Late Cretaceous-Early Palaeogene echinoderms and the K/T boundary in the southeast Netherlands and northeast Belgium — Part 1: Introduction and stratigraphy

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In a series of papers describing Late Cretaceous and Early Palaeogene echinoderm faunas (exclusive of holothurians) of the Maastrichtian type area, the present contribution comprises a detailed account of the litho- and chronostratigraphy and biozonations of these deposits, and of localities from which the echinoderm material to be described stems. In subsequent papers reference will be made to this introductory part.

Contents

Introduction

The present paper is the first in a series of contributions documenting echinoderm faunas of Late Cretaceous and Early Palaeogene age from the extended Maastrichtian type area. These contributions will be principally taxonomic in nature. On the basis of these revisions, the crinoids, echinoids, ophiuroids, and asteroids will then be analysed palaeobiologically and palaeoecologically in the concluding paper of this series. Analyses of functional morphology in turn will provide explanations for changes in echinoderm faunas across the Cretaceous/Tertiary (K/T) boundary in the area (Jagt, in prep. d). Comparisons with extant faunas allow conclusions to be drawn with regard to habitat preference and functional morphology of these fossil echinoderm taxa.

The present paper comprises a lengthy discussion of the litho- and chronostratigraphy (and biozonation) of the fossiliferous strata considered, to which reference will be made in subsequent papers (Jagt, 1999; in prep. a-c). Historical accounts of the research of these echinoderm groups are to precede the systematic descriptions; these will include citations from literature sources not easily accessible.

Geographic and stratigraphic setting

All material discussed in the present paper comes from a number of (disused) quarries and other exposures in the extended type area of the Maastrichtian Stage, which includes portions of the Belgian provinces of Limburg (inclusive of the '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) at Haccourt-Hallembaye, of Cimenterie Briqueterie Réunie (CBR) at Lixhe, of CBR-Romontbos at Eben Emael (Bassenge), and Marnebel-Ankerpoort at Eben Emael. Together, these quarries expose a section of Early Campanian to Late Maastrichtian age, with the exclusion of most of the Early Maastrichtian. The Late Maastrichtian portion of this sequence is complemented by sections exposed along the Albertkanaal at Kanne, Vroenhoven-Riemst and Veldwezelt in the province of Limburg. However, K/T boundary sections formerly accessible at the two last-named localities are now mostly overgrown. The ENCI-Maastricht BV quarry south of Maastricht, which comprises the stratotype of the Maastrichtian Stage, currently exposes part of the Early Maastrichtian and the Late Maastrichtian up to within a metre (or less) of the K/T boundary. Correlation of the upper Gulpen Formation (Lixhe and Lanaye members), as exposed at the CPL SA, CBR-Lixhe, CBR-Romontbos, and ENCI-Maastricht BV, is generally straightforward.

Quarries east of the river include Blom (Berg en Terblijt), Curfs-Ankerpoort (Geulhem), Nekami-Ankerpoort (Bemelen), and are complemented by a number of (natural) exposures in the Heerlen-Kunrade area. In the Curfs-Ankerpoort quarry, a K/T boundary section is currently well exposed, and combined with the underground sections of the Geulhemmerberg nearby, this comprises the most complete boundary section in the area (Brinkhuis & Smit, 1996) and the best outcrop of the Geulhem Member of the Houthem Formation. Outcrops in the Heerlen-Kunrade area expose the Beutenaken Member (Vaals Formation) and the Kunrade Limestone facies of the Maastricht Formation (W.M. Felder, 1978).

Outcrops in the so-called 'Voerstreek' (province of Limburg, Belgium) are located near 's Maartensvoeren and 's Gravenvoeren and expose the Early Maastrichtian, as did a number of temporary outcrops in the Aachen city area, now built over (Keutgen, 1996).

The stratigraphic framework of the echinoderm collections corresponds to the detailed lithostratigraphy proposed by W.M. Felder (1975a, b). Lithologic logs published by that author for the various quarries and outcrops have been used to document the stratigraphic provenance of the specimens. Despite some inconsistencies in correlation between a number of these sections, these provide a detailed picture of the stratigraphic distribution of the various species. Included in the present paper are only lithostratigraphic logs of the key sections (CPL SA, CBR-Lixhe, CBR-Romontbos, Marnebel-Ankerpoort, ENCI-Maastricht BV, Nekami-Ankerpoort, Blom, and Curfs-Ankerpoort).

Formations and members proposed and discussed by W.M. Felder (1975b), Albers & Felder (1979) and W.M. Felder & Bosch (in press) are briefly described below. Their (bio)stratigraphy is discussed in detail, with reference to literature sources and personal observations (macrofossil zonations). The lithostratigraphy, inclusive of horizons separating members of the various formations, is shown in Fig. 2, while Fig. 3 illustrates current correlations of the Maastrichtian type area with the standard section for the northwest German Late Cretaceous white chalk facies (Schulz et al., 1984; Schulz, 1985; Schönfeld et al., 1996b).

