Stratigraphy of the type Maastrichtian – a synthesis

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Jagt, J.W.M. & Jagt-Yazykova, E.A. Stratigraphy of the type Maastrichtian – a synthesis. *In*: Jagt, J.W.M., Donovan, S.K. & Jagt-Yazykova, E.A. (eds.), *Fossils of the type Maastrichtian (Part 1)*. Scripta Geologica Special Issue, **8**: 5-32, 5 figs., 2 tables, Leiden, February 2012.
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Key words – Late Cretaceous, Maastrichtian, type area, localities, stratigraphy.
A synthesis of the stratigraphy of the Maastrichtian Stage in its extended type area, that is, southern Limburg (the Netherlands), and adjacent Belgian and German territories, is presented with a brief historical overview. Quarrying activities at the large quarry complex of ENCI-HeidelbergCement Group will officially come to an end on July 1, 2018. However, the stratotype section below the Lichtenberg farmstead and directly behind the main office building at the Lage Kanaaldijk (Maastricht), will be preserved, as will various faces within the quarry complex. Strata of Maastrichtian age include the Vijlen, Lixhe 1-3 and Lanaye members of the Gulpen Formation, as well as the Valkenburg, Gronsveld, Schiepersberg, Emael, Nekum and Meerssen members of the Maastricht Formation. The lower Maastrichtian portion is comparatively poorly preserved, being characterised by frequent reworking; only elements of the *Belemnella obtusa*, *Belemnella sumensis* and/or *Belemnella cimbrica* zones (the two last-named representing the traditional *Belemnella occidentalis* Zone) have been recorded. *Belemnitella junior* and *Belemnitella lwowensis* define the upper Maastrichtian, both first appearing in interval 4 of the Vijlen Member. At the ENCI-HeidelbergCement Group quarry, the lower/upper Maastrichtian boundary is placed at *c.* 5 m above the Zonneberg Horizon on benthic foraminifer evidence; strontium isotope data are in agreement. The highest portion of the Meerssen Member (uppermost IVf-6 and IVf-7) is missing from the type section; this part of the sequence is exposed at the former Curfs quarry (Geulhem), the Berg en Terblijt Horizon being equated with the Cretaceous/Paleogene (K/Pg boundary).

Contents

Introduction

The aim of the present paper is to furnish a revised overview of the stratigraphy of strata in the type area of the Maastrichtian Stage (Fig. 1), the youngest time slice of the Cretaceous Period (70.6 ± 0.6 to 65.5 ± 0.3 Ma). On numerous occasions it has been pointed out that strata in the historical type area were affected by regional synsedimentary tectonic movements (Fig. 2; compare Bless *et al*., 1987; Rossa, 1987; Bless, 1991a, b; Gras, 1995; S. Voigt *et al*., 2008) and that the refined lithostratigraphical subdivision

(W.M. Felder, 1975a, b, 1996; W.M. Felder & Bosch, 2000) was not matched by a comparably detailed biozonation. In general, there is a consensus amongst members of the Maastrichtian Working Group (Subcommission on Cretaceous Stratigraphy) that, for various reasons, sections in the historical type area of the stage cannot be used for the definition of the Campanian/Maastrichtian boundary. This has now been ratified as a GSSP (Global Boundary Stratotype Section and Point) at Tercis les Bains, near Dax (Landes, southwest France; Odin, 1996, 2001). Similarly, the GSSP for the Maastrichtian/Danian boundary has been designated elsewhere, at El Kef (Tunisia), because of the widely held view that the top of the Maastrichtian and the overlying basal portion of the Danian were missing in the type area of the Maastrichtian Stage. In recent years, it has appeared that this is not the case, and that the K/Pg boundary section here is more complete than previously held possible (Brinkhuis & Schiøler, 1996; Jagt, 1996, 1999a, b, 2000a-d; Kuhnt, 1996; A.J.T. Romein *et al*., 1996; Schmitz & Speijer, 1996; Smit & Brinkhuis, 1996; Smit & Zachariasse, 1996; Vonhof & Smit, 1996; Willems, 1996; Witte & Schuurman, 1996; Vonhof *et al*., 2011).

Geographical and stratigraphical setting

Macrofaunas to be described and illustrated in the present series of papers come from a number of (disused) quarries and other exposures in the extended type area of

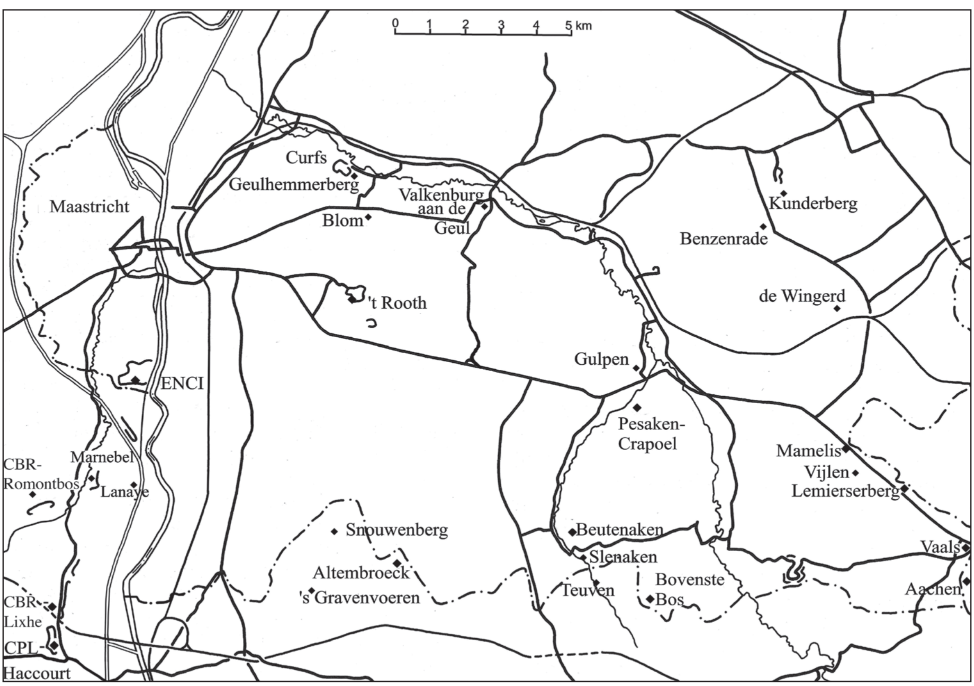

Fig. 1. Map of southern Limburg (the Netherlands) and contiguous areas in northeast Belgium (Voerstreek, Limburg and Liège) and western Germany (Aachen area), showing the most important localities ([temporary] outcrops and quarries) in the type area of the Maastrichtian Stage.

the Maastrichtian Stage, which includes portions of the Belgian provinces of Limburg (Voerstreek) and Liège, and the Aachen area in western Germany (Fig. 1). West of the River Maas (Meuse), the most important localities in the province of Liège are the working quarries of Ciments Portland Liégeois (CPL SA-Haccourt; now Kreco) at Haccourt (Hallembaye), Cimenterie Belge Réunie (CBR-Lixhe) at Lixhe, CBR-Romontbos at Eben Emael (Bassenge), Marnebel at Eben Emael and ENCI-HeidelbergCement Group at Maastricht (St Pietersberg). The late Maastrichtian portion of this sequence is complemented by former sections exposed along the Albertkanaal between Vroenhoven-

