13, but at Moen, none are recorded above 14c, apart from a single specimen of *Planorotalites* sp. in Unit 12b. This is the only record of this genus in the Kortrijk area.

Units 5 and 4. Planktonic foraminifera reappear here in low abundance (**P** < 1%). A flood of pyritised planktonic foraminifera (**P** probably >50%) is recorded in a sample, probably from Unit 5 (here decalcified) in the Pottelberg A14 section (point 5 on Fig. 4).

5.5.3. Main features within the Roubaix Member

The main features of the Roubaix assemblages are the consistent and often relatively high proportions of planktonic foraminifera up to Unit 18b, abruptly decreasing until virtually absent above Unit 14, but reappearing in Unit 5; and the *Subbotina*-dominated interval in the higher part of the lower Roubaix clay.

5.6. Benthic foraminifera

Benthic foraminiferal assemblages of moderate to high diversity are present throughout the Roubaix Member. They are similar to the assemblages recorded from the middle of the 'Ieper Clay' (Roubaix Member) in the Kallo borehole by Willems (1980), and correspond to benthic foraminiferal assemblage IV of Willems (1982). Approximately 50 species are recorded (Figs 13, 14). Taxonomy is based on Willems (1980), as revised by King (1989). The assemblages are dominated by *Anomalinoides anomalinoides*, *Cibicidoides alleni* and *Pulsiphonina prima*, with common *Euuvigerina batjesi* at some levels. No major faunal changes have been identified within the Roubaix Member of the Moen and Marke sections, but some taxa have restricted vertical ranges.

Foraminiferal diversity (Fig. 19) is highest in the lower part of the succession (Units 26 to 15); highest in Unit 24 (c. 30 taxa). It is generally lower between Units 13c to 6a, although no clear trends can be identified.

Gaudryinopsis ashfordi, Gyroidinoides danvillensis and *Karreria fallax* are restricted to the Lower Roubaix Member. *A. b. kaasschieteri* is abundant in the Lower Roubaix Member up to the top of Unit 23 (much less and inconsistently occurring higher up) and represented by large 'frilled' specimens (with wide and 'ragged' peripheral keel) in Unit 25.

The nodosariids *Percultazonaria wetherellii* and *Pyramidulina latejugata*, characteristic taxa of the 'nodosarid-rich assemblage' (NRA) of the middle London Clay Formation (King, 1981), occur in the upper part of the Lower Roubaix Member (Units 23 and 22).

Gyroidinoides octocameratus is restricted to Units 18 and 17. It occurs in the same interval at other localities (Wardrecques, Mont Saint-Aubert borehole, etc.) and appears to be a valuable stratigraphic marker within the upper Roubaix Member.

Ceratocancris sp. occurs in Units 23 and 22c; it is recorded at an equivalent level in the Kallo borehole and at Wardrecques (CK, unpublished data), and appears to be restricted to this interval in Belgium and northern France.

Miliolids (*Quinqueloculina*) are present only in Units 20-18 and 16-14b. *Textularia smithvillensis* is restricted to the interval between Units 14b and 7a; it is common to abundant within most of this interval.

Nummulites planulatus occurs sporadically through the Roubaix Clay Member, most commonly in the sand units. It occurs in abundance in Units 24, 23, 20 and 10c, forming a coquina in 10c, which is partially silicified.

5.7. Calcareous microproblematica

Approximately 17 taxa of calcareous 'microproblematica' (calcitic microfossils of uncertain affinity) have been recorded from the Ypresian of Belgium (Keij, 1969, 1970; Willems, 1972; Szczechura, 1979; Steurbaut & King, 1994). The Belgian Ypresian has the highest diversity of these enigmatic organisms known anywhere in the Paleogene. They are dominantly Pseudarcellids (Bignot, 1989), but include also *Calvina* (Willems, 1972) and *Voorthuyseniella* (Keij, 1970).

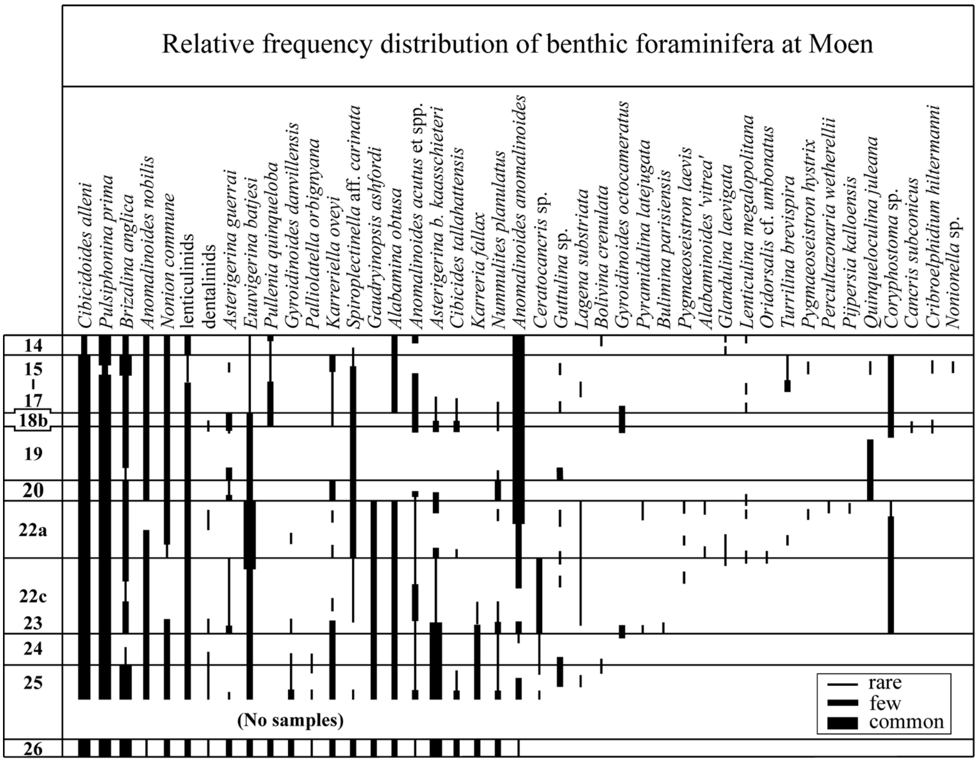


Figure 13. Benthic foraminifera of the Roubaix Clay Member from the Bossuit canal section at Moen. The interval above Unit 14 was not sampled in detail and is not included here.

The morphology of these taxa (Szczechura, 1994), and their localised distribution patterns, indicate a benthic mode of life. Pseudarcellids have been referred to the Tintinnida (see the discussion in Bignot, 1989), but are now believed to be probably individual zoecia of cheilostome bryozoan colonies (Szczechura, 1994). Bryozoan affinities are also strongly indicated for *Calvina* (Szczechura, 1990) and *Voorthuyseniella* (Szczechura, 1994). Most taxa are short-ranging, some occur in large numbers, and the distribution and relative abundance of several taxa can be related to specific lithofacies. Thus they probably have both biostratigraphic and palaeoenvironmental potential. These aspects require further study; only some salient features are noted here.

In the Kortrijk area (Figs 15, 16), pseudarcellids (*Bignotella*, *Pseudarcella* and *Yvonniellina*) are dominant, although *Voorthuyseniella* is also common in some units. Comments on individual records are as follows:

Calvina kalloensis was recorded previously only in one sample (323.5 m) from the Roubaix Clay Member of the Kallo borehole (Willems, 1972). A single specimen was found in Unit 8 at Marke, stratigraphically somewhat higher than at Kallo.

Claretinella helenae is a very rare species, recorded previously only in the middle Ypresian of northern Spain, and in the Mons-en-Pévèle Formation at Mont St.-Aubert, north of Tournai (Bignot, 1989) and in the Mont-Panisel borehole (Steurbaut & King, 1994). Several specimens were recorded in Unit 20 at Marke.

Pseudarcella campanula is common in the fine sands of Units 23 and 24. It is recorded consistently in the Mons-en-Pévèle Formation of the Mont-Panisel borehole (Steurbaut & King, 1994) and appears to be characteristic of sandy lithofacies.

Pseudarcella 'rhumbleri' (see Appendix 1) occurs only in Units 10 and 24, in both cases in very fine sands. It occcurs commonly in the Mons-en-Pévèle Formation (Keij, 1969; Steurbaut & King, 1994) and seems characteristic of sandy lithofacies.

P. trapeziformis is recorded only in Unit 26. In the Kallo borehole (Willems, 1972), it is recorded at a similar level, at and below 310.8 m (at event **I**5 and below).

Voorthuyseniella includes three morphotypes, as in the Mont-Panisel Borehole (Steurbaut & King, 1994), with somewhat different stratigraphic distributions: the 'ovoid' and 'spindle-shaped' morphotypes of *V. gracilis* and an inflated form with a short ovoid slit. This latter form is somewhat similar to *V. bearnensis* Poignant (Poignant, 1990). These are all grouped on the range-chart as *V. gracilis*, pending more detailed study.

Yvonniellina concava occurs only in Units 23 - 26. In the Kallo borehole (Willems, 1972) it is recorded at a similar level, between 310.8 - 318.5 m (between events **I**5 and **I**3).

The association of *Bignotella polygona*, *Yvonniellina campanula* and *Pseudarcella 'rhumbleri'* in the sandy Unit 24 is very similar to the association in the lithologically comparable

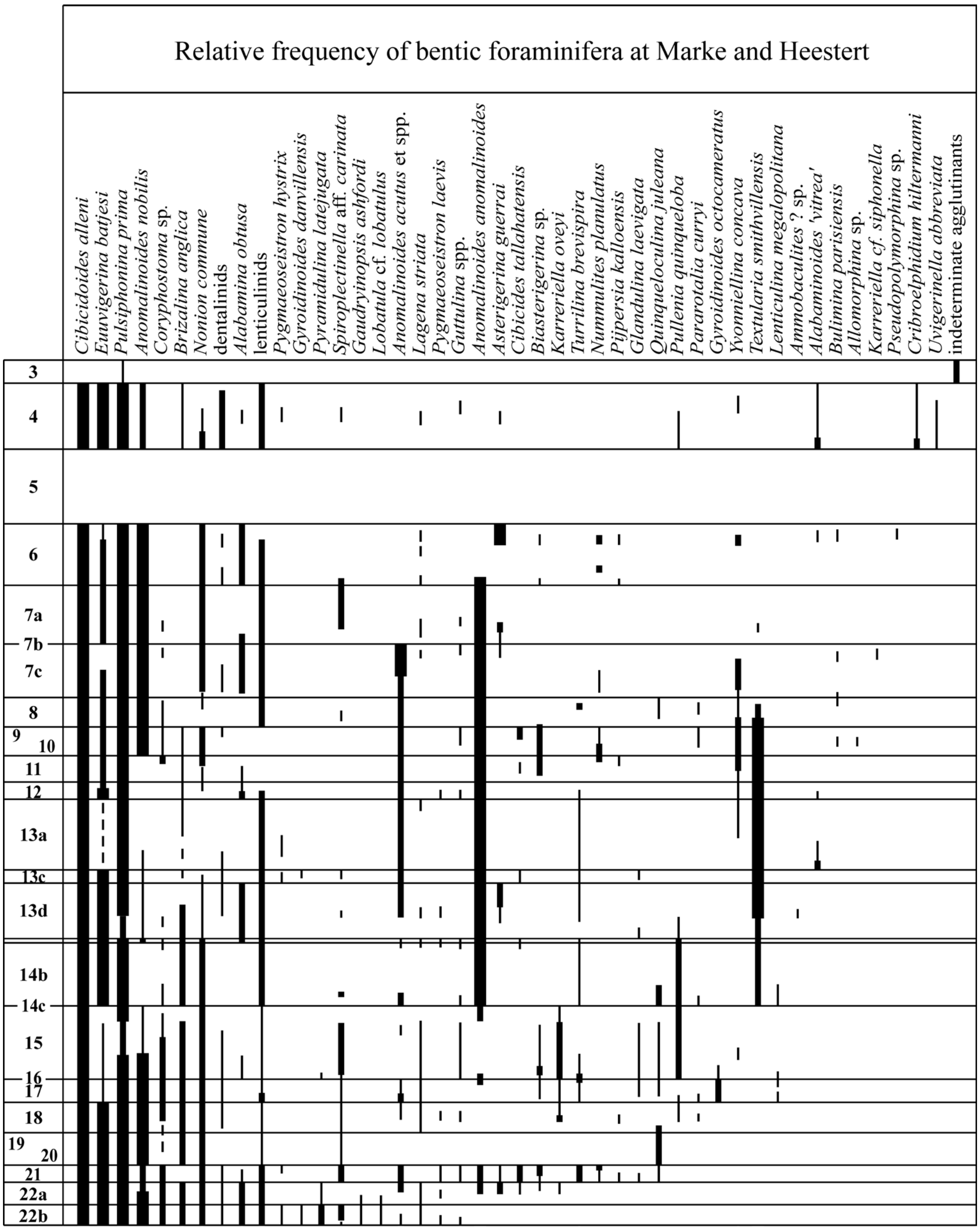


Figure 14. Benthic foraminifera of the Roubaix Clay Member, based mainly on Marke (Koekelberg quarry) and the Pottelberg A14 roadcut, with data from Units 4 and 3 from the Heestert (Kwadestraat) section.