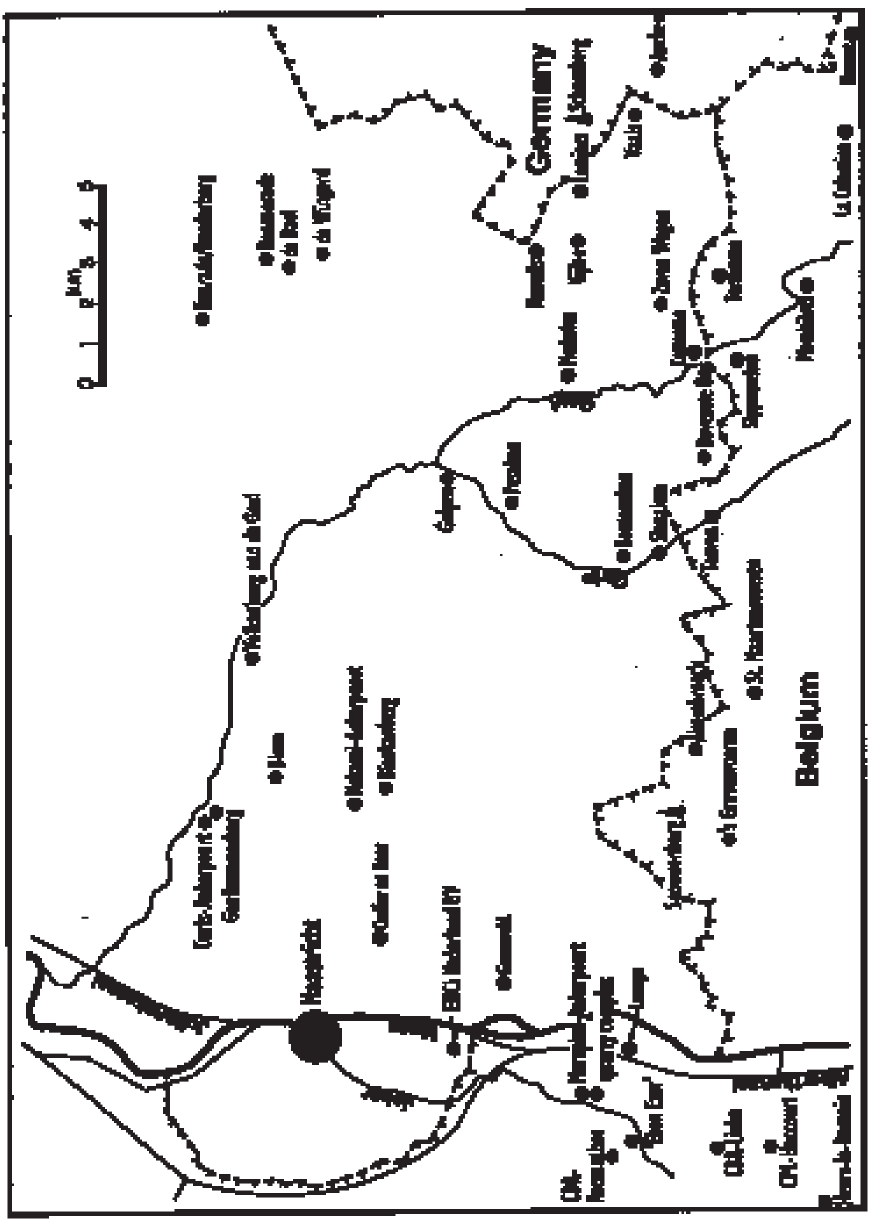

Fig. 1. Map of southern Limburg (The Netherlands), portions of the Belgian provinces of Limburg (Voer) and Liège, and the Aachen area (Germany), showing localities mentioned in the text.

Formation	Member	Horizon
		Lutterade
Houthem Formation	Geleen Member	
		Geleen
	Bunde Member	
		Bunde
	Geulhem Member	
		Vroenhoven
Maastricht Formation	Meerssen Member	
		Caster
	Nekum Member	
		Laumont
	Emael Member	
		Romontbos
	Schiepersberg Member	
		Schiepersberg
	Gronsveld Member	
		St. Pieter
	Valkenburg Member	
		Lichtenberg
Gulpen Formation	Lanaye Member	
		Nivelle
	Lixhe 1-3 Members	
		Wahlwiller
	Vijlen Member	
		Bovenste Bosch
	Beutenaken Member	
		Slenaken
	Zeven Wegen Member	
		Zeven Wegen
Vaals Formation	Benzenrade Member	
		Benzenrade
	Terstraten Member	
		Terstraten
	Beusdal Member	
		Beusdal
	Vaalsbroek Member	
		Overgeul
	Gemmenich Member	
		Gemmenich
	Cottessen Member	
		Cottessen
	Raren Member	
		Raren
Aken Formation	Hauset Member	
		Flög
	Aken Member	
		Schampelheide
	Hergenrath Member	
		Hergenrath

Fig. 2. Local lithostratigraphic subdivision of Upper Cretaceous-Lower Palaeogene strata (after W.M. Felder, 1975a; W.M. Felder & Bosch, in press), with indication of horizons separating the various members.