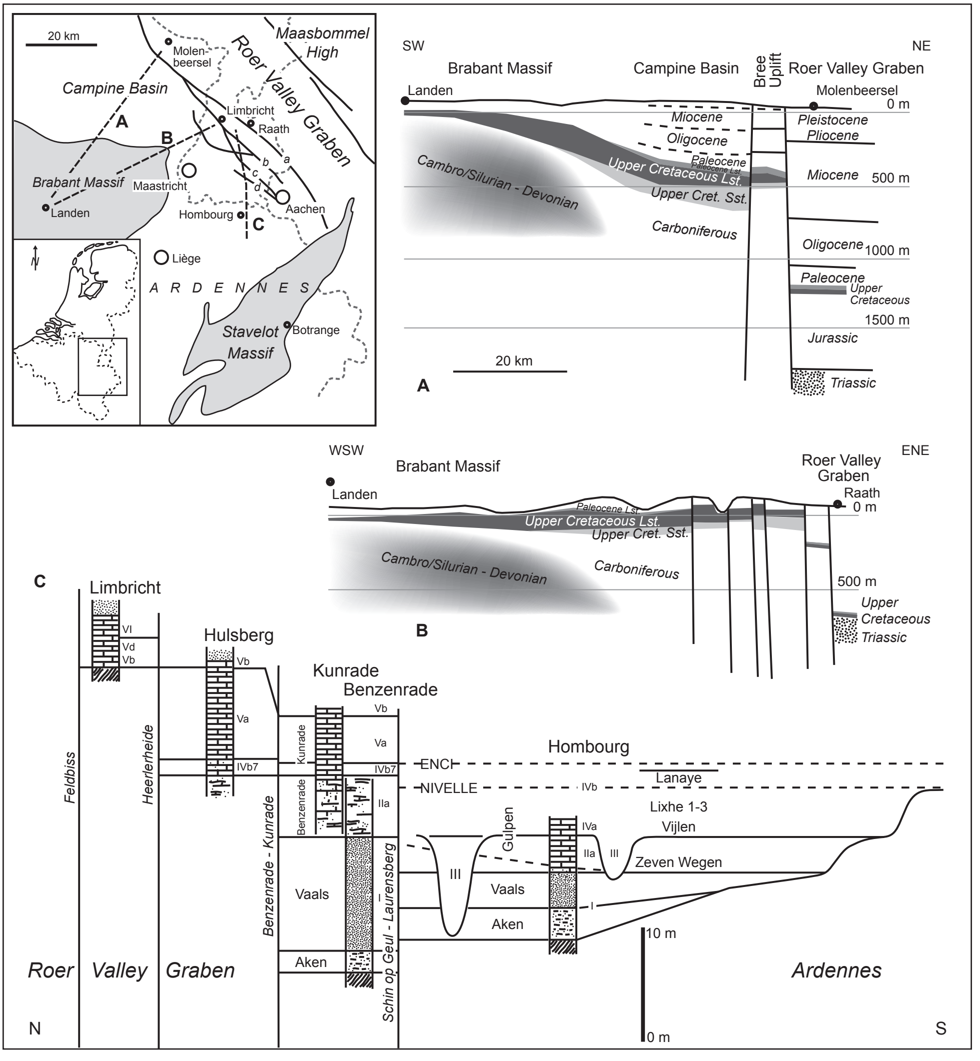

Fig. 2. Structural map and cross sections (A-C) of the Liège-Limburg basin. During mid-Santonian to early Maastrichtian times, the Roer Valley Graben became inverted, while the Brabant and Stavelot massifs formed structural highs. Latin numerals in cross section C refer to bioclast ecozones (after S. Voigt *et al*., 2008, fig. 15.16).

Riemst and Veldwezelt (province of Limburg, Belgium). Exposed currently at the ENCI-HeidelbergCement Group quarry are part of the lower Maastrichtian and the entire upper Maastrichtian up to within 2 m (or less) of the K/Pg boundary. In general, correlation of the upper Gulpen Formation (Lixhe and Lanaye members), as exposed at the CPL SA, CBR-Lixhe, CBR-Romontbos and ENCI-HeidelbergCement Group quarries is straightforward. More problematic are correlations of certain levels within the Maastricht Formation, where lithostratigraphical subdivisions and bioclast ecozonal schemes occasionally clash.

Quarries east of the river include the former Blom (Berg en Terblijt) and Curfs (Geulhem) quarries, and the working 't Rooth (Bemelen) quarry, which are complemented by a number of (natural) exposures in the Benzenrade-Kunderberg area (Fig. 1). At the former Curfs quarry, a K/Pg boundary section was, until recently, well exposed, and, combined with the subterranean gallery sections of the Geulhemmerberg nearby, this comprises the most complete boundary section in the area (Brinkhuis & Smit, 1996; Jagt *et al*., 1996; Machalski *et al*., 2009) and the best outcrop of the Geulhem Member (Houthem Formation) of early Paleocene (early/middle Danian) age. Outcrops in the Benzenrade-Kunraderberg area expose the Kunrade Limestone facies of the Maastricht Formation (Jagt, 1988, 1999a; P.J. Felder & Bless, 1989; W.M. Felder & Bosch, 2000).

Table 1. Lithostratigraphy of Maastrichtian and lower Paleocene strata in the type area of the Maastrichtian Stage (after W.M. Felder, 1975a, b; see also W.M. Felder & Bosch, 2000), showing also the 'horizons' which separate the various members. The Cretaceous/Paleogene (K/Pg) boundary equates with the Berg en Terblijt Horizon at the top of subunit IVf-6 of the Meerssen Member (see Fig. 5).

Houthem Formation (*pars*)	Geulhem Member	
		Vroenhoven Horizon
	Meerssen Member	**K/Pg boundary**
		Caster Horizon
	Nekum Member	
		Laumont Horizon
	Emael Member	
		Romontbos Horizon
Maastricht Formation	Schiepersberg Member	
		Schiepersberg Horizon
	Gronsveld Member	
		St. Pieter Horizon
	Valkenburg Member	
		Lichtenberg Horizon
	Lanaye Member	
		Nivelle Horizon
Gulpen Formation (*pars*)	Lixhe 1-3 members	
		Wahlwiller Horizon
	Vijlen Member, intervals 0-6	
		Bovenste Bosch Horizon
	Beutenaken Member	
		Slenaken Horizon

Sections in the Voerstreek (province of Limburg, Belgium) are located near 's Gravenvoeren (Altembroeck, Snouwenberg) and expose the lower/lower upper Maastrichtian, as did a number of temporary outcrops in the Aachen city area, now built over (Keutgen, 1996; Keutgen *et al*., 2010; Walaszczyk *et al*., 2010).

The stratigraphical framework for the majority of macrofaunas in the current series corresponds to the detailed lithostratigraphy proposed by W.M. Felder (1975a, b; see also W.M. Felder & Bosch, 2000). Lithological logs published by that author and his colleagues for the various quarries and outcrops have been used to document the stratigraphical provenance (and range) of biota. Despite some inconsistencies in correlation between a number of these sections, they provide a detailed picture of the stratigraphical distribution of the various species. Formations and members proposed and discussed by W.M. Felder (1975b), Albers & Felder (1979) and W.M. Felder & Bosch (2000) are briefly described below. Their (bio)stratigraphy is outlined in more detail, with reference to literature sources and personal observations (macrofossil zonations). The lithostratigraphy of strata of latest Campanian to earliest Paleocene age, inclusive of horizons separating members of the various formations, is shown in Table 1, while Figure 3 illustrates bioclast ecozones (I-VI) and benthic foraminiferal zones (*sensu* Hofker, 1966), in conjunction with cycles and supercycles.

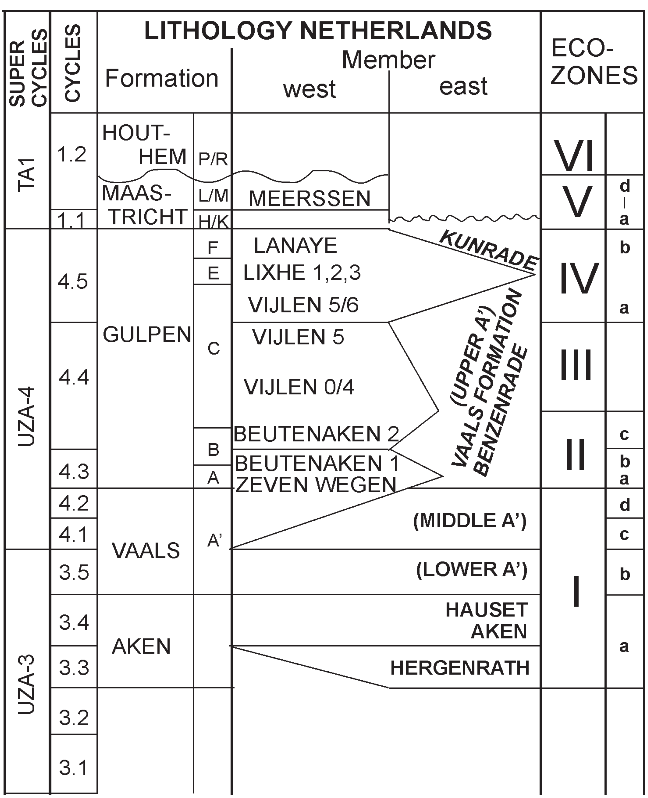

Fig. 3. Lithostratigraphy, cycles and supercycles, and bioclast ecozones (I-VI) for Upper Cretaceous (Santonian-Maastrichtian) and lower Paleocene strata in the type area of the Maastrichtian Stage, correlated with sequence-stratigraphic units and subdivided into benthic foraminiferal zones (A'-R, *sensu* Hofker, 1966) (modified after Keutgen *et al*., 2010, fig. 1).