Mons-en-Pévèle Sand Formation of the Mont-Panisel borehole (Steurbaut & King, 1994).

5.8. Bryozoa

The bryozoans *Dittosaria wetherellii* and *Lunulites* sp. are recorded rarely at several levels (Figs 17-18). These taxa also occur in the London Clay Formation and the Mons-en-Pévèle Formation (see Steurbaut & King, 1994).

5.9. Molluscs

Molluscs are common at most levels in the Roubaix Member of Belgium and northern France. The calcitic shells of anomiids, ostreids and pectinids are well-preserved, but aragonitic shells are generally soft and friable due to partial decalcification, and partly crushed. The records here are a combination of macrofossils collected in the field and 'micromolluscs' obtained from micropalaeontological samples. Large-scale sampling has not been attempted; this would certainly increase the number of taxa recorded, but the diversity at most levels does not appear to be high.

There is virtually no published information on the molluscs of the Roubaix Member, apart from brief notes and short lists of taxa from individual sections (e.g. Ortlieb & Chellonneix, 1879). This probably reflects the generally poor preservation, which has not encouraged study in the past. However, many taxa can be identified to specific level, and most taxa noted here as 'sp. indet.' (due to the low numbers and fragmentary nature of the available material), would be identifiable on the basis of more material. The utility of the nektonic (free-swimming) pectenid bivalves in Ypresian biostratigraphy was demonstrated by King (1981, 1991b). Approximately 50 taxa of molluscs are here recorded from the Kortrijk area (Figs 17 and 18).

5.9.1. Lower Roubaix Member

The mollusc assemblage of the Lower Roubaix Member is of low diversity. Ten taxa are recorded from Units 23 - 21; of the 'macromolluscs', only *Pseudamussium*, *Haustator* cf. *solanderi* and *Venericor* sp. are common. The pectenid '*Pseudamussium*' sp. (*sensu* King, 1991b) ranges through most of the upper part of the Lower Roubaix Member, occurring abundantly in Unit 23 and the lower part of Unit 22a. Its highest occurrence is at the top of Unit 22a. The pectenid *Lentipecten corneum* has its lowest occurrence in the highest part of the Lower Roubaix Member (Unit 21). Small *Venericor* sp. are frequent in the upper part of 22a, and common in the localised sand unit at Zwevegem at the top of Unit 22.

5.9.2. Upper Roubaix Member

The lower part of the Upper Roubaix Member (Units 20 to 14b) is characterised, both at Marke and Moen, by abundant but low-diversity mollusc assemblages in which *Anomia* sp., *Lentipecten corneum* and the turritellid *Haustator* cf. *solanderi* are the most common taxa. In Units 19 (the 'turritellid siltstone'), 18 and 17, *H.* cf. *solanderi* is dominant, although less in Unit 17. Unit 18a, a shell-bed dominated by *Lentipecten*, marks the base of a *Lentipecten*-dominated interval comprising Units 18a to 14b. A correlative *Lentipecten*-rich unit has been identified in the Ooigem borehole, and in exposures at Bailleul and Wardrecques (King, 1991b).

From Unit 13c, the bivalves *Lutetia umbonata* and *Varicorbula globosa* are intermittently common, associated with *Phacoides squamulus*. There is a marked increase in diversity at the base of Unit 10, and relatively diverse assemblages occur through Units 10 to 6, dominated by small infaunal suspension-feeding bivalves. Several turritellid (*H.* cf. *solanderi*) or ostreid (*Cubitostrea multicostata*) dominated shell beds occur in this interval (Units 14c, 13b, 12b and 7b). These contain very low diversity mollusc assemblages, and shells are often broken and abraded. There is a low diversity assemblage in the clay Unit 7a.

The highest diversity in the Roubaix Member occurs in the upper part of Unit 6; 30 taxa are recorded at Marke at this level. The distinctive bivalves *Anisodonta* ? sp. and *Ramsetia* sp. nov., common in Unit 6a, occur in association at a similar level at Bailleul. Low-diversity assemblages are recorded in Units 5 and 4.

The significance of these assemblages for correlation is not yet clear, due to the lack of adequate data elsewhere in Belgium and northern France for this stratigraphic interval. As noted above, the *Lentipecten*-dominated interval can be identified regionally. The mollusc assemblage from the upper part of the Mons-en-Pévèle Formation at Waaienberghe (Ronse) (C. King, unpublished data) is similar to the assemblage from the

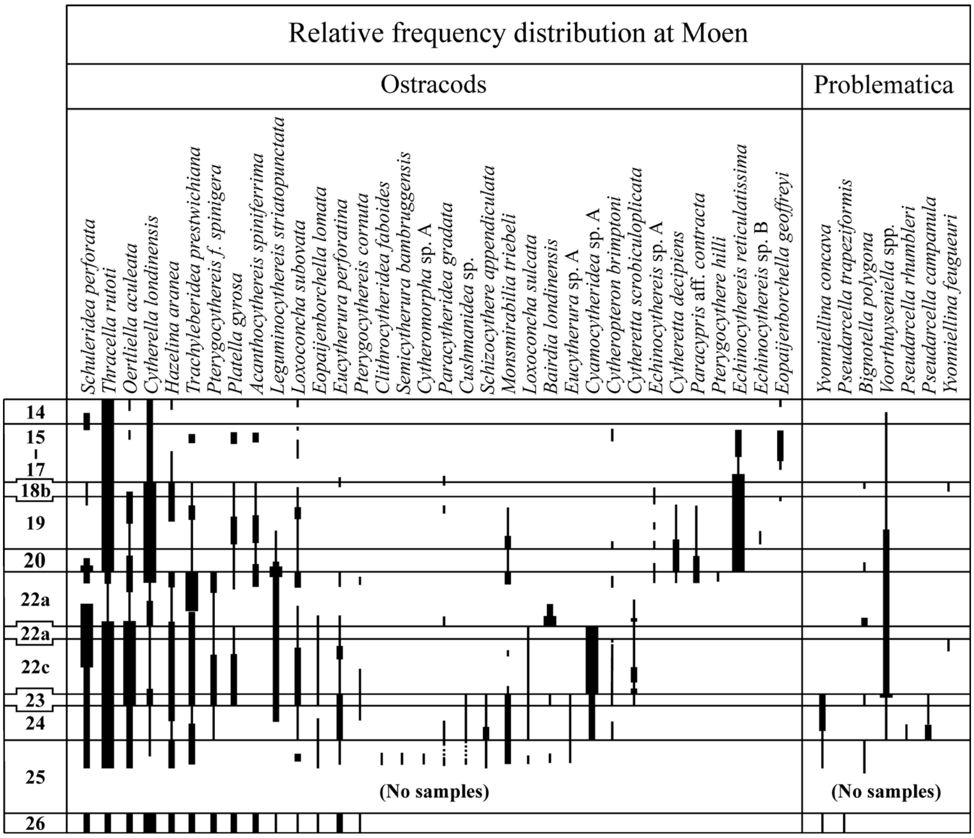


Figure 15. Ostracods and 'problematica' of the Roubaix Clay Member from the Bossuit canal section at Moen. The interval above Unit 14 was not sampled in detail and is not included here.

coeval sand units in the Upper Roubaix Member, including abundant *Haustator* cf. *solanderi*, *Varicorbula globosa*, *Goniomyrtea difficilis* and *Phacoides squamulus*.

The Upper Roubaix Member assemblages are intermediate in character between those of the Paris Basin middle Ypresian ('Cuisian': Montagne de Laon Group) and the London Clay Formation. The association of *Phacoides squamulus* and *Haustator solanderi* is characteristic of the Pierrefonds Sands, in the upper part of the Montagne de Laon Group. The characteristic 'Cuisian' taxa *Goniomyrtea difficilis* and *Caryocorbula striata* also occur in the Upper Roubaix Member. One specimen of a juvenile *Velates* is recorded in Unit 10c, presumably the characteristic Pierrefonds Sands species *V. schmiedeli*. Links with the London Clay Formation are represented by the characteristic London Clay taxa *Varicorbula globosa*, *Aporrhais* sp., and *Ispharina* aff. *sulcifera*, only previously recorded in the Hampshire Basin and London Basin (King ,1981; Jeffery & Tracey, 1997).

Pteropods are rare and poorly preserved; *Spiratella* cf. *mercinensis* (not shown on the range charts) occurs at some levels in the Upper Roubaix Member.

Two fragmentary nautiloids, with oysters attached, were recorded in Unit 7c at Marke.

5.9.3. Aalbeke Member

The only molluscs recorded from the Aalbeke Member are moulds of *Lentipecten corneum* from the silty unit (Unit 2b) in the middle of the Member. Leriche (1927) records abundant silicified turritellids ('*Turritella*' *solanderi*) in silica-cemented blocks in the basal meter of the 'P1m' clay at Stasegem, 3 km east of Kortrijk, associated with nodules containing crabs (*Zanthopsis*). According to its geographic position this clay unit would represent the base of the Aalbeke Clay, but the presence of a coquina with silicified turritellids and nodules probably indicates the highest part of the Roubaix Clay Member (probably Unit 4; similar to what has been observed at Heestert, see Fig. 8) rather than the Aalbeke Clay.

5.10. Ostracods

Several species of ostracods were described from the Ieper Formation by Keij (1957), but the first comprehensive study of Ypresian ostracods from Belgium was carried out by

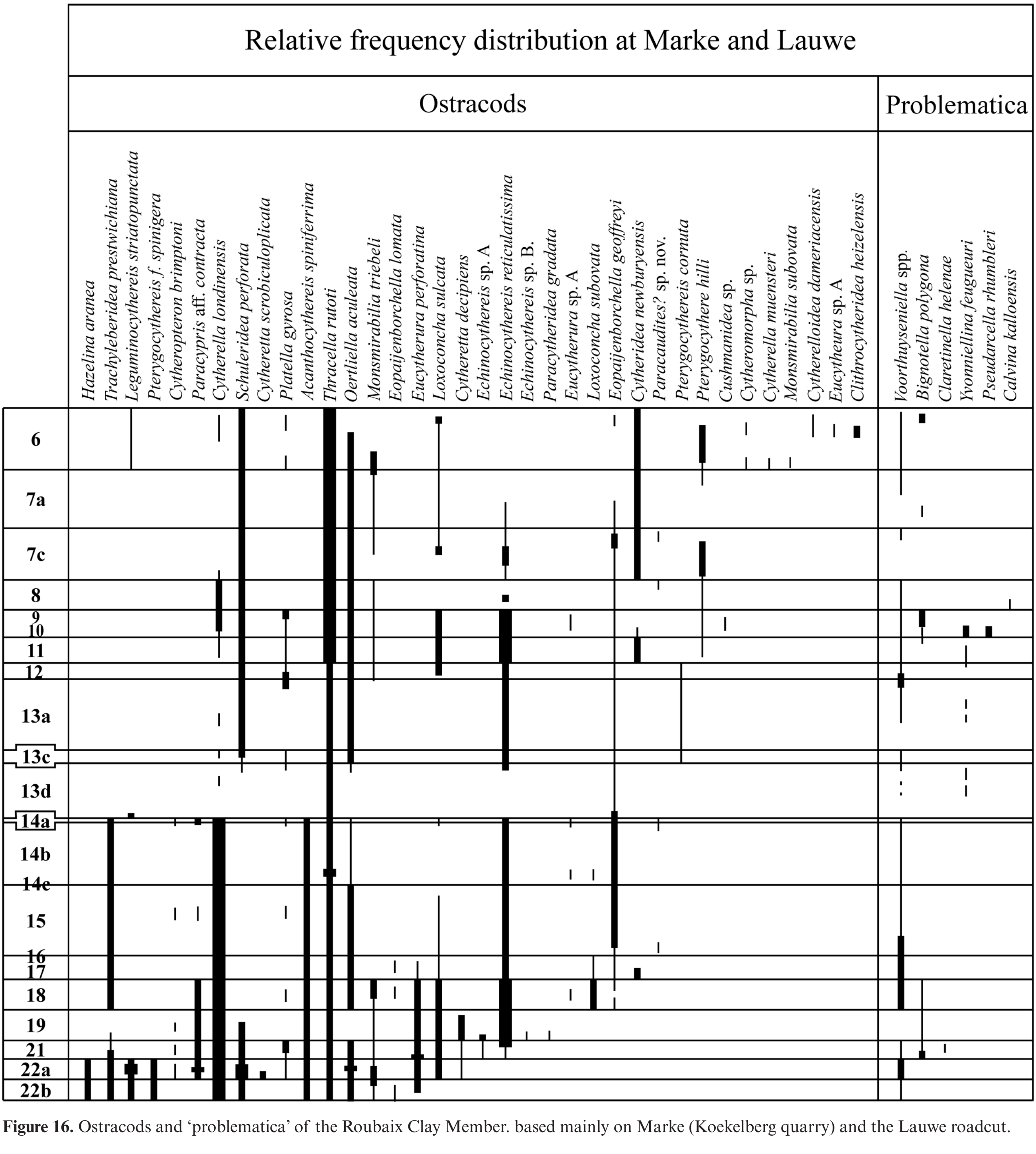


Figure 16. Ostracods and 'problematica' of the Roubaix Clay Member. based mainly on Marke (Koekelberg quarry) and the Lauwe roadcut.