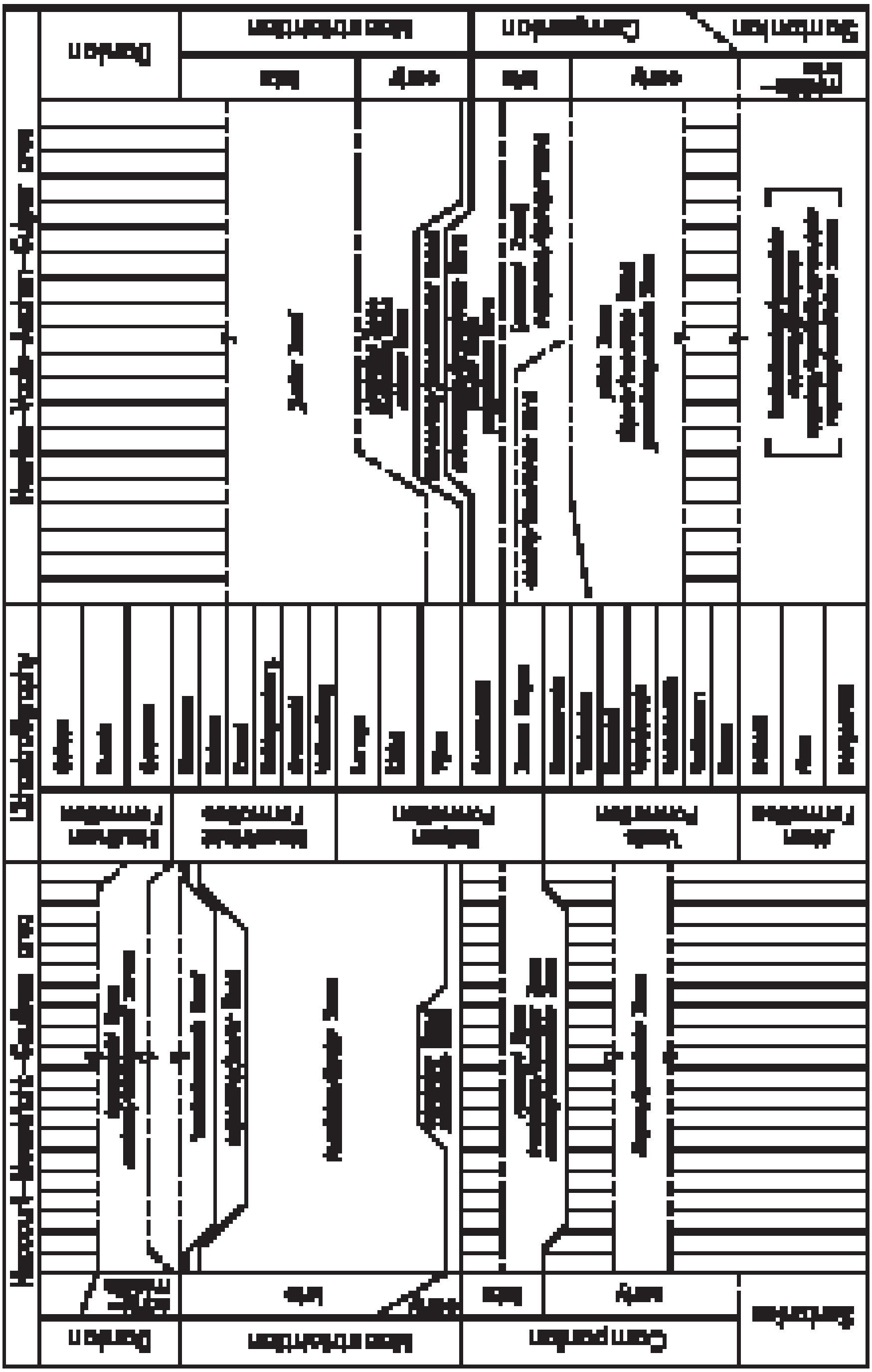

Fig. 3. Biozonation and correlation of strata exposed in the (extended) type area of the Maastrichtian Stage with the Upper Cretaceous white chalk standard section for NW Germany (after Schulz et al., 1984; Schönfeld et al., 1996b).

Currently no echinoderms are known from the entire Aken Formation and from most of the Vaals Formation. However, these two units are also discussed in some detail for the sake of completeness.

Aken Formation

Lithostratigraphy and facies interpretation

The type area of the Aken Formation, a complex unit with a total thickness of up to c. 130 m, is situated south of Aachen in the 'Aachener Wald' (German-Belgian border; W.M. Felder, 1975b; Albers et al., 1978; Albers & Felder, 1979; Batten et al., 1988). This formation, which rests on eroded Palaeozoic carbonate and psammitic/pelitic rocks, comprises three members which have been defined as follows:

Hergenrath Member

Stratotype — Schampelheide quarry (exposure 43/1-2, no. 1) at Kelmis/La Calamine (northeast Belgium), co-ordinates 302.750/201.250.

This unit (thickness: 10-35 m) comprises a sequence of alternating light to dark grey, sandy and silty clays with silty and clayey, light grey fine- to coarse-grained sands, with subordinate fine-grained gravel, silts, minor red clays, and ferruginous horizons. Locally these beds contain large quantities of wood debris, as well as marcasite and pyrite concretions. Common are root horizons, in part associated with thin lignite deposits, especially in the upper portion. These contain rich assemblages of autochthonous and parautochthonous gymnosperm and angiosperm remains. Where this member rests on a carbonate basement, variegated sandy and silty clays occur at the base.

Albers & Felder (1979) interpreted this unit to be of generally terrestrial, fluvial-limnic origin, with probable marine ingressions. The occurrence of channel fills as well as lenticular beds makes a spatial differentiation into several biotopes likely.

Between this unit and the overlying Aken Member there is a minor disconformity, the break in deposition being considered to have been of short duration.

Aken Member

Stratotype — Käskorb quarry (exposure 62D-74) at Kelmis/La Calamine (northeast Belgium), co-ordinates 304.000/199.750.

This unit consists of well-sorted, yellow-white to clean white and limonite-stained fine sands, locally with irregular gravelly sandstone beds and concretions. In most places, small- and large-scale cross-bedding is observed, interfingering laterally and vertically. In the lower part, lenticular bodies of silty clays occur sporadically. Traces of bioturbation are either concentrated locally or irregularly distributed. Total thickness is up to c. 15 m, with a maximum of c. 40 m, inclusive of the overlying Hauset Member.

Albers & Felder (1979) noted the (virtually) complete secondary decalcification and distinguished at least three biotopes. They interpreted this unit as follows: fully marine, invariably above wave base, high energy, rapid erosion and sedimentation of mobile sand bodies, strongly current-influenced, episodic emersion phases linked to formation of large channels, strong lateral subdivision of biotopes.

Silicified (coniferous) wood and cones have been collected from the sands, while the silty clays have yielded twigs and foliage (Dernbach, 1996). J.J.F. Meijer (1994, 1997, work in progress) recorded Taxodiaceae, Pinaceae and Araucariaceae amongst gymnosperms, and various families amongst angiosperms (see Knobloch, 1994, 1997; Knobloch & Mai, 1991; Knobloch et al., 1993; Selmeier, 1996), documenting seasonal and humid warm temperate climate conditions (see also Bless & Fernández Narvaiza, 1996).

Hauset Member

Stratotype — Flög quarry (exposure 43-1/2, no. 3) at Hauset (northeast Belgium), co-ordinates 203.470/303.360.

This member comprises a sequence of alternating well-sorted, light to moderate grey, fine sands with variable amounts of silt and intercalated thin beds of dark grey and brownish fine sandy, weakly clayey silt to silty clay. Flaser cross-bedding occurs commonly; bioturbation is of varying intensity. The base of the overlying unit (Raren Member, Vaals Formation) is a conglomerate of Palaeozoic sandstones and quartzites with bioturbations, and rests on an erosion surface.