A brief history

As pointed out by Jagt (2001, p. 712), probably the most detailed account of the original meaning of the 'système maestrichtien' of Dumont (1849) was provided by van der Heide (1954). That author pointed out that the *Rapport sur la carte géologique du Royaume*, in which the term was first used, was in fact nothing more than a brief report given by Dumont during the presentation of the geological map to the 'Académie' in Brussels, and that additional notes were being prepared. However, Dumont's untimely death in 1857 meant that these notes were not published until 1878 when Mourlon's work came out (Mourlon, 1878). Apparently, Mourlon was aware of the ambiguity surrounding the meaning of the term 'système maestrichtien' and insisted that it was Dumont's maps that provided the clues. In 1832, Dumont had referred the section exposed at the St Pietersberg, south of Maastricht, to the so-called 'Craie' and to the 'Calcaire de Maestricht'. Van der Heide (1954) noted that in this 'Calcaire de Maestricht' was included a certain portion of what we now know as the Gulpen Formation (Lanaye Member).

In 1849, Dumont changed the 'Calcaire de Maestricht' into the 'système maestrichtien', which was characterised as follows, 'Le dernier système, dont le nom rappelle celui de la ville de Maestricht, où il est depuis longtemps connu par les fossils qu'il contient, commence, dans quelques localités de la province de Limbourg, par de la glauconie sableuse ou du calcaire glauconifère; il comprend le calcaire grossier exploité aux carriers de Maestricht, celui de Folx-les-Caves et de Ciply, et correspond au calcaire pisolithique du basin de Paris.' In the legend of the map, which did not appear in print until 1852 (see van der Heide, 1954), the above-mentioned glauconitic level is referred to as 'Calcaire poudingiforme ou glauconifère ….', which Mourlon (1878, p. 334) later described as, '… calcaire … renfermant … de petits corps ovoïdes de 1 à 2 millimètres de long sur 1/2 de large, d'un brun foncé ou clair, extrêmement luisants, translucides, irrégulièrement disséminés (Sluse, Nederheim, Maestricht)' and 'Cette couche, qui forme la base du système maestrichtien …'. Of note in the 1849 citation is the phrase, '… dans quelques localités …'. It is now well known that the coarse-grained phosphatic/glauconitic and pyritic, bioclastic sand resting directly upon the Lichtenberg Horizon at the base of the Valkenburg Member (Maastricht Formation) shows extreme variation in thickness and composition, even within a single quarry (e.g., ENCI-HeidelbergCement Group quarry; compare W.M. Felder, 1975a; Zijlstra, 1994).

B.J. Romein (1962, 1963) also pointed out that originally (that is, in 1849), Dumont referred to the upper part of the section exposed at the St Pietersberg as 'partie supérieure du Système de Maestricht' and to the lower, of which 5-6 m were accessible at that time, as 'partie inférieure', the boundary between these units being a 'couche graveleuse, glauconifère'. Later, he appears to have changed his mind since his field notes dated July 13, 1850 (see Romein, 1963, fig. 4), show that he then considered this 'couche' to be the base of his système maestrichtien. Subsequently, Kedves & Herngreen (1980) have rightly remarked that, as Dumont's field notes of 1850 have never been published, his 1849 interpretation has priority. This means that Dumont's système maestrichtien corresponds not only to W.M. Felder's (1975a, b) 'Formatie van Maastricht', but also comprises the highest member (Lanaye Member, 'Kalksteen van Lanaye') of the underlying 'Formatie van Gulpen'. This interpretation is the one currently favoured by most members of the Maastrichtian Working Group.

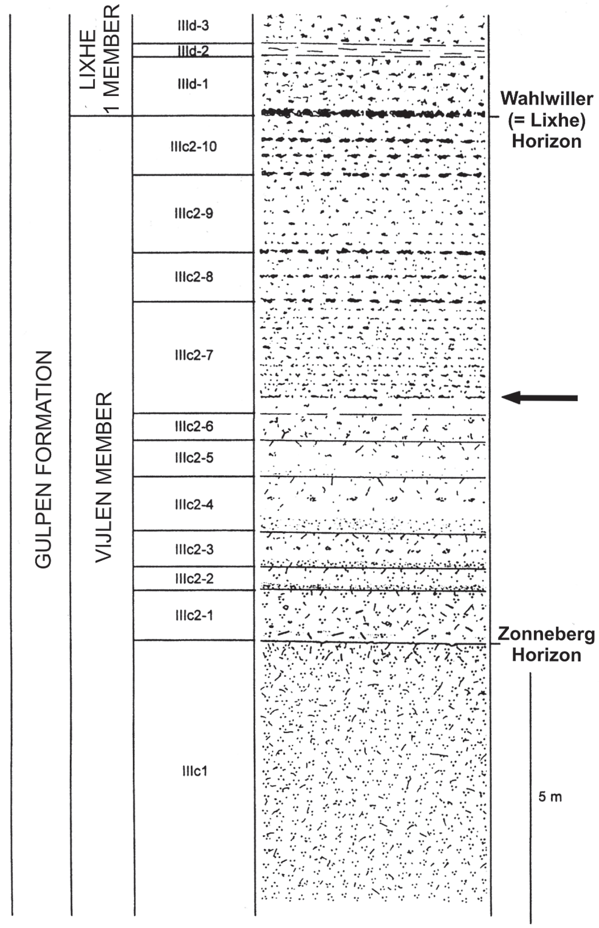

Fig. 4. Litholog of the Vijlen Member (Gulpen Formation) as exposed at the ENCI-HeidelbergCement Group quarry (Maastricht), with indication (arrow) of the lower/upper Maastrichtian boundary on the basis of benthic foraminiferal analyses (modified after W.M. Felder & Bosch, 1998, fig. 5).

Jeletzky (1951, p. 15) opined that Leriche's (1929) concept of the Maastrichtian corresponded entirely with Dumont's original view, and that, to avoid further confusion, that term should be applied to all strata in the type area older than the Danian/Montian and younger than d'Orbigny's (1842) Sénonien or Coquand's (1857) Campanien. We now know that Jeletzky (1951) was right in assuming the Campanian/Maastrichtian boundary to occur within the 'Gulpen Kreide' (= Gulpen Formation) and in accepting an early Maastrichtian age for what he referred to as 'oberste Schichten der Hervien-Grünsande'.

The first lithostratigraphical subdivision of Cretaceous strata in the study area is that by Uhlenbroek (1912), which W.M. Felder (1975a, b; see also Albers & Felder, 1979; W.M. Felder & Bosch, 2000) later considerably refined and formalised by introducing formations and members, and defining type sections for all of these. Flint genesis and Milankovitch rhythmicity, in particular within the middle and upper portion of the Gulpen Formation (Lixhe 1-3 and Lanaye members), was discussed in detail by Zijlstra (1994). Subsequently, the first sequence-stratigraphical interpretation of the type Maastrichtian, on the basis of palynomorph distribution and biozonation, was proposed by

Table 2. Estimated absolute numerical age for sequence boundaries based on the long (0.41 myr) eccentricity cycles and comparison with ages of biozone boundaries in northwest Germany (Kronsmoor and Hemmoor sections). MFm = Maastricht Formation; C/M boundary = Campanioan/Maastrichtian boundary (modified after Keutgen & Jagt, 2009, table 2).

Long cycle basis (Ma)	NW Germany	Keutgen & Jagt (2009)
72.24	*grimmensis/granulosus*; 72.2 Ma	top Beutenaken; 72.2 Ma
71.42	*lanceolata*; 71.3 Ma	hiatus
71.01	*pseudobtusa*; 70.8 Ma	hiatus
70.60 ----- C/M boundary ------	*obtusa*; 70.6 Ma ---------------------------------	hiatus --------------------------
70.19	*sumensis*; 70.4 Ma	base Vijlen 0; 70.2 Ma
69.78	*cimbrica*; 69.9 Ma	base Vijlen 2; 69.8 Ma
69.37	*tegulatus/junior*; 69.3 Ma	base Vijlen 4; 69.4 Ma
68.96	*argentea/junior*; 68.8 Ma	base Lixhe 1; 68.9 Ma
68.55		base Lixhe 2; 68.5 Ma
68.14	*danica/argentea*; 68.1 Ma	base Lixhe 3; 68.2 Ma
67.73		base Lanaye; 67.8 Ma
67.32		top Lanaye; 67.4 Ma
66.91		hiatus
66.50		hiatus
66.09		base MFm; 66.2 Ma
65.68		
65.27		K/Pg boundary; 65.5 Ma

Schiøler *et al*. (1997). Additional work along these lines came from Vandenberghe *et al*. (2004), while Keutgen & Jagt (2009), Keutgen *et al*. (2010) and Walaszczyk *et al*. (2010) added estimated absolute numerical ages for sequence boundaries (see Table 2), proved that the great majority of early Maastrichtian coleoid taxa in the Vijlen Member (up to the base of interval 4) had been reworked and documented that inoceramid bivalves allowed correlation with central Europe (Poland), North America and South Africa, respectively. The most recent addition is a belemnite-based analysis of strontium, carbon and oxygen isotopes from the type section of the Maastrichtian Stage, which allows a more reliable, long-distance correlation to sections in northern Europe, North Africa and the South Atlantic (Vonhof *et al*., 2011).