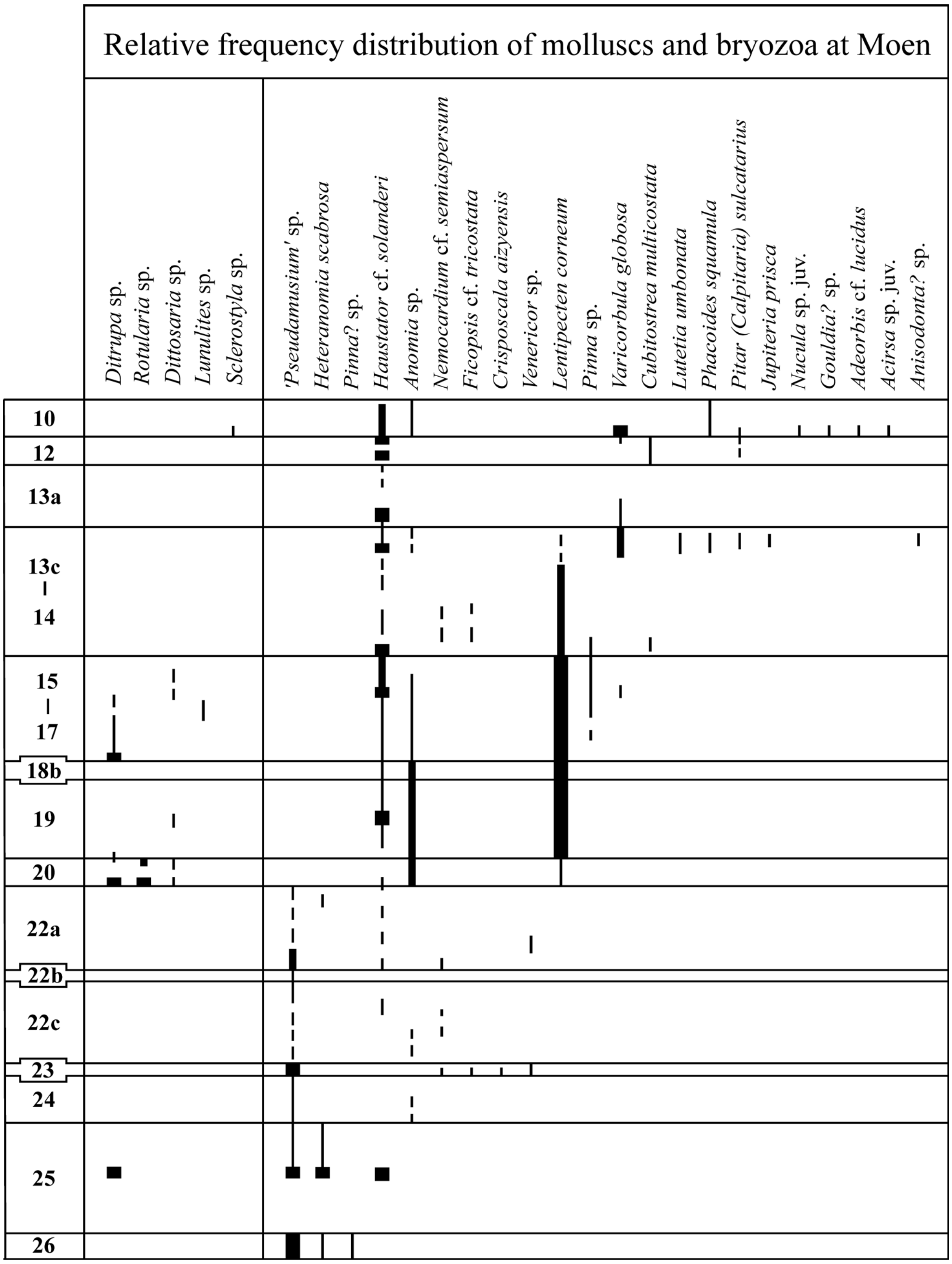


Figure 17. Molluscs, serpulids and bryozoa of the Roubaix Clay Member from the Bossuit canal section at Moen.

Willems (1973, 1977), based on samples from the Kallo and Tielt boreholes. He identified 28 taxa, almost all previously recorded from the London Clay Formation or Wittering Formation of southern England.

52 taxa of ostracods are here recorded from the Roubaix Member of the Kortrijk area (Figs 15-16). The assemblages are the most diverse so far recorded from the Ieper Group, and include a number of taxa not previously recorded from Belgium (though most of these are rare). In most samples, moderately diverse assemblages comprising between 5 - 15 taxa are recorded (Fig. 19). The highest ostracod diversity recorded is 23 taxa, in Unit 24 at Moen.

The dominant ostracod taxa in the Roubaix Member are *Cytherella londinensis* (restricted to Units 26-14), *Thracella rutoti* (throughout the section, but most abundant in Units 11 - 6), and *Echinocythereis reticulatissima* (in Unit 20 and above).

Cytheretta scrobiculoplicata is recorded only in Units 23 and 22. *Cyamocytheridea* sp. A (King, 1989; Steurbaut & King, 1994) occurs only in Units 22b - 24. It is abundant in Units 22a and 22b. *Leguminocythereis striatopunctata* occurs in Units 20-25, and reappears in Unit 6.

Echinocythereis has its lowest occurrence in Unit 21b at Marke and Zwevegem; *E.* sp. A (King, 1989) and *E. reticulatissima* apparently occur together at this level at Marke, but at Zwevegem *E.* sp. A apparently has its lowest occurrence below *E. reticulatissima*. At Moen, *E.* sp. A occurs also in the highest part of Unit 22, but this is believed to be due to contamination by burrowing from the base of Unit 21. *E.* sp. A ranges up to the top of Unit 19 at Moen; at Marke Unit 19 is partially cemented, and preservation is too poor for positive identification of this taxon. *E. reticulatissima* occurs commonly up to Unit 7b.

A group of taxa are restricted to the Lower Roubaix Member and the lower part of the Upper Roubaix Member (up to Unit 14 in the case of some taxa). They include *Acanthocythereis spiniferrima*, *Cytheretta decipiens*, *Eopaijenborchella lomata*, *Eucytherura perforatina*, *Hazelina aranea*, *Pterygocythereis fimbriata spinigera* and *Trachyleberidea prestwichiana.* There is a prominent faunal break at the top of Unit 14 (well-defined at Marke, but less clear at Moen due to wider spaced sampling at this level). It is marked by an abrupt decrease in diversity, associated with the highest occurrence of *Acanthocythereis spiniferrima* and *Trachyleberidea prestwichiana*.

There is a distinctive assemblage in Unit 6, characterised by several taxa restricted to this unit, including *Clithrocytheridea heizelensis*, *Cytherella muensteri*, *Cytherelloidea dameriacensis*, *Cytheromorpha* sp. and *Monsmirabilia subovata*, associated

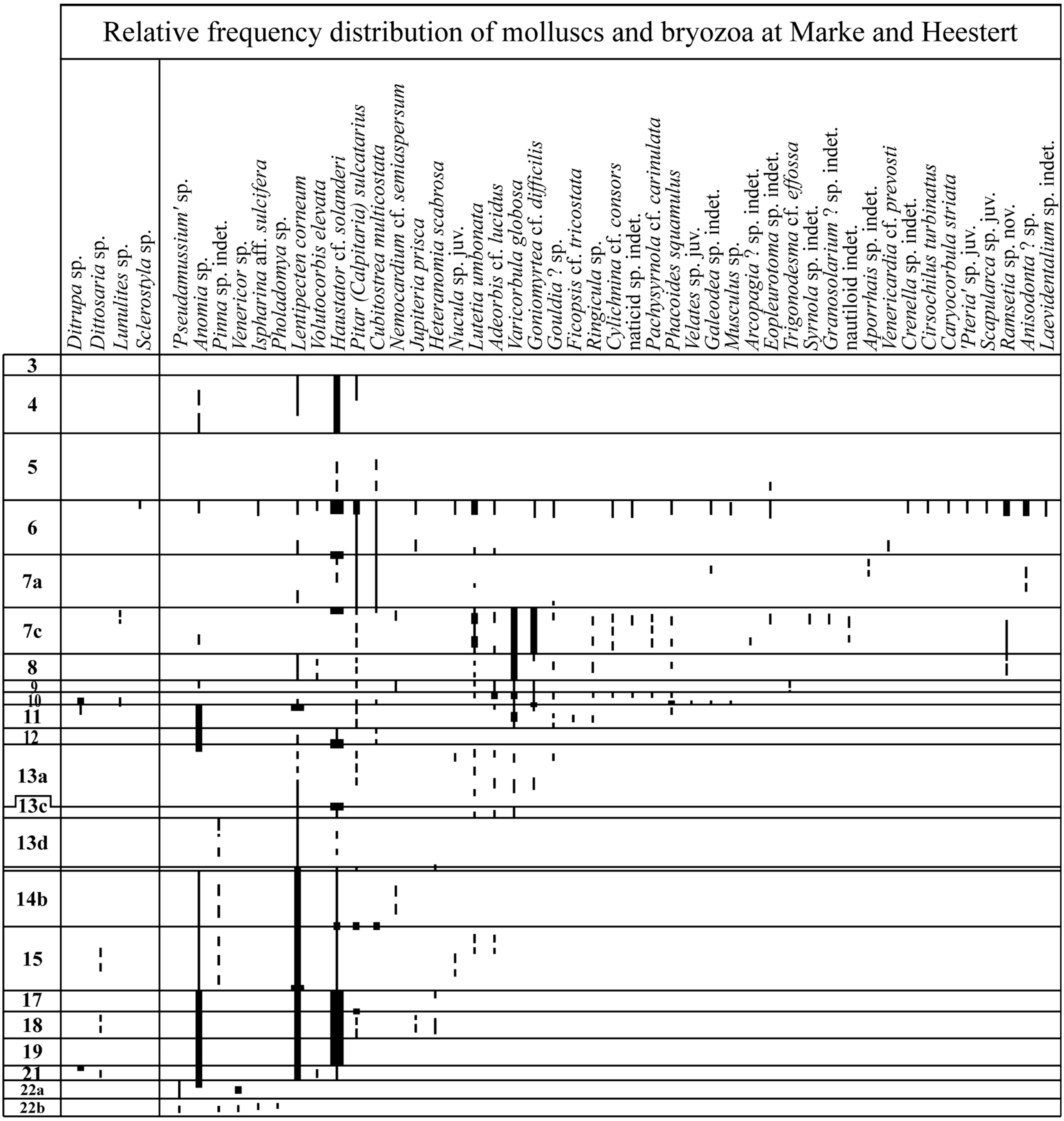


Figure 18. Molluscs, serpulids and bryozoa of the Roubaix Clay Member. based mainly on Marke (Koekelberg quarry) and the Lauwe roadcut, with data from Units 4 and 3 taken from the Heestert (Kwadestraat) section.

with the reappearance of *L. striatopunctata.*

There is an abrupt faunal break at the top of Unit 6; only very rare ostracods are recorded in Units 5 to 3.

It is clear that many of the vertical distribution patterns observed are environmentally controlled, as most taxa have longer or differing ranges in other areas (e.g. in the London Clay Formation), but they have potential for detailed correlation within the Roubaix Formation, as indicated by preliminary results from other localities (e.g. Bailleul and Mont Saint-Aubert borehole: unpublished data).

The assemblages in Units 26, 23 and 22 correspond to ostracod assemblage (faunizone) 2 of Willems (1973), characterised by the occurrence of *Cytheretta scrobiculoplicata*, *Hazelina aranea,* etc., and to the *C. scrobiculoplicata* zone of Keen (1978) in the London Clay Formation. The assemblages in Units 21b to 7 can be assigned to ostracod assemblage 3 of Willems (1973), characterised by the occurrence of *Echinocythereis reticulatissima*, and to the *E. reticulatissima* zone of Keen (1978).

The assemblage in Unit 24 is comparable in overall composition to the assemblage in the lower part of the Mons-en-Pévèle Sand Formation in the Mont-Panisel borehole (Steurbaut & King, 1994), a comparison enhanced by the rare occurrence of *Clithrocytheridea faboides*, *Cytheromorpha* sp. A and *Semicytherura bambruggensis.* These taxa all occur in the Mons-en-Pévèle Formation, but are not known elsewhere in the Roubaix Formation.

5.11. Decapod crustaceans

Carapaces of the crab *Zanthopsis* occur quite commonly in phosphatic nodules at several levels in the Roubaix Member, particularly in Units 22, 21, 6a and 4 (see Figs 5 - 6). Rare crustaceans in similar preservation have been collected at the base of the Aalbeke Member at Heestert, including fragments of lobsters. Van Bakel et al. (2006) recorded common *Zanthopsis* cf. *leachii* (Desmarest, 1822) and rarer *Linuparus scyllariformis* (Bell, 1857) at Marke.