Albers & Felder (1979) noted that locally large channel fills occurred, in part associated with large cross-bedded sediment bodies, and that again at least three biotopes could be distinguished. Records of marine fossils (few and poorly preserved molluscs) from this member are known only from the literature; ichnofossils, however, are common and demonstrate rich endobenthic assemblages. These authors interpreted this unit as (?) fully marine, episodic emersion demonstrated, in part episodically limnic-brackish, otherwise invariably above wave base, decreased dynamics, moderate erosion associated with moderate sedimentation, decreased current activity. The (near) absence of marine fauna is probably the result of decalcification. The erosion surface (Raren Horizon) between this unit and the overlying Raren Member (Vaals Formation) represents a hiatus of unknown duration.

Biostratigraphy

Albers & Felder (1979) noted that the few agglutinated foraminiferal species from the Aken Formation which survived the (near)complete decalcification, were of no stratigraphic value. However, these authors mentioned a fauna of inoceramid bivalves from the Aken and Hauset members which suggested that at least part of the sequence is of Late Santonian age. This then suggests a pre-Late Santonian age for the underlying Hergenrath Member.

In the literature (e.g. Purves, 1883; Holzapfel, 1885, 1887-1889) quite a number of marine macrofossil taxa have been recorded from the Aken Formation, but, as pointed out by Holzapfel, many of these have been misidentified and, more seriously, must be considered lost. The species listed by the latter author suggest a general Late Santonian-Early Campanian age, with many taxa ranging up into the Vaals Formation, generally representing medium- to large-sized, thick-shelled bivalves and gastropods.

Rich associations of spores, pollen and some dinoflagellate cysts have been recorded from the Aken Formation, varying according to lithology and degree of weathering at outcrop. Batten et al. (1988) described dinocysts from the Hauset Member as exposed at the Dickenbusch quarry near Henri-Chapelle (northeast Belgium) and penetrated in two boreholes near Gulpen (southern Limburg, The Netherlands). These document a Middle-Late Santonian age, in accordance with earlier assignments. Palynomorphs recovered by these authors indicate a marginal marine environment, and suggest lagoonal conditions of deposition, under varying hydrodynamic regimes and salinity levels.

A similar, Middle Santonian to pre-Early Campanian palynomorph assemblage is known (Batten et al., 1987) from boreholes at Valkenburg (southern Limburg, The Netherlands) and 's Gravenvoeren (Limburg, Belgium), from a lithostratigraphic equivalent of the Hergenrath Member, as well as from the Aachen city area (Streel et al., 1994).

Coeval strata in the Houthalen and Zolder/Voort areas (Limburg, northeast Belgium) as described by Jagt, Kennedy et al. (1995) have yielded typically (Middle) Santonian (- Early Campanian) ammonoid and coleoid cephalopods such as *Placenticeras polyopsis* (Dujardin, 1837), *Scaphites kieslingwaldensis fischeri* Riedel, 1931, and *Gonioteuthis westfalicagranulata* (Stolley, 1897). Associated inoceramid bivalves, *Cordiceramus brancoiformis* (Seitz, 1961) [Middle-Late Santonian] and *Platyceramus* cf. *cycloides* (Wegner, 1905) [Santonian-Early Campanian], and calcareous nannofossils corroborate this age assignment. The latter group includes taxa that range from the late Early Santonian to the Santonian/Campanian (zones CC15 to CC17).

It is quite possible that the numerous borehole cores stored at the Service Géologique de Belgique (Brussels) may yield many new data regarding the geographic-stratigraphic extent not only of (lateral equivalents of) the Aken and Vaals formations (see e.g. P.J. Felder et al., 1985; Louwye, 1992; Christensen, 1994; Malchus et al., 1994, 1996) but also of parts of the overlying Gulpen and Maastricht formations. Many of these cores contain numerous coleoid cephalopods, especially in Gulpen Formation strata (pers. obs.), and may also yield material of the distinctive and stratigraphically highly important crinoid genera *Uintacrinus* and *Marsupites*. These benthic crinoids (Milsom et al., 1994a, b) have lately been considered in detail in discussions on the stage boundaries of the Santonian and Campanian (Klikushin, 1985; Mitchell, 1995; Lamolda & Hancock, 1996; Hancock & Gale, 1996).

Vaals Formation

Lithostratigraphy and facies interpretation

In the type area near Vaals-Vaalserberg, the Vaals Formation comprises six members with a total thickness of c. 150 m, to which W.M. Felder & Bosch (in press) added a seventh, the Benzenrade Member.

Raren Member

Stratotype — Roadside exposures along the 'Sandbergweg' (exposure 62G-14), Aachen-Vaalserquartier (Germany), co-ordinates 308.700/200.600.

In the type area, this member comprises predominantly laminated, yellow to greyish-green glauconitic fine-grained sands in channel fills. Lenticular sandstone bodies with a rich fauna occur in places. In a westerly direction, these interfinger with silty fine-grained sands and fine-grained sandy silts. Total thickness of this unit varies between 12 and 18 m.

Cottessen Member

Stratotype — Roadside exposures along the 'Holle weg' (exposure 62D-105) at Cottessen (Vaals, The Netherlands), co-ordinates 308.200/194.540.

In the type area, this unit consists of a cyclic alternation of yellow to greyish-green, glauconitic laminated channel sands and light grey-brown fine-grained sandy silts to silty fine-grained sands. Fossil-rich sandstone banks occur locally. Towards the west, a facies change similar to that in the Raren Member is observed, but more irregular siliceous concretions intercalate. The top of this unit corresponds to the Gemmenich Horizon (= Grenspaal 7 Horizon), which represents a fossiliferous, dark grey-green glauconitic illuvial horizon.

Gemmenich Member

Stratotype — Roadside exposures between Terstraten and 'grenspaal 6' (exposure 62D-114) near Bleiberg (northeast Belgium), co-ordinates 196.120/307.300.

Similar to the Cottessen Member; thickness c. 10-12 m.

Vaalsbroek Member

Stratotype — Roadside exposure at Mechelen-Overgeul, The Netherlands (exposure 62D-31), co-ordinates 311.820/192.000.