Lithostratigraphy

Gulpen Formation

Vijlen Member – The Vijlen Member is comprised of yellowish grey, glauconitic, fine-grained chalks, with a basal glauconite-rich portion, which locally occurs also higher up in the section. Total thickness generally is between 15 and 25 m, but locally up to *c*. 100 m (Albers & Felder, 1979).

The most complete section of Vijlen Member sedimentary rocks known to date results from combining sections exposed in outcrop 62D-79 (stratotype) and borehole 62D-168 near Mamelis, *c*. 300 m southwest of the stratotype (Fig. 1). Here the total thickness amounts to 65-70 m. P.J. Felder & Bless (1994) subdivided this section into seven intervals, numbered 0 to 6 (see also P.J. Felder, 1997). Intervals 0 to 3 were defined in the Mamelis borehole, while intervals 4 to 6 were defined at the stratotype. These units have subsequently been adopted by Keutgen (1996) and correlated with his biozones. Keutgen (1996) recorded many hardground and erosion surfaces in the Vijlen Member. These document the following sequence of genesis: sedimentation break, omission surface, erosion surface, fossil hash, nodular chalk, incipient hardground and hardground.

P.J. Felder & Bless (1994) noted major changes in lateral and vertical composition of bioclast and microfossil contents in the Vijlen Member in the type area (see also P.J. Felder, 1997). South of Mamelis, echinoderm bioclasts predominate and indicate sedimentation in a low-energy setting below storm wave base. North of Mamelis, molluscan bioclasts predominate and glauconite-rich, quartz pebble-bearing beds with abundant clasts of belemnites occur repeatedly, attesting to deposition in a high-energy, shallow subtidal (above storm wave base) to occasionally intertidal environment. The rhythmic succession of belemnite-rich and belemnite-poor intervals in the Mamelis section may reflect rhythmic variations in relative sea level, which may have been responsible for the regional appearance/disappearance of various microfossil taxa or for (occasionally repeated) changes in relative frequency or abundance.

The seven intervals proposed by P.J. Felder & Bless (1994) are as follows. Interval 0 (thickness 3.2 m) is characterised by numerous horizons with quartz pebbles floating in glauconite-rich clayey and limy marls. Belemnites are particularly common at 1.7 m above the Bovenste Bos Horizon. It is correlated with early early Maastrichtian belemnite peaks at the base of the Vijlen Member in the Bovenste Bos and Zeven Wegen sections. Interval 1 (thickness 10.5 m) consists of comparatively indurated, glauconitic clayey and limy marls; belemnites are slightly commoner just below the upper limit. Interval 2 (thickness 10.0 m) comprises soft, glauconite-rich clayey and limy marls, with a twofold subdivision: a lower portion (thickness *c.* 5.4 m) with numerous quartz pebble horizons and extremely common belemnites, and a higher portion (thickness 4.6 m) characterised by many echinoderms and a few belemnites. This is correlated with the upper lower Maastrichtian (upper *sumensis* Zone) interval of Aachen-Vaalserstraße. Interval 3 (thickness > 7.3 m) comprises glauconitic clayey and limy marls with scattered quartz pebbles. Belemnites are missing, but echinoderms are common. Interval 4 (thickness 8.5 m) is characterised by at least three glauconite concentration levels with quartz pebbles floating in whitish grey, glauconitic clayey and limy marls, belemnites being common. It is correlated with the upper lower Maastrichtian of Aachen-Hans Böckler Allee. Interval 5 (thickness 12.0 m) consists whitish grey clayey and limy marls with low glauconite content. Belemnites are almost totally missing, except at the upper interval limit where they are slightly commoner. Interval 6 (thickness 11.5 m) is similar to interval 4 in having three glauconite concentration levels with quartz pebbles, floating in whitish grey clayey and limy marls. These levels are between 0.3 and 0.5 m thick, indurated and of a reddish brown colour. Locally they contain small, light grey, rarely greyish black flints (bioturbation flints). As in interval 5, belemnites are virtually absent and are commoner only near the upper limit.

In the stratotype area, the Vijlen Member is capped by the Lixhe Member, which comprises white to yellowish white chalks, with narrow, black-grey small flint bands. The base is developed as the 0.1-0.3 thick Wahlwiller Conglomerate, which is a glauconite-rich molluscan packstone with numerous quartz pebbles and comminuted fossil fragments. Temporary outcrops in the Aachen city area (Friedrichberg, Vaalserstraße, Wilkensberg, Schurzelterstraße and Hans Böckler Allee) were discussed in detail by Keutgen (1996), who documented P.J. Felder & Bless's (1994) intervals 0 (at Friedrichberg), 1-2 (Vaalserstraße), 3-5 (Schurzelterstraße and Hans Böckler Allee), and 5-6 (Wilkensberg). For the classic Schneeberg locality (northwest of Aachen), Keutgen (1996) documented all of P.J. Felder & Bless's (1994) intervals outcropping in various fields. According to Robaszynski *et al*. (1985), the Vijlen Member as exposed at the CPL SA quarry (Haccourt), corresponding to interval 6, was deposited in a relatively offshore setting (*c*. 20-25 km), at a palaeowater depth of *c*. 80 m and in a low-energy environment.

Lixhe 1-3 members – The total thickness of these three units is up to 25 m; they comprise white, fine-grained chalks with irregular dark blue-grey to black flint nodules. West of the River Maas a threefold subdivision can be recognised on the basis of flint type and abundance. Albers & Felder (1979) interpreted these members to be fully marine, deposited invariably below wave base, with decreased erosion and sedimentation dynamics, at least temporarily decreased O_2 supply of the substrate and, in the eastern part, a pinching out of the euphotic zone on account of increased terrigenous sedimentation, which resulted in zonal subdivision of differing diversities. Zijlstra (1994) considered the Lixhe 3 Member to be a pure coccolithic wackestone, with silt-sized bioclasts, horizontal flint beds and considered it to be homogeneously bioturbated (*Planolites*, *Zoophycos*, *Chondrites*, *Bathichnus* and *Thalassinoides*-type deep burrows).

Flint genesis in the upper Gulpen Formation (Lixhe and Lanaye members) was unravelled by Zijlstra (1994), who demonstrated a regular succession of *c*. 75 thickening-upwards, continuous flint layers. These nodule layers were considered to have formed when detrital skeletal opal dissolved during late diagenesis and concentrated in sites of relatively high early diagenetic authigenic silica polymorph concentration. The highest concentrations of authigenic silica occurred during periods when deposition rate was low, and when sediment resided for a relatively long period in the anoxic redox zone. The rhythmic vertical variation of the flint nodule concentration is held to reflect the influence of the periodic variation of the earth's orbital parameters (precession index) on climate, oceanography and periodically varying deposition rates. Zijlstra (1994) also attempted to relate the flint-rich sequence of the Lixhe and Lanaye members to the Milankovitch rhythmicity. His conclusion was as follows: the chalk with flint contains 75 flint layers, with individual members containing 20, 15, 20 and 20 flint layers, respectively, and with flint layers forming bundles of five, suggesting that this sequence may be interpreted as E4 (1300 kyr), E3 (413 kyr) and E1 (98 and 126 kyr) eccentricity cycles, and P (20 kyr) precession cycles.

The Gulpen Formation as exposed south of Maastricht reaches a total thickness of some 40 m and contains about 75 precession induced sedimentary cycles. Zijlstra (1994) assumed these cycles to have been deposited during approximately $75 \times 20 = 1.5$ million years (compare Table 2 here). The increase of the mean cycle thickness from 4 dm at the base to 1 m at the top of the Gulpen Formation sequence would then reflect an increase in mean deposition rate from 2 to 5 cm/kyr. To Zijlstra (1994), this fine-grained chalk with a high flint concentration and symmetrical, thin-bedded, eccentricity cycles reflects a low-energy environment with a low deposition rate. The coarser grained (tuffaceous) chalk, on the other hand, with a lower flint concentration and asymmetrical thick-bedded eccentricity cycles, reflects a high-energy environment with high erosion/deposition rates.

Lanaye Member – This member comprises white, fine-grained chalks with irregular light to dark blue-grey flint nodules. West of the River Maas, south of the St Pietersberg, 23 flint levels are distinguished; east of the river these are less conspicuous and bedding is absent, with only randomly distributed flint nodules occurring. The total thickness amounts to *c*. 20 m. Albers & Felder (1979) noted that in the southeast the Lanaye Member consisted of fine-grained chalks and in the west of pure biodetrital chalks, which graded into the sedimentation of the Maastricht Formation biocalcarenites.