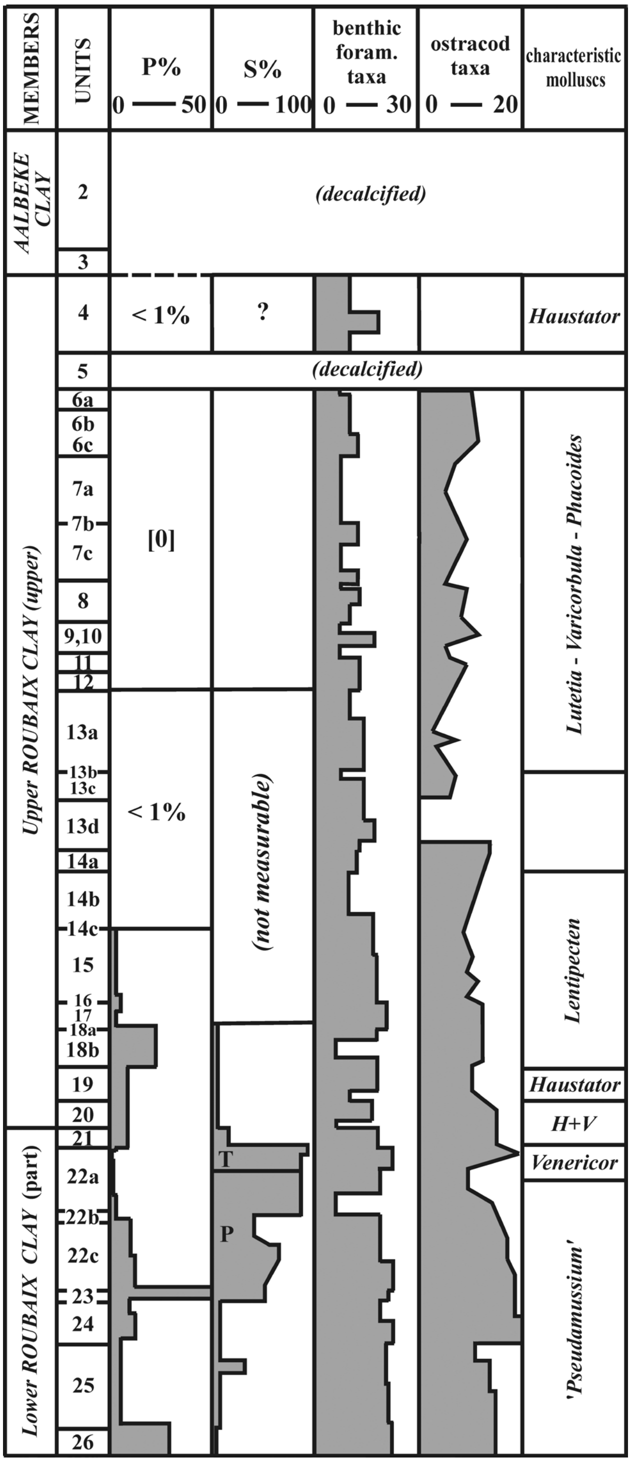


Figure 19. Features of the foraminiferal, ostracod and mollusc assemblages in the Kortrijk area. Based on the Marke (Koekelberg quarry), Bossuit and Heestert sections. P: planktonic foraminifera as a proportion of the total foraminiferal numbers. S: *Subbotina* spp. as a proportion of the total planktonic foraminiferal numbers. T: '*S. triangularis*' - dominated interval. P: '*S. patagonica*' - dominated interval (see text for details).

5.12. Vertebrates

Chondrichthyan teeth and toothplates, mainly of odontaspids and myliobatids, have been recorded at several levels in both the Lower and Upper Roubaix Member, concentrated in shell beds and the erosionally based Unit 20. Systematic sampling for smaller teeth has not been carried out during the present study. Casier (1950) illustrated an associated series of teeth of the shark *Lamna obliqua subserrata* (Agassiz, 1843) from the 'P1m clay' at Aalbeke. It was collected in a clayey deposit, at approximately 2.50 m depth in the Sterreberg claypit, which according to its stratigraphic and geographic position has to be included in the Aalbeke Member. No other vertebrates are recorded from this unit. Specimens from the Roubaix Member in the Bossuit canal section have been included in a series of taxonomic revisions of Eocene fish faunas of Belgium (Herman, 1979, 1982, 1984). Iserbyt & De Schutter (2012) recorded 36 species from Units 4 and 7 in the Marke (Koekelberg) quarry and discussed their palaeoenvironmental implications.

Teleost otoliths occur in low numbers in most units, and are common in some shell beds and glauconitic units. Otoliths from the Bossuit-Kortrijk canal (Moen), the Aalbeke, Heestert and Lauwe quarries and E17 motorway cutting near Kortrijk were included in a general study of Belgian Ypresian otoliths by Steurbaut & Nolf (1991). No material from Marke has been studied, but assemblages here are probably similar. The samples from Moen (see Steurbaut & Nolf, 1986, fig. 3) were apparently collected from Units 22c/23 and 13. All samples studied contain similar assemblages, dominated by the ophidiid *Glyptophidium polli* (Casier, 1946). Samples cited by Steurbaut & Nolf from the Upper Roubaix Member at Bailleul and Halluin (France) also contain comparable assemblages.

The dominance of *G. polli* (comprising >80% of the assemblage in most samples) is characteristic of the Upper Roubaix Member (and at least the uppermost part of the Lower Roubaix Member), and of the coeval upper part of the Mons-en-Pévèle Formation. Quite distinct otolith assemblages occur in the younger Egem Sand Member (Steurbaut & Nolf, 1991).

5.13. Microfaunal events

King (1991b) identified nine biostratigraphic events within the middle Ypresian of northern France and southwest Belgium, designated **I** (for Ieper), **I1** to **I9**. Events **I5** to **I9** were identified in outcrops in the Kortrijk area (Fig. 21).

Event I4. The relatively high planktonic foraminiferal abundance at the base of the exposed interval (in Unit 26) indicates that this lies just above the planktonic foraminiferal influx defining event I4**.**

Event I5 was originally defined by the combined acme occurrences of *Asterigerina bartoniana kaasschieteri* and *Subbotina* gr. *linaperta* [now *S. rosnaesensis*]. The more detailed analysis now carried out has shown that the *A. b. kaasschieteri* acme corresponds to the lowest occurrence of abundant *Subbotina* (base of the '*Subbotina*-dominated interval'). The latter event is now regarded as the more reliable marker, with the *A. b. kaasschieteri* acme being used as a supplementary criterion. At Moen, the influx of *Subbotina* occurs at the base of Unit 23.

Event I6 was defined by a decrease in the percentage of planktonic foraminifera (**P**) from >10% to c. 2%. This was equated with the highest important glauconite bed in the middle of the Kortrijk Formation (defining the base of the Upper Roubaix Member), but the enhanced detail now available indicates that it lies slightly above this level. In the Kortrijk area, it occurs at the base of Unit 18a.

Event I7 was defined by an influx of the benthic foraminiferal taxon *Textularia smithvillensis*. This occurs in Unit 14c at Marke. At Moen, it apparently occurs at the same level, but this is slightly uncertain due to limited sampling in this interval.

Event I8 was defined by the highest occurrence of *Echinocythereis reticulatissima.* This occurs in Unit 7a at Marke. The highest occurrence of *T. smithvillensis* is at approximately the same level.

Event I9 was defined by the highest occurrence of calcareous microfossils in the middle Ieper Formation (now the Kortrijk Formation). It corresponds to the contact of the Roubaix Clay with the Aalbeke Clay.

6. Magnetostratigraphy

The magnetostratigraphy of several Ypresian sections in Belgium was studied by Ali (1989) as part of a regional

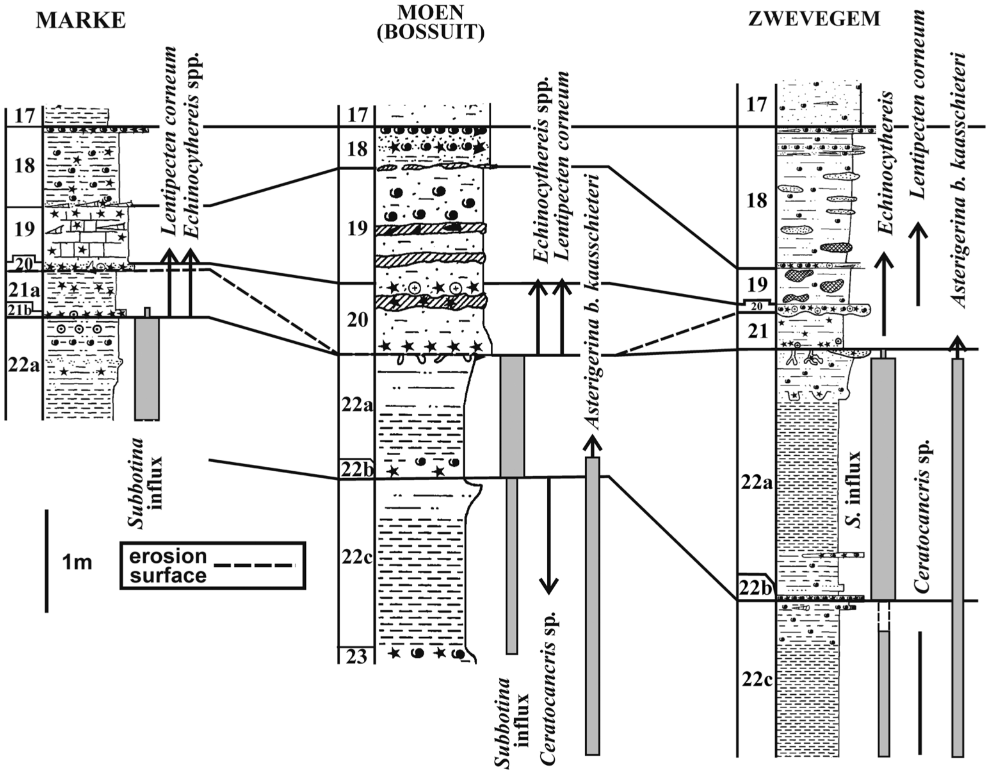


Figure 20. Details of the interval including the erosion surface at the base of Unit 20. Horizontal datum is the base of Unit 17.

magnetostratigraphic study of the Ypresian in the southern North Sea Basin. The results were summarised by Ali et al. (1993). The sections studied in the Kortrijk area were Moen, (Bossuit), Heestert, Marke (Koekelberg quarry) and Moeskroen (Bois Fichau quarry). The original data have been recalibrated to the revised sections presented in this study (Figs 21 - 22), based on section logs recorded by one of the present authors (C.K.) during the original fieldwork.

In the original study of the Marke (Koekelberg) quarry, the section was incorrectly correlated across a minor fault; there is thus an interval of 3.5 m (within Units 13 - 15) for which no data is available. This interval has been interpreted from the samples analysed through the corresponding interval at Moen.

The revised interpretation is as follows:

a) The *base of Chron C24n.1n* (formerly Chron 24AN; Ieper-2 normal magnetozone of Ali et al., 1993), is difficult to identify due to unreliability of the data at this level, but lies at or below the base of Unit 23 at Moen. Correlation with data from Wardrecques (northern France) (King, 1991b; Ali, 1989; Ali et al., 1993) suggests that the base of this normal polarity interval is slightly below event I5, which coincides approximately with the base of Unit 23 at Moen. As Unit 23 is probably significantly condensed, its base is tentatively calibrated with the base of C24n.1n.

b) The *top of Chron C24n.1n* lies between the base of Unit 17 and the middle of Unit 15, based on the combined data from Moen and Marke.

c) The *base of Chron C23n* (Ieper-3 normal magnetozone of Ali et al., 1993) is within the lowest Aalbeke Member at Heestert. Identification of the Aalbeke Member at the top of the Marke section by Ali et al. (1993, p. 114) was erroneous, as Units 4 and 5, which represent the top of the Roubaix Member but are decalcified here, were thought to be part of the Aalbeke Member. The reverse polarity recorded in these units is in line with the observations made at Heestert.

7. Depositional environments

7.1. General features

King (1991b, p. 369) recognised three major lithofacies belts within the middle Ieper Formation (Roubaix Member as currently classified). The Kortrijk area lies within the 'intermediate' facies belt, characterised by silty clays with interbeds of sandy clays and sandy silts, with diverse benthic calcareous microfaunas and common molluscs. It lies between a proximal sand-dominated facies belt to the south and east (Mons-en-Pévèle Sand Formation), and a distal more homogenous clay facies to the northwest. Water depths of around 50 to 100 m were suggested for this lithofacies on the basis of the fish fauna (Steurbaut & Nolf, 1991), but, according to the data presented here, this is probably an overestimation and certainly an oversimplification, as the palaeoenvironmental conditions had been fluctuating substantially throughout the Roubaix Clay.

The generally fine-grained sediments indicate deposition mainly below fairweather wavebase. The sand units are interpreted as 'tongues' of the Mons-en-Pévèle sand facies, prograding in response to episodically lowered sea levels. These oscillating shoreface sands likely represent significantly shallower water depths.