This unit comprises a cyclic alternation of yellow to greenish-grey, glauconitic, laminated fine-grained sands without silt and glauconitic silty fine sands with extensive bioturbation. Thickness up to 4-6 m.

Beusdal Member

Stratotype — Roadside exposure between Sippenaeken and Teuven (exposure 62D-133), east of Beusdal castle (northeast Belgium), co-ordinates 306.830/192.240.

In the east, this sequence comprises a cyclic alternation of poorly indurated, yellow to greyish-green, glauconitic, laminated fine sands without silt and glauconitic, silty fine-grained sands with extensive bioturbation. Thickness between 14 and 25 m.

Terstraten Member

Stratotype — Roadside exposure east of Terstraten (exposure 62D-114), at the

Netherlands/Belgium border, near 'grenspaal 6', co-ordinates 307.420/196.420.

This unit reaches a thickness of up to c. 15 m, and in the west comprises greyish green, silty fine-grained sands and fine-grained sandy silts with glauconite. The base is characterised by a poorly indurated, light grey, fine-grained sandy silt with fossil hash, yielding many specimens of the arcoid bivalve *Cucullaea subglabra* d'Orbigny, 1850.

Benzenrade Member

For stratotype designation and lithologic interpretation reference is made to W.M. Felder & Bosch (in press).

For the Vaals Formation, Albers & Felder (1979) distinguished three widely different biotope types which are laterally equivalent and alternate cyclically vertically.

The 'channel sands biotope' in the eastern part of the type area consists of generally poorly glauconitic, very well-sorted, fine-grained sands without silt as laminated fill of numerous successive channel generations. Bioturbation is absent or occurs only locally, being capped by abrasion. Nektonic faunal elements include littoral and pelagic fish species, but unequivocal bathypelagic taxa are absent. Albers & Felder (1979) interpreted this biotope as follows: fully marine, invariably above wave base, currents not demonstrated, mobile sand plates; emersion leading to episodic channel formation, not moving laterally (i.e. tidal influence absent); higher water levels leading to increased erosion and sedimentation dynamics, shallow abrasion at storm layers leading to erosion on the sand bodies, with partial destruction of biocoenoses and truncation of bioturbation; suspended matter later fills the channels.

The 'sand/silt biotope' (mud flat) with hash comprises silty, glauconitic, extensively bioturbated, fine-grained sands. The renowned Vaalsbroek locality (= fourth sand/silt horizon below the Beusdal Horizon in the Vaals-Eschbergweg section) represents an original biocoenosis of high diversity, including many gastropod species which suggest a rich thallophyte growth. Albers & Felder (1979) interpreted this biotope as fully marine, invariably above wave base, currents not demonstrated, decrease of erosion and sedimentation due to higher consistency of silt flats at increased hydrodynamic levels, increased bioturbation, episodically shallow abrasion, favourable environment for high-diversity biocoenoses, probably rich thallophyte growth.

The 'sand/silt without hash' comprises silty sand or sandy, strongly silty clay, less glauconite, moderate to low sorting, decalcification locally demonstrated. Extensive bioturbation; faunas probably less diverse, isolated finds only. Albers & Felder (1979) interpreted this biotope as fully marine, invariably below wave base, decreased erosion and sedimentation dynamics.

A spatial-temporal replacement of these three biotope types has been documented by Albers (1976), who distinguished four transgressive and three regressive phases. The Terstraten Horizon belongs to the youngest transgressive phase, being characterised by a marked decrease in diversity coupled with a high abundance of *Cucullaea subglabra*; this occurrence may represent the thanatocoenosis of an extreme biotope type.

It should be borne in mind that the boundaries between the six members originally defined in the type area of the Vaals Formation cannot be recognised outside that area. It is therefore impossible to establish bed-by-bed correlations with the clayey, smectite facies of the Vaals Formation, characterised by a *Gyrolithes* ichnofacies (Bromley & Frey, 1974), which occurs e.g. in the Haccourt-Lixhe area (Liège, northeast Belgium) and at Battice (Liège). This unit reaches a thickness of some 20 m at the CPL SA quarry (Haccourt), but only the upper 8-10 m have been exposed during recent years. Benthic foraminiferal faunas suggest that only correlatives of the lower part of the type Vaals Formation are represented in (the ? upper part of) the smectite facies (J.P.M.T. Meessen, pers. comm., 1988).

Biostratigraphy

Although portions of the Vaals Formation in its type area have yielded rich macrofaunal assemblages, important index biota such as inoceramid bivalves and ammonoid and coleoid cephalopods are rather rare. In addition, benthic foraminifera which have been shown to include excellent marker species for regional correlations, have suffered from extensive decalcification.

In the type area of the formation, Albers (1976) recorded the coleoid cephalopods *Gonioteuthis granulataquadrata* (Stolley, 1897) and *Belemnitella praecursor* Stolley, 1897 from the uppermost Cottessen Member. The former species, index of the *granulataquadrata* Zone of northwest German sections (Schulz et al., 1984), was also collected from the middle Gemmenich Member, as was a fragmentary specimen tentatively identified as *G. quadrata* (de Blainville, 1827). A *Gonioteuthis* 'population' from the base of the Beusdal Member was assigned to *G. quadrata* by Albers (1976) and compared with material from the interval of the *lingua/quadrata* to *senonensis* zones of northwest German sections. While the middle Beusdal Member yielded *B. praecursor*, no belemnites were recorded by Albers (1976) from the upper part of this member, nor from the overlying Terstraten Member.

On this evidence, Albers correlated the Vaals Formation in its type area with the upper *granulataquadrata* Zone to middle *pilula* Zone of the northwest German biozonal scheme, but noted that the age of the basal and uppermost portion was still under debate. The base of the *granulataquadrata* Zone has been shown to correspond with the United States Western Interior *Scaphites leei* III Zone dated at 83.5 ± 0.5 Ma (McArthur et al., 1993a).