Villain (1977, p. 7) interpreted the 'Craie grossière Cr4' (= Lanaye Member) as a compact biomicrite (with biomicrosparite patches), deposited in an environment still under oceanic influence, with horizontal transport of sediment particles by episodic currents and a palaeowater depth of 40 to 80 m. Liebau (1978) described the depositional setting as a platform environment with minor open oceanic influences (middle sublittoral) and subtropical temperatures.

Zijlstra (1994) considered this unit to represent a pure (97 per cent) coccolithic bioclastic silty, homogeneously bioturbated packstone, with large-scale wavy lamination preserved in places. Well-developed planar-parallel flint nodule layers occur at 0.5-1.5 m interspaces. Nodules are either tubular (formed around crustacean burrows) or platy; traces of shallow burrowing and sediment mixing are common, but poorly preserved. The activity of deep burrowers is preserved as ghost structures in flint.

The Kunrade Limestone facies, which is widely distributed in the Benzenrade-Kunderberg area (Fig. 1), was subdivided by P.J. Felder & Bless (1989) into two bioclast zones, ecozones IV and V, both of late Maastrichtian age on cephalopod evidence. According to these authors, ecozone IV is best correlated with Hofker's (1966) benthic foraminifer zone F (or possibly the base of zone J); this zone equates with the Lanaye Member (Fig. 3). Ecozone V was equated with the lower half of foraminifer zone J in the Thermae (Valkenburg aan de Geul) and Maastricht-Kastanjelaan boreholes, and with zone H at the ENCI-HeidelbergCement Group quarry. In this correlation, the upper limit of the Kunrade facies, the so-called 'Koraalbank van Kunrade' and 'Oesterlaag van Craubeek' match the Romontbos Horizon at the base of the Emael Member, suggesting that equivalents of the (remainder of the) Emael, Nekum and Meerssen members (= benthic foraminifer zones I, K, L, and M) are not represented in the Kunrade area (Fig. 3).

Maastricht Formation

Valkenburg Member – In the western part of southern Limburg this member consists of poorly indurated, white-yellowish to yellowish-grey, fine- to coarse-grained chalks with greyish brown flint nodules of varying size. In the east, this sequence changes into an alternation of poorly and more intensely indurated chalk beds, which are part of the so-called 'Kunrade Limestone'. Here flints do not occur everywhere; where they do, they are crumbly, light grey nodules. The total thickness increases from west to east. At the ENCI-HeidelbergCement Group quarry it amounts to *c*. 2.5 m, while just east of Valkenburg aan de Geul it is *c*. 45 m.

Zijlstra (1994) noted the occurrence of depressions that are several tens of metres wide and decimetres-deep at the top of the Lanaye Member, filled with coarse-grained phosphatic/glauconitic and pyritic bioclastic sand, representing the base of a fining-upward cycle. Depositional lamination was shown to be virtually entirely destroyed by bioturbation, and the sand to contain skeletal remains, reworked chalk, and low concentrations of sand-sized extrabasinal quartz and heavy mineral grains. At the ENCI-HeidelbergCement Group quarry, this member shows a fining-upward trend, with an upper cycle of 1.5 m in thickness, having a rather fine-grained, slightly lithified (proto-hardground), pure carbonate top with poorly developed flint nodules around spreiten and *Thalassinoides*-type burrows. Of note is Zijlstra's (1994) observation that the glauconitic cycles of the Valkenburg Member at the ENCI-HeidelbergCement Group quarry change laterally towards the south into cycles with flint nodule layers very similar to those of the Lanaye Member. This correlation is corroborated by analyses of bioclast contents.

Gronsveld Member – In the west this unit comprises poorly indurated, white-yellowish to yellowish-grey, fine- to coarse-grained chalks. In the lower portion small, light to dark greyish-brown flint nodules of varying sizes and shapes occur; in the higher portion they are arranged in more or less regular beds of light-grey to greyish-blue nodules. Towards the east the upper portion is missing. The chalks change into a cyclic alternation of less and more indurated chalk beds, which are part of the so-called 'Kunrade Limestone'. Total thickness varies between 4.5 and *c*. 10 m. According to Zijlstra (1994), the lower part of this unit also consists of fining-upward cycles with a phosphatic, glauconitic/pyritic bioclastic sand at the base, the sand of the lowermost cycle being characterised by well-developed wavy lamination. Wavy laminated sediment at the base of these cycles changes upwards via (sub)horizontally laminated sediment towards lithified homogeneously bioturbated, fine-grained, purer carbonate sedimentary rock at the top. The upper part of this member consists of well-sorted, bioclastic, fine-grained sandstone with low-angle, large-scale wavy lamination (hummocky stratification), with flint nodules forming laterally restricted curvi-planar layers.

Schiepersberg Member – In the west this unit is comprised of poorly indurated, white yellowish, fine- to coarse-grained, homogeneous chalks with numerous regular beds and randomly distributed, light-grey to bluish-grey flint nodules. Towards the north the flints disappear. The homogeneous chalk changes into an alternation of chalk beds of varying induration, and are part of the so-called 'Kunrade Limestone'. Total thickness varies between 5 and 6 m.

Emael Member – In the west this member comprises poorly indurated, white-yellowish and yellowish-brown, fine- to coarse-grained, homogeneous chalks, in the lower portion with numerous light grey flint nodules. Typical are especially large, regular flat and pipe-shaped flint bodies. In the east, between Valkenburg aan de Geul and Benzenrade-Kunraderberg, these homogeneous chalks change into an alternation of more and less indurated chalk beds, which form the highest part of the so-called 'Kunrade Limestone'. Total thickness varies between *c*. 5 and *c*. 7.5 m.

Prior to 1975, the Valkenburg, Gronsveld, Schiepersberg, and Emael members were referred to as units Ma-Mb (*sensu* Uhlenbroek, 1912), which Villain (1977) considered to represent a gravelly intrabiomicrosparite, with regional currents constant enough to horizontally displace sediment particles over the entire platform, at shallow palaeowater depths of 20 to 40 m and free from oceanic influence. Sediment reworking resulted in their homogenisation over depths of some decimetres, resulting in a relatively firm sea floor and clear waters. Liebau (1978) typified the setting as middle sublittoral, with subtropical temperatures and characterised by the occurrence of seagrass communities.

Albers & Felder (1979) characterised the 'Kunrader Kalkfazies' as a cyclic alternation of highly indurated, silicified calcisiltites and less indurated biocalcarenites. The latter generally contain a higher glauconite content and terrigenous component. Cross-bedding has been demonstrated and bioturbation occurs commonly, especially in glauconite-rich portions. In comparison with the Maastricht facies, a less diverse fauna occurs. Rich thallophyte assemblages are known, in particular seagrass and many washed-in terrestrial plants, some of which have also been recorded from various levels within the Maastricht Formation west of the River Maas (see, for example, van der Ham & van Konijnenburg-van Cittert, 2003; van der Ham & Dortangs, 2005; van der Ham *et al*., 2001, 2003, 2004, 2010).

The depositional setting was interpreted as fully marine, invariably above wave base in the euphotic zone, the proximity of land masses being demonstrated by strong terrigenous influence (land plants), which explains decreased coral growth and slightly less diverse biocoenoses. Ostracod faunas suggest decreased hydrodynamics in a lagoon-like setting near a flat coastline and a low hinterland.

Nekum Member – This unit comprises poorly indurated, white-yellowish, coarse-grained, homogeneous chalks, in the lower part with a few randomly distributed greyish brown flint nodules. Locally coarse-grained fossil hash lenses and beds occur, which are characterised by high numbers of holasteroid echinoids and ostreid bivalves. The total thickness varies between *c*. 7 and *c*. 15 m. The chalks are medium- to coarse-grained biocalcarenites (mainly packstones and grainstones; gravelly intrabiomicrosparite according to Villain, 1977), with an indurated calcarenite resting upon the Laumont Horizon. Flint nodules in the lower part of this member (the highest *in situ* occurrence of flints in the type Maastrichtian) have a crypto/microcrystalline texture and are often associated with concentrations of large skeletal grains. Nodules are tubular when related to bioturbation. The upper part of the member comprises porous, fine-grained carbonate sands, with undulating erosion surfaces. Sand lenticles resting on such erosion surfaces may show tangential cross bedding; the Kanne Horizon represents an undulating erosion surface overlain by coarse-grained bioclastic sand.

Meerssen Member – In the west this member comprises a poorly indurated, white yellowish, coarse- to very coarse-grained chalks with clearly developed hardgrounds and fossil hash layers. These lenses and layers comprise to a large extent bryozoan remains and large foraminifera. Total thickness varies between *c*. 15 and 20 m.