7.2. Biofacies

In the Kortrijk area, almost all units within the Roubaix Member contain benthic foraminiferal assemblages of the 'APA' type (King, 1984), characterised by the association of *Anomalinoides* and *Pulsiphonina*, with very low proportions of nodosariids (excluding lenticulinids). Similar assemblages characterise much of the London Clay Formation in the Hampshire Basin (King, 1991a) and the upper London Clay Formation in the eastern London Basin (King, unpublished data), and are interpreted as indicating water depths of 20 - 100 m (mid-neritic).

7.2.1. Lower Roubaix Member and lower part of Upper Roubaix Member (Units 26 - 14)

This interval is characterised by the consistent occurrence of planktonic foraminifera (**P** > 10% at most levels), and dominantly 'mid-neritic' ostracod assemblages, including *Cytherella londinensis*, *Cytheretta scrobiculoplicata*, *Hazelina aranea* and *Trachyleberidea prestwichiana.* Detailed correlation between **P** and water depths is uncertain as **P** reflects the influence of oceanic watermasses rather than being directly depth related, but values of **P** > 10% are seen in the middle London Clay Formation in the central and eastern London Basin, where water depths of >50 m are probable (King, unpublished data).

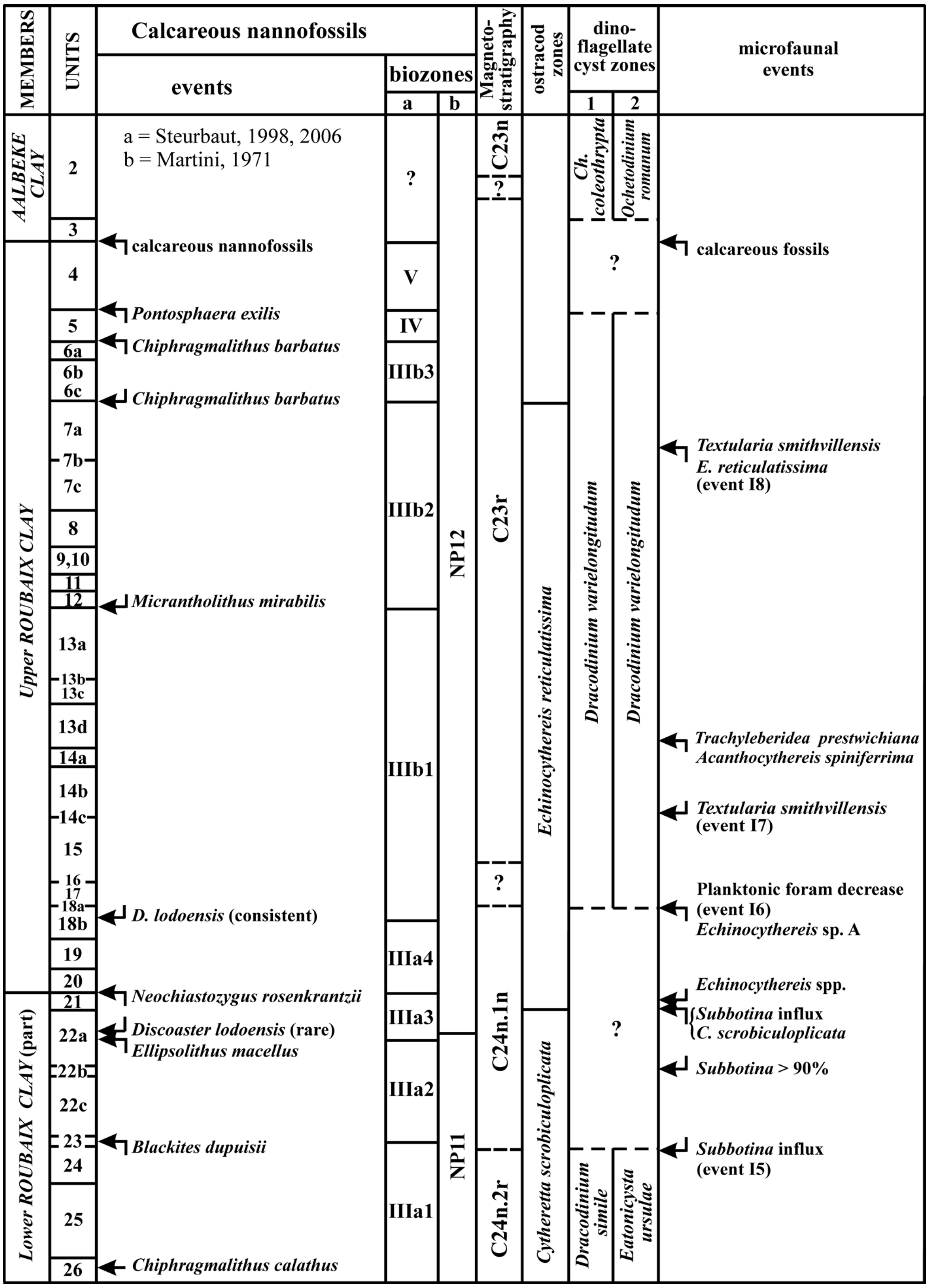


Figure 21. Biostratigraphy and magnetostratigraphy of the upper Kortrijk Clay Formation in the Kortrijk area (based on a combination of the Marke and Moen composite sections). Dinoflagellate cyst zones: 1. Costa & Downie (1976) [*Ch*: *Charlesdowniea,* originally cited as *Wetzeliella*]; 2. De Coninck (1991). Calcareous nannofossil zones: a. Steurbaut, 1998; b. Martini, 1971.

The greatest water depths, as determined from the faunal assemblages, were during deposition of Units 23 - 21. In the benthic microfaunas this is indicated by the occurrence of the ostracods *Cytheretta scrobiculoplicata* and *Hazelina aranea*, and the nodosariid foraminifera *Percultazonaria wetherellii* (only in the Ooigem borehole) and *Pyramidulina latejugata*, which characterise the deepest water environments (mid-outer neritic) in the London Clay Formation of the Hampshire Basin (King, 1981, 1991b). Proportions of planktonic foraminifera are also relatively high through much of this interval, reaching c. 50% during Unit 23. The influx of *Subbotina*, a dominantly thermocline and sub-thermocline dweller, in Units 22 and 23, supports this interpretation, although elsewhere this event does not appear to be directly related to an increase in water depths (King et al., 2013), and may be due to other factors.

The prominent influx of *Asterigerina [bartoniana] kaasschieteri* in the mid Ypresian of Belgium, in Units 24 to 22 in the Kortrijk area (with its termination apparently varying slightly between sections: Fig. 20) has been proposed to mark a hyperthermal event (Speijer et al., 2012).

7.2.2. Upper Roubaix Member (Units 13 - 4)

This interval is characterised by the absence or very low proportions of planktonic foraminifera, ostracod assemblages with common *Cytheridea newburyensis*, *Echinocythereis* spp. and *Thracella rutoti*, and low to moderately diverse mollusc assemblages, including shell beds. These criteria suggest water depths around 20 to 50 m, undoubtedly shallower than at lower levels. The clay units tend to be *Chondrites*-burrowed, and have relatively low-diversity microfaunal and mollusc assemblages (Fig. 17), indicating probably somewhat lowered oxygen levels. The turritellid *Haustator* and the corbulid *Varicorbula*, common at a number of levels within this interval, are both members of opportunistic families (e.g. Australian Government, 2008; Dominici et al., 2011), adapted to exploit environments unfavourable for most molluscs.

8. Sequence stratigraphy

In the North Sea Basin, the early and middle Ypresian (excluding the earliest Ypresian) comprises a major (second-order) depositional sequence, bounded by prominent surfaces representing the sequence boundaries, represented in marginal areas of the Basin by regional erosion surfaces (King, 2006). In the Hampshire and London 'Basins' this lower bounding surface is at the base of the Blackheath Formation and its correlatives, a major incised channel filling unit, which is overstepped by the overlying Harwich Formation (King, 2006). In NW Belgium it is represented by the base of the Oosthoek Sand Member (base of sequence A2 of Steurbaut et al., 2000 and Steurbaut, 2006), which represents the uppermost member of the Landen Group, just below the base of the Ieper Group, and it corresponds to surface MLD2 of Dupuis et al. (2011) in northern France. Elsewhere in Belgium the Oosthoek Sand Member and the overlying Zoute Silt Member (together equivalent to the Harwich Formation of SE England) are overstepped by the Mont-Heribu Member (base of sequence Y-B of Steurbaut, 1998, 2006), corresponding to the base of the London Clay Formation in southern England.

In southern England this surface is within the lower part of Zone NP10 (c. 55.5 Ma) (King, 2016). The initial lowstand deposits are rarely preserved, and in most areas this surface is a composite sequence boundary and transgressive surface.

The following transgressive phase terminates within the middle Ypresian, but is not sharply defined due to overprinting by higher-order sequences. The lower part of the highstand phase is marked by the maximum extension of the Ypresian sea, with high proportions of planktonic foraminifera in the more distal facies. The upper part of the Orchies Member and the Lower Roubaix Member were deposited during this interval. The succeeding highstand phase is marked by progressive progradation of more marginal sediments, including initially in Belgium the Mons-en-Pévèle Formation. The majority of the Upper Roubaix Member and overlying sediments were deposited during this phase, which was ended by a major sea-level fall in the late middle Ypresian.

The upper bounding surface is represented in southern England by the basal erosion surface of the Bracklesham Group (King, 2006), probably corresponding in Belgium to the sequence boundary at the base of the Egem Sand Member (base of sequence Y-G in Steurbaut, 1998). In the Hampshire Basin this is within Chron C23n (c. 51.5 Ma) (King, 2016).

This sequence corresponds approximately to the Paleogene 3 R/TF cycle of Neal (1996) and to the Yp 8 sequence of Hardenbol et al. (1998). Calibration of this and the higher-order sequences recognised in the North Sea Basin to the Hardenbol *et al.* sequence stratigraphic model is not discussed further, as their scheme lacks adequate published calibration to lithostratigraphic units, and is difficult to validate.

8.1. Sequence stratigraphy in the Ieper Group

Third-order depositional sequences were identified in the Mont-Panisel borehole (Mons Basin) by Steurbaut & King (1994). A comprehensive sequence stratigraphic framework for the Ypresian of Belgium was proposed by Steurbaut (1998) and Vandenberghe et al. (2004, an update of Vandenberghe et al., 1998), based largely on analysis of petrophysical logs and grain-size data. Steurbaut (1998) identified seven sequences (YA - YG), partly subdivided into lower-order sequences (e.g. Y-C1 to Y-C3). This scheme was based on many sections and boreholes, including preliminary studies of the Marke quarry and the Bossuit (Moen) section. These lower-order sequences are bounded by specific surfaces (omission surfaces, erosion surfaces, ...), which can be traced throughout the Belgian Basin (Steurbaut, 1998, figs 4 and 11), as they coincide with the bases of resistivity maxima (Rm) and gamma-ray minima on the wireline logs (Steurbaut et al., 2016b: bases of Rm 6 or layer 6, Rm 5, Rm 4, Rm 3, etc., correspond to the bases of Steurbaut's lower-order sequenes Y-C3, Y-D1, Y-D2, Y-D4, etc., respectively; see Fig. 22). Some of these lower-order sequences may have a duration of about 400 kyr, e.g. one complete sequence and two partial have been identified during Chron C23r (see Fig. 22), which according to Vandenberghe et al. (2012) has a duration of about 790 kyr. Others seem to have much shorter durations, e.g. 3 sequences in Chron C24n.3n (see Steurbaut, 1998, fig. 4), which has a total duration of 570 kyr. Each lower-order sequence consists of a series of bed sets, which may show fining-upward or coarsening-upward trends, separated by glauconite levels, glauconitic shell beds, or levels marked by conspicuous lithological changes. The subdivision of a depositional sequence into system tracts and their bounding surfaces, which has initially been introduced for the identification and interpretation of third order sequences with a duration of 1 to 10 myr (e.g. Vail et al., 1977; de Graciansky et al., 1998), also seems to be applicable to our lower-order sequences. Similar small- and medium-scale sequences, corresponding to the 100- and 400-kyr eccentricity cycles, have been identified in the Upper Berriasian-Lower Valanginian and Upper Oxfordian strata of Switserland (Strasser et al., 2000). The term 'depositional sequence' or simply 'sequence' is used here for these medium-scale sequences, which in fact represent successions of strata deposited during a full cycle of change in accommodation or sediment supply (Catuneanu et al., 2012). The sequence stratigraphic framework presented here appears to be the best fitted to the available data, although problems of interpretation remain, and many details are still to be resolved by further study.

8.2. Differentiation of sequence tracts and depositional sequences

Identification here of key surfaces and tracts, and their included parasequences (as defined by Catuneanu et al., 2012: individual prograding sediment bodies or upward shallowing successions of facies, bounded by flooding surfaces) follows criteria used by King (1981, 1991b), Steurbaut & King (1994) and Steurbaut (1998, 2006).

Sequence boundary (SB). Where the overlying LST is represented, the sequence boundary is generally an erosion surface, which may be irregular and locally deeply incised. Here it is marked by an abrupt increase in grain-size, with faunal or nannofossil assemblages indicating a decrease in water depth. Where the LST is not represented by sediments (the usual situation) the combined SB/TS is represented by an interburrowed omission surface.