It cannot be ruled out that the lower part of the Vaals Formation (in its type area as well as in the smectite facies of the Haccourt area) may be of Late (? latest) Santonian age. At a number of localities in the Vaals area, Albers (pers. comm., 1995) collected (silicified) ammonites, which have not yet been described. These may comprise Santonian taxa. On neoselachian evidence, Reynders (pers. comm., 1997) assumes a Santonian age for part of the Vaals Formation in the type area.

Neither facies of the Vaals Formation has yielded crinoids of the *Marsupites-Uintacrinus* group, so typical of the Santonian-Campanian boundary interval elsewhere (Bailey et al., 1984; Cobban, 1995; Hancock & Gale, 1996; Löser, 1985; Mitchell, 1994, 1995).

Ammonites from the uppermost 4-6 m of the smectite facies at the CPL SA quarry (Jagt, 1989) include *Pachydiscus duelmensis* (Schlüter, 1872), *P. launayi* de Grossouvre, 1894, *Eupachydiscus levyi* (de Grossouvre, 1894), and *Scaphites hippocrepis* (DeKay, 1828). These represent the Early (though not earliest) Campanian in ammonite terms (*Placenticeras bidorsatum* Zone, Hancock, 1991). On this evidence, (this part of) the Vaals Formation can be correlated with the Early Campanian in the Western Interior (Cobban, 1969, 1993; Lillegraven, 1991), in France (Kennedy, 1986a; Thomel, 1988), in northwest and northeast Germany (Ulbrich, 1971; Kennedy & Kaplan, 1995; Lommerzheim, 1995; Niebuhr, 1995; Wippich, 1995), in southern England (Gale, 1980; Mortimore, 1983, 1986), in northeastern Spain (Küchler & Kutz, 1989; Küchler, 1996a; Wiese et al., 1996), in Poland (B1aszkiewicz, 1979, 1980), and on the Russian Platform (Naidin, 1979; Akimetz et al., 1983). Associated coleoids corroborate this age assignment, the two species recorded (*G. q. quadrata* and *B. praecursor*) being typical of the upper part of the *lingua/quadrata* Zone sensu germanico (Christensen & Schmid, 1987).

Kennedy & Jagt (1995) noted that material of *Scaphites hippocrepis* in particular from Haccourt was comparable to Cobban's (1969) form II and included transitions to III. This part of the Vaals Formation thus spans the upper *granulataquadrata* to lower *lingua/quadrata* zones (top CC17 and CC18; McArthur et al., 1994). The latter authors recorded inflections in the strontium isotope curve which provide event markers for point calibration, and gave a date of 81 Ma for the *Scaphites hippocrepis* III Zone.

On coleoid cephalopod evidence (part of) the Vaals Formation can be correlated with the arenitic facies at Folx-les-Caves (Belgian Brabant; Bless et al., 1991). Repeated warm water pulses recognised there have also been recorded from coeval strata in borehole Metelen 1001, Münsterland (Germany; see Hiß, 1991; Lommerzheim, 1991).

The Benzenrade Member, a nearshore, shallow-water deposit representing a high-energy setting, corresponds with (part of) the so-called 'pre-Valkenburg strata' of P.J. Felder et al. (1985). It is dated on benthic foraminifera and coleoid/ammonoid cephalopod evidence as Late Campanian (Jagt et al., 1987), and considered to at least be part time equivalent with the Zeven Wegen Member (Gulpen Formation) (see Bless, 1988; Bless & Robaszynski, 1988; Jagt, 1988). In the literature, concentrations of large-sized ammonoids such as the one occurring at the De Dael outcrop (Jagt et al., 1987) have been recorded from close to sequence boundaries in relatively proximal deposits. This, following Wiese (1995), is seen as indicating regressive development and concomitant proximality.

A mass occurrence in the Benzenrade Member of the scleractinian genus *Micrabacia* in (temporary) sections at Benzenrade and De Wingerd, may correlate with comparable occurrences in the Zeven Wegen Member at Haccourt/Lixhe (Liège) and further to the west (Belgian Brabant; see Binkhorst van den Binkhorst, 1858).

The uppermost Vaals Formation in southeastern Limburg has yielded typically early Late Campanian ammonoid taxa (Jagt, Burnett & Kennedy, 1995), including *Hoplitoplacenticeras (H.) marroti* (Coquand, 1859), allowing correlation with the Campanian stratotype area (Kennedy, 1986a) and northern Spain (Küchler & Kutz, 1989; Küchler, 1996b). Nannofossil assemblages date these occurrences as CC/B20 of the boreal scheme proposed by Burnett (1990). Other Late Campanian ammonites recorded from these strata at Zeven Wegen-Vijlenerbosch are *Hoplitoplacenticeras (H.)* cf. *coesfeldiense* (Schlüter, 1867) and *Trachyscaphites spiniger* (Schlüter, 1872), as recorded by Kennedy (1986b, 1987).

Wiese et al. (1996) and G. Ernst et al. (1996) distinguished in the Santander area

(Cantabria, northern Spain) a *marroti* Zone or *marroti/coesfeldiense* Zone in the early Late Campanian, respectively. Its lower boundary corresponds to a sequence boundary, the Spanish equivalent of the northwest German Peine Tecto-Eustatic Event (Niebuhr, 1995; Niebuhr et al., 1997), and to a distinct acme in the distribution of the index ammonite in the upper half of the zone, some 15 m below its LAD (last appearance datum). In contrast, Kaever & Lommerzheim (1991) recorded from the Münsterland the occurrence of *Gonioteuthis quadrata gracilis* (Stolley, 1892), a typically latest Early Campanian coleoid subspecies (Christensen, 1990), at 19 m above the FAD of *H. marroti*.

Gulpen Formation

Lithostratigraphy and facies interpretation

Zeven Wegen Member

Stratotype — Exposure 62D-15b, along the tourist road Vaals-Epen, near the Zeven Wegen (Vijlenerbosch), co-ordinates 308.550/194.940.

This unit comprises light grey, fine-grained chalks with basal layer of glauconitic zone. Towards the west randomly distributed black, fine-grained flints with glassy fracture occur. Total thickness up to c. 30 m.