Zijlstra (1994) observed that the upward-coarsening of grain size and the increase of average bed thickness indicated a gradual increase of average hydrodynamic energy and deposition rates. The most strongly silicified/lithified layers formed when deposition rate was nil, that is, when hydrodynamic energy increased and the consequent increase of erosion equalled the relative sea level rise. During a further increase of hydrodynamic energy, previously lithified sediment was eroded during storms and wavy beds formed. A hardground, that is, a bored, encrusted and mineralised rocky sea bottom, formed when the sediment that was eroded during a storm was not redeposited after the storm, so that the previously lithified layer was continuously exposed.

Villain (1977, p. 8) described this unit as a gravelly intrabiomicrosparite, deposited 'sous une tranche d'eau réduite (15 à 2 mètres), une agitation supérieure à celle du Mb permet le déplacement de particules plus grosses (...) déposées en stratification obliques sous les énergies maximales du Md inférieur; elle favorise la prolifération de Lithothamniées dès le Mc, et de Polypiers solitaires au Md.' Liebau (1978) typified these sedimentary rocks as high-energy deposits, with a high production of carbonate detritus leading to the establishment of a broad, shallow, well-lit, warm carbonate platform with rich phytal association. Water temperatures are held to have risen to 20-25° C allowing the growth of scleractinian corals, especially in the lower/middle portion of this member (see also Sprechmann, 1981). Hofmann (1996), on the basis of microborings, concluded that such traces could be ascribed to endolithic algae, thus documenting a euphotic to maximally disphotic depositional environment. Zijlstra (1994) also noted the extreme thickness of the uppermost portion of this member and suggested that this may have been caused by rapid increase of local subsidence rate related to increased tectonic activity connected with Deccan Trap volcanism. Van Harten (1972) also pointed out that deposition of the upper Meerssen Member could have occurred in deeper water, in contrast to the continuous shallowing trend up to halfway this member.

Albers & Felder (1979) characterised the Maastricht tuffaceous facies as biocalcarenites and biocalcirudites, with rare cross-bedding and occasionally with channels. Biocoenoses show a high diversity of tropical-subtropical, warm water faunas, mainly consisting of bivalves, and, in comparison with the Kunrade facies, increased numbers of scleractinians, echinoids and brachiopods. Related to substrate consistency, these biodetritus chalks contain numerous representatives of burrowing endobenthos and, with increased hardground development in the Meerssen Member, epibenthos became more dominant. The rich microfaunas show a high diversity with moderate abundance and rapid evolutionary rates, sharply separated from conditions that prevailed during deposition of the Gulpen Formation. These authors interpreted the depositional setting to have been fully marine, tropical-subtropical, invariably or generally above wave base in the euphotic zone, very strongly decreased suspension, with rich biocoenoses of high diversity and an active biochemical cycle in the formation of exo- and endoskeletons.

Biostratigraphy

As noted above, the Tercis les Bains section (Landes, southwest France), proposed as GSSP of the Campanian/Maastrichtian boundary, has now been ratified. However, correlation with the belemnite zones established in northern Europe was far from clear, until Niebuhr (2003, 2004; see also Niebuhr, 2006; Niebuhr *et al*., 2011) equated the boundary, as defined at Tercis les Bains, close to the top of the *Belemnella pseudobtusa* Zone at Kronsmoor (northern Germany), on ammonite evidence. This agrees with views expressed previously by Hancock *et al*. (1993) and Burnett *et al*. (1998). Ogg *et al*.

(2004) dated the Campanian/Maastrichtian boundary at 70.6 Ma, close to the base of the *Belemnella obtusa* Zone. This interpretation is followed here (see Table 2).

The lower/upper Maastrichtian boundary has not yet been formally defined (compare Odin, 1996). At the type section (ENCI-HeidelbergCement Group quarry), this boundary has been drawn, on benthic foraminiferal evidence, within interval 6 of the Vijlen Member, at *c.* 5 m above the Zonneberg Horizon (Fig. 4). Strontium isotope data (Vonhof *et al*., 2011) corroborate correlation of the lower/upper Maastrichtian boundary (as defined at Hemmoor, northern Germany; marl bed T100) with a level either close to the base of Vijlen Member interval 6 or within that interval. Ever since Jeletzky (1951), the FAD of *Belemnitella junior* has been used to define the base of the upper Maastrichtian in northwest Europe (Christensen, 1990, 1996, 1997). This concept can still be applied to the study area, where *Belemnitella junior* first appears close to the base of Vijlen Member interval 4, *c.* 20 m below the base of interval 6. At Hemmoor, however, the FAD of *Belemnitella junior* is *c.* 4.9 m above marl bed T100. These discrepancies between belemnite zonation on the one hand, and strontium isotopes and benthic foraminiferal zones on the other, cannot be explained at this moment.

Vijlen and Lixhe members – As noted by Albers & Felder (1979), the Maastrichtian age of the Vijlen Member has never been questioned. However, assignments and correlations with sections elsewhere have varied considerably. Schulz (1979) mentioned middle *Belemnella obtusa* Zone belemnites from the Beutenaken area, while Keutgen & van der Tuuk (1991) recorded early forms of *Belemnella* (*Pachybelemnella*) *obtusa* Schulz, 1979, from burrow fills in the uppermost Beutenaken Member at the Habets (Beutenaken) and Bovenste Bos quarries. In addition, Keutgen (1996) noted *Belemnella* (*Belemnella*) *lanceolata* (von Schlotheim, 1813) and *Belemnitella minor* (*sensu* Christensen, 1995), an association typical of the lower *obtusa* Zone (*sensu* Schulz, 1979). Keutgen (2011) noted that, similar to the late late Campanian *Belemnitella minor* II Zone, there are no *in situ* occurrences in the type area of the Maastrichtian Stage of the *Belemnella obtusa* Zone. Only remanié elements of this zone, such as *Belemnella obtusa* and *Belemnitella minor* II, have been recorded from the base of the Vijlen Member in the Beutenaken area. Reworked specimens of *Belemnella* (*Belemnella*) *lanceolata*, from the base of the same member in that area, co-occur with *Belemnella obtusa* and are tentatively considered to be of *obtusa* Zone age, at least for now.

As the highest early Maastrichtian coleoid zone, Keutgen (2011) distinguished the *Belemnella* ex gr. *sumensis/cimbrica* Zone, documented in interval 3 of the Vijlen Member at Aachen-Schurzelterstraße (see also Keutgen *et al*., 2010). Material that matches the 'population' concepts of both *Belemnella sumensis* Jeletzky, 1949, and *Belemnella cimbrica* Birkelund, 1957, is common in the Vijlen Member, but most specimens must be considered reworked (see Keutgen *et al*., 2010). The latter authors noted but a single larger sample of *Belemnella* from below the FAD of *Belemnitella junior*, namely from interval 3 at Aachen-Schurzelterstraße, where the typically early Maastrichtian scaphitid ammonite *Acanthoscaphites tridens* (Kner, 1848) is associated. This sample represents either a late form of *Belemnella sumensis* or, alternatively, *Belemnella cimbrica*.

Interval 4 of the Vijlen Member at Altembroeck (Voerstreek) yielded common early forms of *Belemnella sumensis* and rare *Belemnella praearkhangelskii* Naidin, 1964 (see Keutgen, 1997), which co-occur with *Belemnitella junior* Nowak, 1913, and *Belemnitella* *lwowensis* Naidin, 1952. Therefore, species of *Belemnella* from this interval are considered reworked; at Kronsmoor (northern Germany), *Belemnella praearkhangelskii* is known from the middle *Belemnella sumensis* Zone. Vijlen Member intervals 5 and 6, and the Lixhe 1-3 members, are assigned to the *Belemnitella junior* Zone.

On the basis of inoceramid bivalves, Walaszczyk *et al*. (2010) equated Vijlen Member intervals 3 and 4, and the basal portion of interval 5, with the *Trochoceramus radiosus* Zone, and interval 6 with the *'Inoceramus' ianjonaensis* Zone.

In a sequence-stratigraphic context, the following can be stated about the Vijlen Member. Keutgen (1996) noted that rhythmic changes in palaeowater depth could be seen which might have sequence-stratigraphic value, cycles of 4th to 6th orders being interpreted as short-lived sea level fluctuations, possibly explained by climatic fluctuations. Third-order cycles are used to correlate on a worldwide scale, distinguishing between lowstand, transgressions, high stand and maximum flooding surfaces. Cycle 4.4 can be assumed at the base or in the lower part of the Beutenaken Member, the Slenaken Horizon possibly matching the transgressive tract at the 4.3/4.4 cycle boundary (see Fig. 3), the glauconitic (= greensand) portion representing a lowstand deposit and the remainder of the member, together with the basal Vijlen Member (interval 0), representing a transgression (palaeowater depth to a maximum of 40 m). Intervals 1-5 of the Vijlen Member possibly correspond to the highstand phase of cycle 4.4 (palaeowater depths between 80-100 m), while the base of interval 6 could well be the maximum flooding surface at the 4.4/4.5 cycle boundary. Interval 6 and the basal Lixhe 1 Member could then be interpreted as lowstand deposits of cycle 4.5 (palaeowater depth to a maximum of 60 m). Lower-order cycles may be either climate controlled or the result of synsedimentary regional tectonic processes.