Lowstand systems tract (LST). A basal lag is often present (with reworked clasts or shell concentrations), followed by relatively coarse grained glauconitic sediments (silts and sands) with features indicating wave and/or current activity (hummocky cross-stratification, lamination, minor channelling, etc.).

Transgressive systems tract (TST) Based by a sharply defined omission surface (the transgressive surface), often interburrowed, corresponding to a decrease in grain-size. The TST is generally thin, typically represented by a glauconitic shelly clay or sandy clay. The most diverse mollusc assemblages usually occur in the TST. Glauconite may be concentrated at the base. Parasequences are often difficult to differentiate due to condensation, but their boundaries may also be marked by glauconite concentrations.

Maximum-flooding surface (MFS). This is often marked by a thin glauconite concentration (the highest such level in each sequence). The highest proportion of planktonic foraminifera (if present) is in the immediately overlying interval.

Highstand systems tract (HST). This is characterised by relatively fine-grained lithofacies (clays and silty clays), tending (if sufficiently thick) to coarsen slightly upwards. Glauconite is generally absent. Parasequence boundaries are marked by thin shell beds, in some cases capping small-scale coarsening-upwards units.

8.3. Sequence stratigraphy of the Kortrijk area

Six depositional sequences are tentatively recognised (Y-D1 to Y-E2 of Steurbaut, 1998), based on the criteria summarised above (Fig. 22).

8.3.1. Sequence Y- D1 (part)

HST (Unit 26). This clay unit, with high proportions of planktonic foraminifera, indicating a mid-neritic environment, is interpreted as part of the HST of sequence Y-D1. The base is not seen.

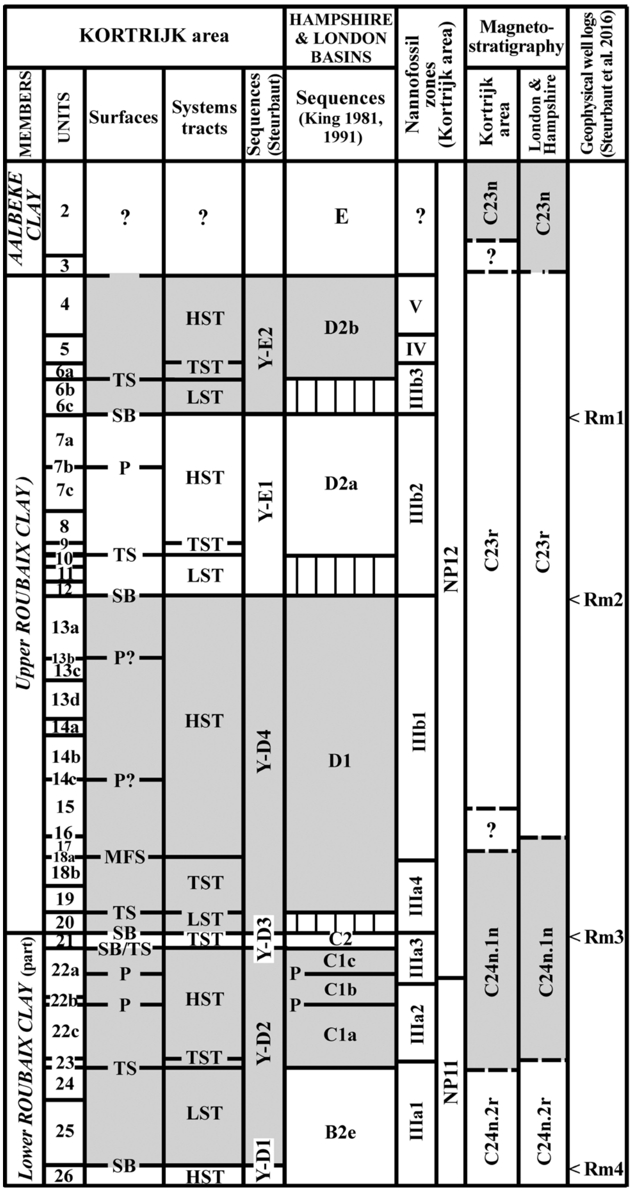


Figure 22. Depositional sequences in the upper Kortrijk Formation in the Kortrijk area, and correlation with depositional sequences in the London Clay Formation. HST: highstand systems tract; LST: lowstand systems tract; MFS: maximum flooding surface; P: parasequence boundary; SB: sequence boundary; TS: transgressive surface; TST: transgressive systems tract. Rm: base of resistivity maximum on geophysical well logs (Steurbaut et al., 2016b).

N.B. Direct stratigraphic correlation between the Kortrijk area and the Hampshire and London Basins is possible only at sequence or parasequence boundaries. The calcareous nannofossil zones (NP zones of Martini, 1971 and zonation of Steurbaut, 1998) have been recorded in Belgium, and do not refer to the English sections.

8.3.2. Sequence Y- D2 (Units 25-22)

SB: The base of Unit 25, which coincides with resistivity maximum 4 on the wireline logs (Rm 4 in Fig. 22; see also Steurbaut et al., 2016b), is a sharp and apparently planar surface (although exposure is very limited), with burrows filled by sand penetrating Unit 26. It marks an abrupt shift in facies from mid neritic clay to inner neritic sand, interpreted as a sequence boundary.

LST - ? early TST (Units 25, 24). The lower part of this sand-dominated interval is partly laminated and low-angle? hummocky cross-stratified, indicating an inner neritic environment above SWB (storm wave-base). The microfauna, including *Nummulites*, and with low proportions of planktonic foraminifera, confirms an inner neritic environment. This interval represents the LST; the upper part, bioturbated and with an increase in the proportion of planktonic foraminifera, may well represent the early TST. This interval (as for the other sand units within the Roubaix Formation) is interpreted as a distal 'tongue' of the Mons-en-Pevele Formation, prograding distally following a sea-level fall.

TST (Unit 23). A rapid decrease in sand content, accompanied by a major influx of planktonic foraminifera, is interpreted as indicating the TST. A thin shelly glauconitic layer at the top of Unit 23 is interpreted as a condensed interval representing the MFS.

HST (Unit 22). This clay-dominated interval comprises two coarsening-upward untervals (22c and 22a), separated by a thin shelly glauconitic bed (22b). These are interpreted as parasequences. A further thin glauconitic level in Unit 22a at Marke may represent another parasequence boundary. An upward decrease in the proportion of planktonic foraminifera indicates progressive shallowing, confirmed by the incoming of diffuse sandy streaks, probably representing storm-generated sand layers reworked by bioturbation. This trend culminates in a thin silty sand, recorded only in the Zwevegem sluice section.

8.3.3. Sequence Y- D3 (Unit 21)

SB: Unit 21 is represented at Marke and in the Zwevegem sluice section, but is missing at Moen, probably truncated by the erosion surface at the base of Unit 20. It has a sharp interburrowed base, with glauconite concentrations and phosphatic nodules with *Zanthopsis* immediately above. These features indicate a hiatus. Consequently, the base of Unit 21 is tentatively interpreted as a sequence boundary (Y-D3 of Steurbaut, 1998).

TST-?HST: The thin glauconite-rich fossiliferous sandy silt layer at the base of Unit 21 (21b) is probably a condensed interval, considered to represent the TST. The overlying interval (21a) may represent a condensed HST, but as the upper boundary of Unit 21 is an erosion surfcae, it has clearly been truncated, and this interval may fall entirely within the TST.

8.3.4. Sequence Y-D4 (Units 20-13)

SB: The base of Unit 20 is a prominent erosion surface, variably truncating the immediately underlying sediments. It marks an abrupt increase in grain-size of the sediment (corresponding to the base of resistivity maximum 3 on the wireline logs; Steurbaut et al., 2016b; see also Fig. 22) and the incoming of abundant coarse-grained glauconite, with frequent shark teeth, reworked ? phosphatic nodules and abraded *Nummulites*. This is interpreted as the SB. The erosional character of this surface is clearly identified by comparing the Marke, Moen and Zwevegem sections (Fig. 21), with the biostratigraphic data (also including nannofossil date cited above) confirming correlation of Units 20 to 23 between these sections.

LST- ?early TST (Units 20 and 19). The markedly varying thickness of units within this interval (Fig. 21), and its variable truncation of underlying units, suggest that it fills shallow incised channels. A basal fine glauconitic cross-bedded sand at Moen suggests a shallower, inner neritic environment, than represented elsewhere in the Roubaix Member. The complex nature of this interval, with several levels of coarse glauconite, shark teeth, abundant molluscs and several diffuse calcareous sandstone layers, amalgamated into a single calcareous sandy siltstone at Marke, indicates a variably condensed interval, with clastic starvation and intermittent sedimentation. The occurrence of abundant turritellids, *Nummulites* and miliolid foraminifera confirms an inner neritic environment. The high numbers of the nannofossil *Braarudosphaera bigelowii* seems to suggest hyposaline conditions. This is the second 'tongue' of the Mons-en-Pevele Formation.

TST (Unit 18). An abrupt increase in the proportion of planktonic foraminifera at the base, with the incoming of a more diverse mollusc assemblage, indicates deepening. Unit 18a (the 'black *Lentipecten*' shell bed), at the top of this interval, is interpreted as a condensed interval marking the MFS.

HST (Units 17-13). The decrease in grain-size at the base, with a major decrease in planktonic foraminifera, and the disappearance of glauconite (except as very fine grains in the lower part), marks the base of the HST. Several thin shell beds in this interval probably represent condensation at parasequence boundaries.

8.3.5. Sequence Y-E1 (Units 12-7)

SB: The base of Unit 12 is a sharp planar surface, with burrows penetrating the underlying unit. It marks an abrupt increase in grain-size (from clay to sand), which corresponds to the base of resistivity maximum 2 on the wireline logs (Steurbaut et al., 2016b; see also Fig. 22). Microfaunas and sedimentological characteristics indicate a major fall in base-level at this level. This is is interpreted as the SB.

LST (Units 12 -10). This interval of fine sand, partly laminated, with thin shelly layers and some clay laminae, and a microfauna including *Nummulites*, indicates deposition in an inner neritic environment, above SWB. It represents the third tongue of the Mons-en-Pévèle Formation.

TST (Unit 9). This sparsely glauconitic sandy clay is tentatively interpreted as the TST.

HST (Units 8 and 7). Silty clay/clayey silt with laminae and lenses of, partly reworked by bioturbation, indicate deposition above SWWB. This coarsens upwards into sandy clayey silt, with several decimetre-scale beds of laminated silt, indicating progressive shallowing. A thin shell-bed with abraded oysters, in the middle of this interval (Unit 7b), is probably also a storm-generated unit.

8.3.6. Sequence Y-E2 (Units 6-4)

SB: The basal surface of Unit 6 is undulating and marked by an increase in grainsize, accompanied by abundant molluscs and dispersed glauconite. It is believed to correspond to the base of resistivity maximum 1 on the wireline logs (Steurbaut et al., 2016b; see also Fig. 22). Although not as sharply defined as underlying sequence boundaries, this is interpreted as the SB.

LST? (Units 6c and 6b). The basal thin (10 cm) shelly sand, with oysters, turritellids and *Nummulites*, and the overlying slightly coarsening upward silty sand (85 cm), indicating an inner neritic environment, may represent the LST.

TST (Unit 6a). The occurrence of glauconite, common and diverse molluscs and phosphatic nodules in this thin unit (0.4 m) indicates slow and probably interrupted sedimentation. Common phosphatic nodules at the top are interpreted as representing the MFS.

HST (Units 5 and 4 and ? Aalbeke Clay, see below). This interval coarsens upwards from clay to sandy silt with diffuse laminae and lenses of very fine sand. The microfauna indicates a mid neritic environment, with molluscs and lithology suggesting upward shallowing from ? middle to inner neritic. A flood of small pyritised planktonic foraminifera is recorded in one sample from Unit 5; this may represent the MFS, but only limited sampling was carried out in this interval. This interval is interpreted as the HST, although the occurrence of dispersed phosphatic nodules in Unit 4 is somewhat unusual. However the boundary between Unit 5 and Unit 4 seems transitional.

8.3.7. Aalbeke Clay (Units 3-2)

The sequence stratigraphic interpretation of the Aalbeke Clay is still uncertain as the characteristics of the basal surface are not consistent throughout the studied section. At Heestert this is marked by phosphatised burrow-fills, not recorded at Marke, Aalbeke and Mouscron, but here and elsewhere it is not sharply defined. This surface may represent a SB, but could also been interpreted as a MFS. The Aalbeke Member is a rather homogenous silty clay, with a thin diffuse sandy silt in the middle. It is decalcified and its depositional environment is uncertain.

8.3.8. Mont-Panisel Sand Member (Unit 1)

The base of the overlying Mont-Panisel Sand Member is a sharp and deeply interburrowed surface marking an abrupt contact between silty clay and clayey glauconitic sand. This is the sequence boundary defining the base of sequence Y-G (Steurbaut, 1998, 2015).