Villain (1977) considered the biomicrites (wackestones) of the 'Craie blanche à la Craie tigrée' (= Zeven Wegen, Beutenaken, Vijlen, and Lixhe members) to represent deposition in a setting under oceanic influence (based on the occurrence of calcareous nannofossils and planktonic foraminifera), but in the absence of transport or horizontal currents, at palaeodepths between 80 and 150 m. However, Bless (1988, 1989), on ostracod evidence, has put forward arguments in favour of a much shallower setting.

Beutenaken Member

Stratotype — Disused Habets quarry (exposure 62C-22), near Beutenaken, co-ordinates 309.270/188.250.

This member consists of light greyish to whitish yellow, glauconitic fine-grained clayey and limy marls, with a glauconite concentration in the lowermost metre. Total thickness up to c. 10 m. The Slenaken Horizon forms the boundary between the Zeven Wegen Member and the overlying Beutenaken Member in the type section, while the Bovenste Bos Horizon corresponds to the top of this member, now no longer accessible there.

Keutgen (1996, pp. 11-13) noted that according to Robaszynski et al. (1985, fig. 3) the upper part of the Vaals Formation and the lower portion of the Gulpen Formation were once exposed at this quarry. In this respect it is of note that amongst the type lot of *Pachydiscus colligatus* (Binkhorst, 1861) there is a specimen from an outcrop at Slenaken, which Kennedy (1987) assigned to *Eupachydiscus levyi* (de Grossouvre, 1894). This species is exclusively known from the Vaals Formation (Kennedy & Jagt, 1998).

At the disused Bovenste Bos quarry near Epen, which constitutes the stratotype of the Bovenste Bos Horizon, the Zeven Wegen, Beutenaken, and Vijlen members are exposed. The hardground at the top of the Zeven Wegen Member corresponds to the Slenaken (= Froidmont) Horizon, and forms the base of the Beutenaken Member, which attains a total thickness of c. 6.5 m. It comprises glauconitic clayey and limy marls with a c. 1 m thick glauconite concentration at the base. Except for the uppermost 0.7 m, the Beutenaken Member yields Late Campanian belemnitellids, documenting a '*langei*' Zone age (sensu Christensen, 1990) (see below). *Thalassinoides*-type burrows penetrate the uppermost metre of the member, and are filled with a glauconitic greensand-type of sediment, which corresponds to the sediment found locally in depressions on top of the Beutenaken Member.

On top of the local depression, infills follow at least 2 m of yellowish grey clayey and limy marls with a relatively high glauconite content and few quartz pebbles, with an up to 0.05 m thick basal lag deposit, which attests to a hiatus or a condensed sequence at the base of this unit. This base corresponds to the early and late Early Maastrichtian boundary (sensu Schulz, 1979). On coleoid evidence, this portion of the Vijlen Member is unequivocally coeval with interval 0 of P.J. Felder & Bless (1994).

At Pesaken-Crapoel, Vaals Formation strata underlie the Zeven Wegen, Beutenaken and Vijlen members. Resting on the Slenaken Horizon erosion surface are 3.5 m of glauconitic greensand to sandy chalk with few quartz pebbles, assigned to the Beutenaken Member. Belemnites are concentrated at the base and at the top of this unit, and suggest a latest Campanian ('*langei*' Zone) to earliest Maastrichtian (*lanceolata* and/or *pseudobtusa* zones) age. Resting on this unit are at least 1.5 m of yellowish grey clayey and limy marls, referred to the Vijlen Member, and probably corresponding to interval 0 of P.J. Felder & Bless (1994). These yield *Belemnella (Pachybelemnella) sumensis* Jeletzky, 1949, and in the absence of *B. (P.) obtusa* Schulz, 1979, this suggests a low sedimentation rate across the Beutenaken/Vijlen boundary.

A road cutting northeast of Teuven (Keutgen, 1996) exposed a section of Beutenaken Member sediments, consisting of soft, glauconite-rich clayey and limy marls with few, scattered quartz pebbles. Belemnites suggest a '*langei*' Zone age (sensu Christensen, 1990).

Vijlen Member

Stratotype — Roadside exposure between Mamelis and Bocholtzerheide north of Vijlen (exposure 62D-79), co-ordinates 312.330/196.450.

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

The most complete section of Vijlen Member sediments known to date results from combining sections exposed in outcrop 62D-79 (stratotype) and borehole 62D-168 near Mamelis, c. 300 m SW of the stratotype. 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 borehole Mamelis, 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 and paid particular attention to these. These document the following sequence of genesis: sedimentation break, omission surface, erosion surface, fossil hash, nodular chalk, incipient hardground, and hardground (see also Kennedy & Garrison, 1975).

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, and these variations 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:

Mamelis 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 (with *B. (P.) obtusa*) at the base of the Vijlen Member at the Bovenste Bos and Zeven Wegen sections, on the basis of the benthic foraminifer *Bolivinoides delicatulus regularis* Reiss, 1954.

Mamelis interval 1 (thickness: 10.5 m) comprises comparatively indurated, glauconitic clayey and limy marls. Belemnites are slightly commoner just below the upper limit.

Mamelis interval 2 (thickness: 10 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 late Early Maastrichtian (upper *sumensis* Zone) interval of Aachen-Vaalserstraße, with an acme of the benthic foraminifer *B. australis* Edgell, 1954 in the lower half of this interval. This interval also corresponds to the highest occurrence of the benthic foraminifera *B. draco miliaris* Hiltermann & Koch, 1950, *Neoflabellina permutata* Koch, 1977 and the ostracod *Bythoceratina laevis* (Marsson, 1880).

Mamelis interval 3 (thickness: > 7.3 m) comprises glauconitic clayey and limy marls with scattered quartz pebbles. Belemnites are missing, but echinoderms are common.

Mamelis 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 late Early Maastrichtian upper *sumensis* Zone of Aachen-Hans Böckler Allee on the basis of co-occurrence of the benthic foraminifera *Eponides beisseli* Schijfsma, 1946 and *Nonionella troostae* (Visser, 1951).