Vandenberghe *et al*. (2004) recognised the following sequence boundaries: M1 (dated at 70.8 Ma), M2 (70.0 Ma = base of Vijlen Member interval 0), M3 (69.4 Ma = base of Vijlen Member interval 4), M4 (68.9 Ma = base of Lixhe Member) and M5 (67.5 Ma = top of Lanaye Member). Later work by Keutgen & Jagt (2009) provided estimates of absolute numerical ages for sequence boundaries, linked to very long (*c.* 2.4 myr) and long (0.41 myr) eccentricity cycles and a comparison with ages of biozone boundaries in the United States Western Interior and northern Germany (Kronsmoor, Hemmoor) (see Table 2).

As far as current concepts of early Maastrichtian belemnitellids are concerned (see Schulz, 1979), ongoing studies in central Poland and northern Germany hint at considerable alterations in taxonomy and biozonation in the near future (Remin, 2006, in press; Niebuhr *et al*., 2011).

Lanaye Member – Albers & Felder (1979) noted the occurrence in this member of benthic foraminifera typical of Hofker's (1966) zone F and Koch's (1977) *Gavelinella danica* Zone, of early late Maastrichtian age. Belemnitellids are common and comprise mostly representatives of *Belemnitella junior* and a minor percentage of *Belemnitella lwowensis.* Ammonites are extremely rare, poorly preserved phosphatised baculitids being the only taxa known to date. Nannofossil assemblages are held to be indicative of the *Lithraphidites quadratus* Zone (Čepek & Moorkens, 1979; Verbeek, 1983; Robaszynski *et al*., 1985), while planktonic foraminifera (Moorkens, 1971; Bellier & Villain, 1975; Robaszynski *et al*., 1985) include *Globotruncana contusa* Zone taxa, confirming the late Maastrichtian age, but unsuitable for detailed correlations.

Maastricht Formation (Valkenburg to Meerssen members) – In recent years it has been amply demonstrated that lithostratigraphical correlations in Upper Cretaceous strata of the Maastrichtian type area, and in particular within the Maastricht Formation, were not as firm as previously believed (e.g., Bless *et al*., 1987; W.M. Felder, 1996). A combination of detailed ostracod, benthic foraminifer and bioclast studies resulted in a kind of ecostratigraphical zonation, which can be readily applied within the type area. Naturally, this synthesis offered solutions for quite a number of correlation problems, but to this day some difficulties still remain. For instance, a bed-by-bed correlation between the section exposed at the ENCI-HeidelbergCement Group and the CBR-Romontbos quarries (Fig. 1) is straightforward for the Lanaye Member (Gulpen Formation), but problems arise especially in the lower part of the overlying Maastricht Formation.

Recent collecting efforts have concentrated on the upper Meerssen Member as exposed at the ENCI-HeidelbergCement Group quarry. In the course of these studies it has become apparent that bed-by-bed correlation in this member is complicated even within this quarry. Storms have obviously played an important role during deposition of these sediments and have had a considerable impact on (macro)fossil preservation. Obrution phenomena have been noted on various occasions. Hydrodynamic energy during storm events can be held responsible for the peculiar distribution pattern (convex-down) of the generally extremely fragile exuvia of numerous species of decapod crustacean (Collins *et al*., 1995). Faunal studies have also led to the realisation that the Meerssen Member at this quarry was more complete and could be correlated with the Geulhem-Berg en Terblijt area in more detail than previously thought (Jagt, 1995a, 1996, 2000d).

Belemnitellids of the *Belemnitella junior* group range throughout the entire Maastricht Formation, to be accompanied by the first representatives of the eastern European group of *Belemnella* (*Neobelemnella*) *casimirovensis sensu* Jeletzky, 1951 (= *Belemnitella kazimiroviensis* Skołozdrówna, 1932) from the top of subunit IVf-3 or the base of IVf-4 of the Meerssen Member onwards (Jagt, 1996). Van der Tuuk & Bor (1980) noted that 'populations' of this species in the Maastrichtian type area consisted mainly of juvenile and subadult specimens, an observation confirmed by subsequent studies. Christensen (1996, 1997) showed the distribution of *Belemnella kazimiroviensis* across Europe, from the eastern part of the Russian Platform to the Maastricht area, to be highly diachronous. The absence of representatives of this species in the uppermost Maastrichtian at Hemmoor which, on other macrofossil evidence, can be well correlated with the coeval part of the Danish White Chalk, is puzzling. However, it should be noted that the section at Hemmoor does not extend above the *baltica*/*danica* Zone (Schulz & Schmid, 1983; Christensen, 1996) and that the uppermost 6 m of the section exposed have not yielded any belemnites. The FAD of *Belemnella kazimiroviensis* in the type Maastrichtian apparently coincides with the demise of the great majority of rudistid bivalves and most (if not all) hermatypic scleractinian taxa in the area, and thus suggests a (?temporary) incursion of cold-water forms into a very shallow, subtropical setting. Of note also is that this 'faunal change' more or less matches the proposed rapid local subsidence to account for the extreme thickness of section IVf-6 of the Meerssen Member (see above). This tectonic activity, dated at *c.* 100,000 years prior to K/Pg boundary, if one accepts Vonhof & Smit's (1996) estimate of *c.* 10 cm/kyr sedimentation rate, could have resulted in deeper waters and an increased sedimentation rate. Representatives of the *Belemnella* *kazimiroviensis* group range to the K/Pg boundary (= Berg en Terblijt Horizon; see Fig. 5) and dominate coleoid assemblages there. Both clearly reworked and fairly well-preserved specimens have been collected from the base of subunits IVf-7 and Va-1 at the former Curfs quarry (Fig. 5), and from the base of IVf-7 at the Geulhemmerberg subterranean sections, where 'battlefields' of the 'resedimented accumulate type' of Doyle & Macdonald (1993) occur. To date, no specimens, fresh or otherwise, are known from the remainder of subunit IVf-7, despite the fact that it contains other, typically latest Maastrichtian macrofossils.

Ammonite ranges in the type Maastrichtian show a considerable preservational bias (Jagt & Kuypers, 1994; Jagt, 1995b, 2005). Most ammonite records stem from (partially) indurated portions in the sequence. The fact that such portions are rare in the upper Gulpen/lower Maastricht formations may in part explain the discrepancies seen when comparing ammonite ranges in the 'Maastricht tuffaceous chalk facies' and in the 'Kunrade Limestone facies'. Amongst stratigraphically important taxa is the pachydiscid *Menuites terminus* (Ward & Kennedy, 1993). To date, a handful of specimens is known from the middle/upper Meerssen Member (Jagt, 1995a, b, 1996; Machalski & Jagt, 1998; Jagt *et al*., 2006). In the Bay of Biscay sections of southwest France and northern Spain, this short-ranging species is the index of the latest Maastrichtian *terminus* Zone, its FAD lying 30-40 m below the K/Pg boundary at Zumaya, Hendaye and Bidart. The species has also been recorded from the upper (uppermost) Maastrichtian of Denmark (Birkelund, 1993), Poland (Machalski & Jagt, 1998), Bulgaria (Ivanov, 1995), Azerbaijan and South Africa (Kennedy & Klinger, 2006).

The scaphitid ammonite *Hoploscaphites constrictus* has often been cited as a valuable marker species for the Maastrichtian. Machalski (2005) documented three subspecies throughout the Maastrichtian of Poland, Ukraine, Denmark and the southeast Netherlands, noting that the youngest subspecies extended into the lower Paleocene (compare Machalski *et al*., 2009). The occurrence of well-preserved baculitid ammonites, inclusive of common *Eubaculites carinatus* (Morton, 1834), in the uppermost part of section IVf-7 (i.e., in the chalkstone underlying the Vroenhoven Horizon), is of note. Similar to localities in Denmark (Machalski & Heinberg, 2005) and New Jersey (Landman *et al*., in press), it appears that the scaphitid and the baculitid survived environmental perturbations triggered by the end-Cretaceous bolide impact at least for a certain length of time.