9. Correlation between the Roubaix Clay Member and the London Clay Formation

9.1. Depositional sequences in the London Clay Formation

Early Eocene clays, the equivalent of the Kortrijk Formation and the lower part of the Tielt Formation, extend across the southern North Sea and are represented in southern England by the London Clay Formation. The London Clay Formation is mainly argillaceous in more distal areas such as the eastern London Basin, further west but includes an increasing proportion of coarser-grained units (silts and sands), indicating a more proximal environment in the western London Basin and the Hampshire Basin (King, 1984, 2006). It should be noted that the 'Hampshire Basin' and 'London Basin' are largely post-Eocene structural features and not sedimentary basins; they are part of the North Sea Basin (see King, 2006).

King (1981, 1984, 2016) identified five major transgressive-regressive 'cycles', (designated 'divisions' A to E), in the London Clay Formation, partly subdivided into 'subsequences', delimited by prominent basal transgressive surfaces. Lithostratigraphic and biostratigraphic criteria were used to correlate the major surfaces throughout the Hampshire and London Basins. Plint (1988) recognised that localised erosionally-based sand units underlying these surfaces, developed mainly within the relatively proximal environments in the Hampshire Basin, were incised lowstand units deposited following falls in sealevel.

Further detailed study has been carried out in the Hampshire Basin (King, 1989) and the central and eastern London Basin (King, 2016). This has enabled recognition and correlation of further lower-order surfaces, including parasequence boundaries. A more comprehensive overall view of the sequence stratigraphy is now possible, although the complexity of the stratigraphic record means that identifying the hierarchy of sequences and parasequences is not always clear. Similar problems are encountered in the Ypresian of Belgium.

Correlation of the London Clay Formation with the standard chronostratigraphic scale has been achieved through a combination of magnetostratigraphic, dinoflagellate cyst and nannofossil data (Aubry, 1986; Aubry et al., 1986; Ali et al., 1993; King, 2016). Chrons C24r, C24n.3n, C24.2r and, C24.1n, C23r and C23n have been identified in the London Clay Formation (Ali, 1989; Ali et al., 1993; King, 2016), mainly in the eastern London Basin and partly in the Isle of Wight (Hampshire Basin). The identification of sequence and parasequence boundaries in the eastern London Basin is difficult due to the relatively distal environment, and the latest revision (King, 2016) has slightly modified the relationship of some boundaries to the magnetostratigraphic record, as noted below.

9.2. Correlation between the London Clay Formation and the Ieper Group

King (1981, 1990, 1991b) proposed biostratigraphic correlations between the London Clay and the Ieper Group of northern France and Belgium, based on diatoms, benthic and planktonic foraminifera, ostracods, pectinid bivalves and pteropods. Divisions A2, A3, B, C, D and E were identified biostratigraphically, although only the lower boundaries of A2, A3 and E could be identified lithologically in Belgium. These correlations were subsequently partially confirmed by magnetostratigraphy (Ali, 1989; Ali et al., 1993). The data now available from the Kortrijk area permits a re-evaluation and refinement of the proposed correlations (Fig. 22).

Division A2

Recent investigation of the Mont-Héribu Member (Steurbaut, unpublished information) has shown that this unit only corresponds to the lower part of Division A2 , and not to its entire stratigraphic range, as previously assumed (King, 1990).

Division A3

The base of Division A3 is close the the lowest occurrence of *Dracodinium simile* (King, 2016). This taxon is very rare in the Belgian Basin (Demey, 2016, p. 50), but its lowest occurrence seems to be very close to the lowest occurrence of *Phthanoperidinium echinatum* (De Coninck, 1991). This event is known to occur at approximately 355 m in the Kallo borehole (Demey, op. cit.) and at ~380 m in the newly drilled ON-Kallo-1 borehole, and falls right in the middle of the Orchies Clay Member. This contrasts with earlier interpretations that the base of Division A3 coincides with the base of the Orchies Clay Member (King, 1990).

Division B1

King (1990) concluded that microfaunal event **I1**, within the Wardrecques Member [as then defined], marked by a change from dominantly agglutinating foraminiferal assemblages to diverse calcareous microfaunas, including the first appearance of 'deepwater' nodosariids, could be correlated with the transgressive event defining the base of Division B, at which similar assemblages appear in the London Basin. Further study has however revealed the presence of calcareous benthic foraminifera, although poorly preserved, within the upper part of the underlying interval at Wardrecques, and (well-preserved) in correlative intervals in Belgium, including the characteristic nodosariid foraminifera. From these records, event **I1** probably corresponds approximately to the base of Division B2. In the lithostratigraphic classification used here, this is close to the base of the Roubaix Member. This event is not exposed in the Kortrijk area, but is identified in the Ooigem and Mouscron boreholes, as noted above.

Division B2

Parasequences B2a - B2d.

The lower part of B2 is only exposed in the Dottignies section (King, 1990, fig. 7). Here the presence of *Textularia smithvillensis* indicates correlation with parasequences B2a or B2b (King, 1991a).

Parasequence B2e.

A planktonic foraminiferal influx at the base of B2e, identified in the London and Hampshire 'Basins' (King, 1989; King, 2016) can be correlated with the planktonic foraminiferal influx defining event **I4**. The LST / early TST represented by Units 25 and 24 can be correlated with the LST/early TST recently identified at the top of Division B2 in the Hampshire Basin, where it is represented by glauconitic sands including the '*Barnea* Bed' and the '*Lingula* sands' (King, 1981, 2016; Kemp & King, 1995).

Division C1

Parasequence C1a.

The base of chron C24AN (now C24n.1n) was identified within division C1 in the Warden Bay borehole, Isle of Sheppey (Ali et al., 1993, fig. 6). There is some uncertainty as to its exact position, due to the occurrence of two apparently reversed samples in the lower part of this normal interval. Current revision of London Clay Formation stratigraphy in the eastern London Basin suggests that the base of C1 in this area (as identified biostratigraphically; in this distal area there is no significant lithological change at the contact) is slightly higher than originally thought. It is probable that the base of Chron 24n.1n in the Isle of Sheppey is c. 2 m above the base of C1, if the two reversed samples at a slightly higher level are regarded as a minor event within C24n.1n. In the Kortrijk area, the base of C24n.1n is probably at the base of Unit 23. There is an influx of *Subbotina* at (or just above) the transgressive surface defining the base of Division C1. This is identified in both the Hampshire and London Basins (King, 1989, unpublished data). It can be correlated with the *Subbotina* influx at the transgressive surface at the base of Unit 23 (event **I5**).

In both the London Basin and the Kortrijk area the base of C24n.1n corresponds approximately to the inception of the *Subbotina* influx, confirming the correlation between these areas. Thus both magnetostratigraphy and biostratigraphy confirm that the base of the TST of Sequence Y-D2 can be correlated with the transgressive surface defining the base of Division C1.

Parasequence C1b.

The increase in dominance of *Subbotina* in Unit 22b to >90% can be identified in the London Basin, at the base of parasequence C1b (C. King, unpublished data). Thus the parasequence boundary at the base of Unit 22b is correlated with the base of C1b. The change in the *Subbotina* population from '*patagonica*' - dominated to '*triangularis*' - dominated forms, which occurs in the Kortrijk area within the middle of Unit 22a, has recently been identified in both the Hampshire and London Basins (C. King, unpublished data), in the upper part of parasequence C1b.

Parasequence C1c.

The latest occurrence of *Cytheretta scrobiculoplicata* in the London and Hampshire Basins is within parasequence C1c (King, 1989, unpublished data). This species has its last occurrence in the Kortrijk area in the lower part of Unit 22a. This suggests that the parasequence boundary within Unit 22a may correspond to the base of C1c.

Division C2

The *Subbotina* influx terminates abruptly in the eastern London Basin at the top of Sequence C1. Its equally abrupt termination in the Kortrijk area (although here probably at a minor hiatus) is at the top of Unit 22. Thus the prominent glauconitic level at the base of Unit 21 (base of sequence Y -D3) probably correlates with the transgressive surface at the base of C2. In the London Basin and the Hampshire Basin, *Echinocythereis* sp. A occurs only in parasequence C1c. The first occurrence of *E. reticulatissima* is just above the base of division D1. In the intervening interval (sequence C2), *Echinocythereis* has not been recorded. However, in the Kortrijk area, both taxa appear at the same level, and coexist through Unit 21 to Unit 19 (? where *E.* sp. A is reworked). This suggests that the overlap in their ranges in Unit 21 correlates with division C2, although ecological factors may be involved.

The probably condensed and complex nature of the interval including Units 21 - 19 means, however, that correlation of this interval is still tentative.

The prominent erosion surface and sequence boundary at the base of Unit 20 (base of Y-D4) is correlated on the basis of its stratigraphic context with the sequence boundary within the upper part of C2, at the base of the Portsmouth Member in the Hampshire Basin (King, 1981, 1989). The Portsmouth Member marks the earliest occurrence in the London Clay Formation of deeply channelled estuarine sands. This suggests a major sea-level fall, comparable in magnitude to the corresponding event in the Kortrijk area.

Division D1

The base of the TST of sequence Y-D4, either at the base of Unit 19 or Unit 18, can probably be correlated with the transgressive surface at the base of Division D1.

The base of Chron C23r in the Isle of Sheppey was placed within Division C2 by Ali et al. (1993). However recent revision of the lithostratigraphy (unpublished data) indicates that here it lies c. 8 m above the base of Division D1. At Kortrijk, it is between the middle of Unit 15 and the base of Unit 17. The HST represented by Units 17 to 13 can therefore be correlated with the HST of division D1.

The sequence boundary at the base of Unit 12 (base of sequence Y - E1) can probably be correlated with the sequence boundary within Division D1, at the base of the Whitecliff Member in the Hampshire Basin (Plint, 1988; King, 1989), on the basis of its stratigraphic context.

Division D2

The transgressive surface at the base of Unit 9 is tentatively correlated with the base of Division D2. In the London Basin, two subsequences can be differentiated within D2. The HST comprising Units 8 and 7 can thus probably be correlated with the HST of the lower subsequence (D2a). The sequence boundary at the base of Unit 6 (base of sequence Y - E2) is tentatively correlated with the combined sequence boundary/ transgressive surface at the base of subsequence D2b. The first occurrence of the dinoflagellate cyst *Charlesdowniea coleothrypta* in the London Basin and Hampshire Basin is in the upper part of Division D2 (King, unpublished data). In the Kortrijk area it is probably close to the base of Unit 4.

This supports the calibration based on sequence stratigraphy.

Division E

The base of Division E was correlated by King (1991b) with the base of the Aalbeke Member. The base of Chron C23n, originally located within the highest part of division D in the Isle of Sheppey (Ali et al., 1993), is probably c. 3 m above the base of division E, according to recent revision of the lithostratigraphy. In the Hampshire Basin it corresponds approximately to the Division D/Division E boundary (Ali, 1989). At Kortrijk, it is within the lowest part of the Aalbeke Member (Ali et al., 1993), confirming this correlation.

10. Conclusions

Exposures and boreholes in the Kortrijk area provide a high-resolution record of middle Ypresian biostratigraphy, magnetostratigraphy, depositional environments and depositional sequences which represents a template for this area of the southern North Sea Basin. Calibration with the succession in southern England confirms that a closely similar set of depositional sequences can be identified in both areas.

A significant difference is that lowstand units are represented in the Kortrijk area, but are unrepresented in southern England, while early transgressive channelled estuarine units are prominent in proximal areas in southern England, but unrepresented in Belgium. This probably reflects the differing source areas of the sediments: the marine sediments in southern England thin proximally westwards and there were apparently no major coastal sands or high-energy fluvial input. Here in inner and mid-neritic settings the LST is represented by a hiatus. In Belgium, the succession grades proximally into a major sand body (Mons-en-Pévèle Formation), which prograded distally at each fall in sea-level.

A marine erosion surface has been identified within the mid Ypresian (base of Unit 20 in the Kortrijk area, early Biochron NP12, middle C24n.1n, ~ 52.8 Ma) corresponding to the first occurrence of estuarine channel-fill units in southern England. This indicates a brief but profound sea-level fall, either eustatically or tectonically controlled.

Because of the great similarity with the Aktulagay area in Kazakhstan (King et al., 2013; Deprez et al., 2015) and the Suvlu-Kaya area in the Crimea (King et al., 2017), in biofacies succession (e.g. *Subbotina* influx) as well as biostratigraphic events (especially calcareous nannofossil and to a lesser degree dinoflagellate cyst events), the composite Kortrijk section is proposed as a reference for mid-Ypresian stratigraphy in middle to high latitudes of the Northern Hemisphere.