The range of the stratigraphically important 'tegulated' inoceramid bivalve *Tenuipteria argentea* (Conrad, 1858) in the type Maastrichtian is still rather poorly known. Undoubted specimens are known from the entire Meerssen Member, with an acme in subunit IVf-6. However, a coquina-like concentration of what appears to be the equivalve inoceramid *Spyridoceramus tegulatus* (von Hagenow, 1842) is known from the upper Nekum Member and recent finds of flint-preserved material documents this species from the Lanaye Member in the Haccourt/Lixhe area (northeast Belgium). In this respect, it appears that *Spyridoceramus tegulatus* ranges from the Vijlen Member (intervals 3, 5 and 6; see Walaszczyk *et al*., 2010) to the top of upper Nekum Member, and that *Tenuipteria argentea* is more or less confined to the *Belemnella kazimiroviensis* Zone, as in central Poland (Abdel-Gawad, 1986; compare Dhondt, 1983, 1992).

Amongst echinoids there are very few taxa that can be used for interregional correlations. Although psychocidarine echinoids are now also known to occur in the type

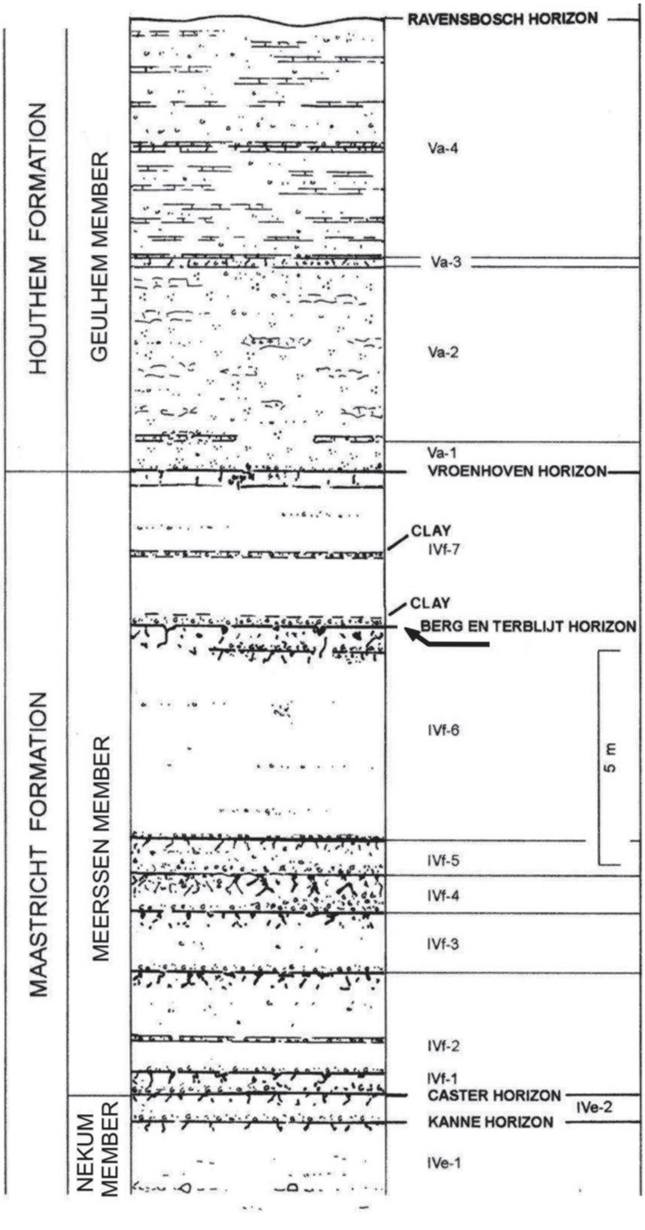

Fig. 5. Litholog of the section formerly exposed at the Curfs-Ankerpoort quarry (Geulhem), with indication (arrow) of the Cretaceous-Paleogene (K/Pg) boundary, equating with the Berg en Terblijt Horizon at the top of subunit IVf-6 (modified after Jagt *et al*., 1996, fig. 7).

Maastrichtian (entire Meerssen Member), such forms are more typical of the overlying Geulhem Member (Houthem Formation) of early Paleocene age. The fact that occasional finds of abraded spines, all apparently assignable to *Tylocidaris* (*Tylocidaris*) *hardouini* (Desor, 1855), are known from the top of the Meerssen Member (subunit IVf-6) at the ENCI-HeidelbergCement Group and former Blom quarries, proves that Geulhem Member sediments must at one time have been present there. It is assumed that the late Eocene/early Oligocene transgression removed such strata.

Planktonic foraminifera (Hofker, 1966; Moorkens, 1971) in the type Maastrichtian are rare, are often ill preserved and do not allow precise age assignments. Amongst the rich benthic assemblages, large 'Tethyan' forms predominate especially in the upper Nekum Member and throughout the overlying Meerssen Member (Bignot & Neumann, 1991), although some species first occur considerably lower in the section (pers. obs.). In the literature, comparable forms have also been recorded from northern Europe, at the southern limit of the deeper-water white chalk facies (E. Voigt, 1951, 1963; Hagn & Voigt, 1986; see also Diener, 1967; Trümper, 1970; Fahrion, 1984). A combination of 'Tethyan' migratory pulses reaching far into northern Europe on account of favourable ocean currents intimately linked with inversion tectonics in some areas (Bless, 1989, 1991a) and suitable substrates/preferred temperature ranges in (extremely) shallow-water settings could explain this picture. In this respect, the term 'endemic' to explain why quite a number of faunal elements seem to be restricted to the Maastrichtian type area should be used with caution.

The highly diverse selachian faunas of the type Maastrichtian have received ample attention over recent years, but taxonomic work has not been completed yet. Preliminary results are promising as far as intercontinental correlations are concerned. The 'Tethyan' pulses apparently have a (?combined) North African/South European as well as a North Atlantic origin (compare Bless, 1991a; Malchus, 1996). In this respect it is of note that Haslett (1994) noted a palaeoceanographical change for the Bay of Biscay sections from a Tethyan- to a North Atlantic-dominated setting during the latest Maastrichtian. Schönfeld & Burnett (1991) remarked that the warm water outflow from the northwest European epicontinental seas through the Channel could well have been the dominant factor in separating the Boreal and Tethyan bioprovinces on the western European shelf. They considered that the palaeoceanographical setting as well as wind-driven surface currents and bottom currents could also have played an important role. During the late Maastrichtian, tectonic movements resulted in changes in circulation patterns, which were superimposed on the late Maastrichtian sea level highstand. Tethyan planktonic foraminifera, common in northwest Germany and the North Sea Basin during that time, could thus reach the northwest European epicontinental seas and the same scenario probably explains the occurrence of ammonite taxa such as *Eubaculites carinatus* in the Meerssen Member.

Brinkhuis & Schiøler (1996) documented that the uppermost Meerssen Member in the Geulhemmerberg section (= subunit IVf-6) could be correlated with the uppermost Maastrichtian in other parts of the North Sea Basin (see also Brinkhuis & Smit, 1996; Schiøler *et al*., 1997). Dinoflagellate distribution in the section exposed at the ENCI-HeidelbergCement Group quarry has also enabled the first sequence-stratigraphic interpretation of the type Maastrichtian (Schiøler *et al*., 1997). Those authors documented a change from open marine to marginal marine conditions at the boundary between the Lixhe 3 and Lanaye members. In addition, they interpreted changes in lithology and palynological assemblages in the light of a sequence-stratigraphic scheme, noting that parts of four cycles (UZA 4.5, TA 1.1, TA 1.2 and a fourth of probably higher order) could be recognised.

A cooling trend during the latest stages of the upper Maastrichtian in the type area is indicated by the marked decrease in spore diversity and the disappearance of pollen of the conifer family Cheirolepidiaceae (*Classopollis*-*Classoidites*) in the upper Maastricht Formation, from about the Lava Horizon (= middle of Emael Member) upwards (Herngreen *et al*., 1998; van der Ham *et al*., 2003, 2010). Obviously, this contrasts with the highly diverse rudistid bivalve and scleractinian coral assemblages from the top of the Nekum to the middle of the Meerssen Member (subunit IVf-4), which document warm- and shallow-water conditions. A temperature decrease is suggested for the upper Meerssen Member, with typically cold-water coleoids entering the basin, although a brief return to warm-water conditions is indicated for the very top of this member (subunit IVf-7, of early Paleocene date). Otherwise, early Paleocene assemblages appear to be of a generally Boreal signature, with the absence of certain crinoids (isocrinids) and echinoids (echinocorythids) probably depth related.

Finally, Vonhof & Smit (1996) were the first to use the strontium isotope profile for the type Maastrichtian for correlation with Bidart (southwest France) and El Kef (Tunisia). In addition, they calculated a sedimentation rate of *c.* 10 cm/kyr for the upper 30 m of the type Maastrichtian (= base Emael Member to top Meerssen Member).

Acknowledgements

We are grateful to various colleagues who commented on (parts of) earlier incarnations of the typescript.

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