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Appendix. Taxonomic details of taxa cited

Calcareous microproblematica

Bignotella polygona Willems, 1975
Calvina kalloensis Willems, 1972
Claretinella helenae Keij, 1974 (= *Aurelianella keiji* Szczechura, 1979)
Pseudarcella campanula Le Calvez, 1959
Pseudarcella sp. nov. *‘P. rhumbleri’* of Willems, 1973, *non P. rhumbleri* Spandel, 1909. Topotype specimens of the German Oligocene species *P. rhumbleri*, kindly provided by D. Curry, are clearly morphologically distinct from the Belgian Ypresian specimens, confirming the observations of Keij (1974).
P. trapeziformis Willems, 1972
Voorthuyseniella bearnensis Poignant, 1990
V. gracilis Keij, 1970
Yvonniellina concava Willems, 1972
Y. feugueri (Le Calvez, 1959)

Calcareous nannofossils

Aubrysphaera deconinckii Steurbaut, 1991
Blackites dupuisii (Steurbaut, 1991) Steurbaut, 2011
Blackites solus (Perch-Nielsen, 1971) Aubry, 1999
Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, 1947
Chiasmolithus aff. *expansus* (Bramlette & Sullivan, 1961) Gartner, 1970
Chiphragmalithus barbatus Perch-Nielsen, 1967
Chiphragmalithus calathus Bramlette & Sullivan, 1961
Coccolithus pelagicus (Wallich, 1877) Schiller, 1930
Discoaster lodoensis Bramlette & Riedel, 1954
Ellipsolithus macellus (Bramlette & Sullivan, 1961) Sullivan, 1964
Micrantholithus mirabilis Locker, 1965
Neochiastozygus rosenkrantzii (Perch-Nielsen, 1971) Perch-Nielsen, 1971
Pentaster sp.
Pontosphaera excelsa (Perch-Nielsen, 1971) Perch-Nielsen, 1977
Pontosphaera exilis (Bramlette & Sullivan, 1961) Romein, 1979
Toweius pertusus (Sullivan, 1965) Romein, 1979

Dinoflagellate cysts

Charlesdowniea coleothrypta (Williams & Downie, 1966) Lentin & Vozzhennikova, 1989
Charlesdowniea reticulata (Williams & Downie, 1966) Lentin & Vozzhennikova, 1989
Dracodinium simile (Eisenack, 1954) Costa & Downie, 1979
Dracodinium varielongitudum (Williams & Downie, 1966) Costa & Downie, 1979
Eatonicysta ursulae (Morgenroth, 1966) Stover & Evitt, 1978
Ochetodinium romanum Damassa, 1979

Planktonic foraminifera

Subbotina patagonica (Todd & Kniker, 1952)
S. roesnaesensis Olsson & Berggren, 2006
S. triangularis (White, 1928)

Benthic Foraminifera

Taxonomy is based mainly on Willems (1980, 1991), with generic and specific nomenclature updated following Loeblich & Tappan (1988) and King (1991a). Eocene neritic benthic foraminifera are imperfectly documented, and the identifications are subject to further revision.

Alabamina obtusa (Burrows & Holland, 1897)
Alabaminoides sp. nov. [‘*Epistominella vitrea*” of Murray & Wright (1974) and Willems (1980, 1991), *non Epistominella vitrea* (Parker, 1953)]. Apertural characteristics indicate assignment to *Alabaminoides* (King, 1991a).
Anomalinoides acutus (Plummer, 1926)
A. anomalinoides (ten Dam, 1944). The Early Eocene form referred to this species is probably subspecifically distinct from the Middle Eocene type specimens (King, 1991a).
A. nobilis Brotzen, 1948. The type population of this species is Late Paleocene. The Early Eocene populations are regarded as subspecifically distinct by King (1991a).
A. ypresiensis (ten Dam, 1944). This species occurs only sporadically, and is here included on the distribution charts with *A. acutus*.
Asterigerina bartoniana kaasschieteri Zaneva, 1972. This taxon is sufficiently distinctive to qualify for specific status.
A. guerrai (Bermudez, 1952)
Bolivina crenulata Cushman, 1936
Brizalina [*Bolivina*] *anglica* (Cushman, 1936)
Bulimina parisiensis Kaasschieter, 1961
Cancris subconicus (Terquem, 1882)
Ceratocancris sp. This genus has not previously been recorded from the Ypresian in Belgium.
Cibicides tallahatensis Bandy, 1949
Cibicidoides alleni (Plummer, 1926). This variable species is recorded as *C. proprius, C. acutimargus* and *C. pseudoungerianus* by Willems (1980, 1991).
Coryphostoma sp. Recorded as *Fursenkoina* sp. by Willems (1991, plate 15, fig. 2)
Cribroelphidium [*Elphidium*] *hiltermanni* (Hagn, 1952) *nov. comb*. The small size, few inflated chambers, and pustulose apertural face of this species are all characteristics of *Cribroelphidium* (King, 1991a).
Euuvigerina [*Uvigerina*] *batjesi* (Kaasschieter, 1961) *nov. comb*. *U. garzaensis* of Willems (1980, 1991). The morphology of this species indicates assignment to *Euuvigerina* (King, 1991a)
Gaudryinopsis [*Gaudryina*] *ashfordi* (Bowen, 1954) *nov. comb*. This species is probably recorded as *Dorothia fallax* by Willems (1980, 1991). It was illustrated as *Textularia agglutinans* by Murray & Wright (1974). The holotype and other specimens from the London Clay Formation have a triangular initial stage, rather inflated chambers, a rounded adult cross-section and a semicircular basal aperture, indicating assignment to *Gaudryinopsis* (King, 1991a; see Loeblich & Tappan, 1988, p. 133).
Glandulina laevigata (d’Orbigny, 1846)
Gyroidinoides danvillensis (Howe & Wallace, 1932)
G. octocameratus (Cushman & Hanna, 1927)
Karreria fallax Rzehak, 1891
Karreriella oveyi (Bowen, 1954)
K. cf. *siphonella* (Reuss, 1851)
L. striata d’Orbigny, 1839
L. substriata Williamson, 1848
Lenticulina megalopolitana (Reuss, 1855). Recorded by Willems (1980, 1991) as *L. (Astacolus) platypleura*, a morphologically distinct Late Paleocene species (King, 1991a).
Lobatula [*Cibicides*] cf. *lobatulus* (Walker & Jacob, 1798)
Nonion [*Florilus*] *commune* (d’Orbigny, 1846)
Nummulites planulatus (Lamarck, 1804)
Oridorsalis cf. *umbonatus* (Reuss, 1851)
Palliolatella [*Fissurina*] *orbignyana* (Seguenza, 1826).
Pararotalia curryi Loeblich & Tappan, 1957
Percultazonaria [*Marginulinopsis*] *wetherellii* (Jones, 1854) *nov. comb*. This includes *M. decorata* of Willems (1980, 1991).
Pijpersia kalloensis Willems, 1991
Pullenia quinqueloba (Reuss, 1851)

Pulsiphonina prima (Plummer, 1926)
Pygmaeoseistron [Lagena] laevis (Montagu, 1803)
P. [Lagena] hystrix (Reuss, 1863)
Pyramidulina [*Nodosaria*] *latejugata* (Guembel, 1868). This includes *N. minor* of Willems (1980, 1991).
Quinqueloculina juleana d'Orbigny, 1846
Q. seminula (Linne, 1758)
Spiroplectinella [*Spiroplectammina*] aff. *carinata* (d'Orbigny, 1846). This comprises a highly variable group of forms, here regarded as genetically linked (see King, 1991a), identified by Willems as *Spiroplectammina adamsi*, *S. deperdita*, *S*. cf. *flabelliformis* and *S. plummerae*.
Textularia smithvillensis Cushman & Ellisor, 1933
Turrilina brevispira ten Dam, 1944
Uvigerinella abbreviata (Terquem, 1882)

Bivalves

Anisodonta ? sp. This thin-shelled form is common in Unit 6a, but represented mainly by bivalved external moulds.
Anomia sp. A small, strongly convex species, probably undescribed.
Caryocorbula striata (Lamarck, 1806)
Cubitostrea multicostata (Deshayes, 1824)
Goniomyrtea cf. *difficilis* (Deshayes, 1857)
Heteranomia scabrosa (Wood, 1861)
Jupiteria prisca (Deshayes, 1858)
Lentipecten corneus (J. Sowerby, 1818)
Lutetia umbonata Deshayes, 1858
Nemocardium cf. *semiasperum* (Deshayes, 1858)
Phacoides squamulus (Deshayes, 1825)
Pitar (Calpitaria) sulcatarius (Deshayes, 1825)
'*Pseudamussium*' sp. (see King, 1991b).
Ramsetia sp. nov. A mud-boring pholad, occurring mainly as bivalved external moulds in Unit 6a, appears referable to this genus, recorded previously only from the Late Cretaceous of the USA (Cox et al., 1969, p. N717, fig. E183,3).
Trigonodesma cf. *effossa* (Deshayes, 1858)
Venericardia cf. *sulcata prevosti* (Deshayes, 1858)
Venericor sp. Juvenile specimens only.
Varicorbula globosa (J. Sowerby, 1818). A common London Clay Formation species.

Gastropods

Adeorbis cf. *lucidus* (Cossmann, 1881)
Cirsochilus turbinatus (Deshayes, 1864)
Crisposcala aizyensis (Deshayes, 1861)
Cylichnina cf. *consors* (Deshayes, 1862)
Ficopsis cf. *tricostata* (Deshayes, 1835)
Haustator cf. *solanderi* (Mayer, 1877). Although this turritellid is abundant, the poor preservation (generally crushed) impedes accurate specific identification.
Ispharina aff. *sulcifera* (Deshayes, 1834). This is similar to specimens from the London Clay Formation of the Hampshire Basin referred to *I.* aff. *sulcifera* by Jeffery & Tracey (1997).
Pachysyrnola cf. *carinulata* Cossmann, 1888
Velates sp. juv. A single fragmentary juvenile specimen, presumably referable to the Early Eocene Paris Basin species *V. schmiedeli* (Chemnitz, 1786)
Volutocorbis elevata (J. de C. Sowerby,1840)

Ostracods

Acanthocythereis spiniferrima (Jones & Sherborn, 1889)
Bairdia londinensis Jones & Sherborn, 1887. Recorded by Willems (1973) as *Bairdia* sp.
Clithrocytheridea faboides (Bosquet, 1852)
C. heizelensis (Keij, 1957)
Cyamocytheridea sp. A (King, 1991a) (see Steurbaut & King, 1994). This common London Clay taxon, as yet undescribed, is here recorded for the first time from the Roubaix Clay Member.
Cytherella londinensis Jones, 1857
C. muensteri (Roemer, 1838)
Cytherelloidea dameriacensis Keij, 1957
Cytheretta decipiens Keij, 1957
C. scrobiculoplicata (Jones, 1857)
Cytheridea newburyensis Gokcen, 1970
Cytheropteron brimptoni Bowen, 1953
Echinocythereis reticulatissima Eagar, 1965
E. sp. A (King, 1981, 1991a). See Steurbaut & King (1994)
E. sp. B. (*E.* sp. nov.: Steurbaut & King, 1994)
Three *Echinocythereis* taxa can be differentiated in the Ypresian of N.W. Europe; all have in the past been referred to *E. reticulatissima*, but they have distinct morphological features and stratigraphic and ecological distributions. They are discussed by King (1991a) and Steurbaut & King (1994). *E*. sp. A is a probable precursor of *E. reticulatissima*, occurring in clay facies in England and Belgium. *E. reticulatissima* also occurs predominantly in finer-grained facies. *E.* sp. B (the Ypresian taxon referred to as *E.* sp. nov. in Steurbaut & King, 1994) occurs predominantly in fine sands in Belgium (Mons-en-Pévèle Formation) and the Paris Basin (Montagne de Laon Group). Very rare specimens of *E.* sp. B are recorded in Unit 20 at Marke.
Eopaijenborchella geoffreyi (Anderson, 1964). This taxon has not previously been recorded in Belgium. It occurs commonly in the upper London Clay Formation (Keen, 1978; King, 1991a), and probably evolved from the closely similar taxon *E. lomata*. It is more inflated than *E. lomata*, and more coarsely reticulate, with a variably developed short rib between the lateral and dorsal ribs.
E. lomata (Triebel, 1949)
Eucytherura perforatina (Eagar, 1965)
E. sp. A (King, 1991a). An undescribed species, similar to *E. hyonensis* Keij, 1957, but with a blunt posteroventral node.
Hazelina aranea (Jones & Sherborn, 1887)
Leguminocythereis striatopunctata (Roemer, 1838)
Loxoconcha subovata (von Munster, 1830*)*
L. sulcata Haskins, 1971
Monsmirabilia subovata (Apostolescu, 1955)
M. triebeli (Keij, 1957)
Oertliella aculeata (Bosquet, 1852)
Paracaudites ? sp. nov. An undescribed species, widespread in the London Clay Formation (recorded as '*Loxoconcha* ' sp. X by King, 1991a).
Paracypris aff. *contracta* (Jones, 1857*)*. Specimens of *Paracypris* from the Roubaix Clay Member and the London Clay Formation have previously been identified as the Middle - Late Eocene taxon *P. contracta* (e.g. Willems, 1973), but are consistently more elongated. They are similar to the specimens from the Mons-en-Pévèle Formation illustrated by Guernet (1992) as *P.* aff. *polita*.
Paracytheridea gradata (Bosquet, 1852)
Platella gyrosa (Roemer, 1838)
Pterygocythere hilli Keij, 1957
Pterygocythereis cornuta (Roemer, 1838)
P. fimbriata spinigera Keij, 1957
Schizocythere appendiculata Triebel, 1950
Schuleridea perforata (Roemer, 1838)
Semicytherura bambruggensis (Keij, 1957)
Thracella rutoti (Keij, 1957)
Trachyleberidea prestwichiana (Jones & Sherborn, 1887)

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