Mamelis interval 5 (thickness: 12 m) comprises 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. A find of *B. (Pachybelemnella) cimbrica* Birkelund, 1957 recorded by Keutgen & van der Tuuk (1991) documents a late Early Maastrichtian age.

Mamelis interval 6 (thickness: 11.5 m) corresponds with 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 missing, and are commoner only near the upper limit. An acme of *B. australis* in the upper half of this interval, and its co-occurrence with *B. draco draco* (Marsson, 1878) are indicative of Hofker's (1966) benthic foraminifer zone D. Coleoids assignable to *Belemnitella* ex gr. *junior* Nowak, 1913 document an early Late Maastrichtian age (see below).

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; see also van der Ham & van Birgelen, 1992) documented all of P.J. Felder & Bless's (1994) intervals outcropping in various fields.

The Vijlen Member as exposed at the CPL SA quarry (Haccourt), corresponding to interval 6, according to Robaszynski et al. (1985) was deposited in a relatively offshore setting (c. 20-25 km), at a palaeo-waterdepth of c. 80 m in a low-energy environment.

Lixhe 1-3 members

Stratotype — Disused Dierkx quarry at Lixhe (Liège, exposure 61H-18), co-ordinates 308.400/174.500.

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* ichnotype deep burrows). Mortimore & Pomerol (1991) demonstrated that such trace fossil events are valuable marker horizons which are correlatable with major eustatic events. Seen in this light, the trace fossil assemblages in the Lixhe and Lanaye members deserve to be studied in more detail.

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 5, suggesting that this sequence may be interpreted as E4 (1300 ka), E3 (413 ka) and E1 (98 and 126 ka) eccentricity cycles and P (20 ka) 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 × 20 = 1.5 million years. 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/ka.

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

Stratotype — Western portion of Albert Canal outcrop, north of the bridge at Lanaye (Liège, exposure 61H-36), co-ordinates 311.000/176.150.

This member comprises white, fine-grained chalks with irregular light to dark blue-grey flint nodules. West of the River Maas 23 flint bands are distinguished, east of the river these are less conspicuous and bedding is absent, with only randomly distributed flint nodules occurring. 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 biodetritus chalks, which graded into the sedimentation of the Maastricht Formation biocalcarenites. In the latter area, ostracod faunas show a rapid increase in diversity (Deroo, 1966).

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 palaeo-waterdepth 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%) 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, and 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 flint maximum in this member was correlated by Schulz & Schmid (1983a) with a similar maximum at Hemmoor (northwest Germany), directly below the FAD of the nannofossil *Nephrolithus frequens* Górka, 1957, which is situated in the middle *argentea/junior* Zone. In this respect, it is of note that Ehrmann (1986) showed accumulation rates of carbonate and flint content to have increased in the north Atlantic during the Maastrichtian, connected with an increase in surface productivity of the seas in that period. Van Heck (1979) recorded *N. frequens* from the uppermost Lanaye Member as well; Verbeek (1983) was unable to confirm this, but noted that the type Maastrichtian (i.e. the equivalent of the Maastricht Formation) corresponded to the *N. frequens* Zone.

The Kunrade Limestone facies, which is widely distributed in the Kunrade-Heerlen-Benzenrade area (W.M. Felder, 1978; 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 base of zone J). This zone equates with the Lanaye Member (Gulpen Formation). Crinoid distribution patterns (Jagt, 1988) appear to confirm this correlation; this matter will be considered further in a subsequent paper (Jagt, in prep. d). Ecozone V was equated with the lower half of foraminifer zone J in the Thermae (Valkenburg) and Maastricht-Kastanjelaan boreholes, and with zone H at the ENCI-Maastricht BV 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 (Maastricht Formation), 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.

A number of localities in this area from which echinoderms have been collected should be assigned to the following ecozones according to P.J. Felder & Bless (1989): Kunderberg - ecozone V (upper part); road behind Schunck - ecozone V (uppermost part); de Wingerd - ecozone III (uppermost part) and ecozone IV (lower/middle part); RW 76 motorway - ecozone IV (upper part) and ecozone V (lower part).

Biostratigraphy

Zeven Wegen Member

Albers & Felder (1979) considered the base of this member to correspond to a hiatus comprising the upper *pilula*/lowermost *senonensis* Zone up to the upper *conica*/

papillosa Zone. They recorded the co-occurrence of *Belemnitella mucronata* (von Schlotheim, 1813) and *Gonioteuthis quadrata gracilis* Stolley, 1892, and suggested a late Early Campanian age (*gracilis/mucronata* Zone) for the base. The remainder of the member was assigned an undifferentiated Late Campanian age, and it was noted that echinoids had not yet been collected bed by bed. These authors thought that the Zeven Wegen Member did not extend into the late Late Campanian.

Schönfeld (1990) rightly pointed out that, on coleoid cephalopod evidence, it cannot be determined exactly when the 'Gulpen transgression' started during the Late Campanian, and that in the basal glauconitic portion various biozones might be condensed. On benthic foraminifer evidence, and *Gavelinella monterelensis* (Marie, 1941) in particular, which at Lägerdorf (northwest Germany) first occurs in the middle *conica/senior* (= *conica/mucronata*) Zone, Schönfeld assumed the transgression to have started during the lower *conica/senior* Zone. In so doing, he confirmed Jagt's (1988) views.

The zonation of the Zeven Wegen Member relies mainly on coleoid and ammonoid cephalopods. In situ coleoids comprise two species, *Belemnitella m. mucronata* (sensu Christensen et al., 1975) and *B. woodi* Christensen, 1995 (Keutgen, 1995; Keutgen & Jagt, in press.). These allow the member to be correlated with the Late Campanian of Norfolk (Peake & Hancock, 1970; Wood, 1988; Johansen & Surlyk, 1990; Christensen, 1995) as follows:

The lowermost 5-6 m correspond to Wood's (1988) Pre-Weybourne3-4 Chalk, representing Schulz et al.'s (1984) upper *conica/mucronata* and lower *basiplana/spiniger* zones;

The section between 6 and 17 m above the base of the member corresponds to the Pre-Weybourne5 Chalk and Weybourne1 Chalk, representing the upper *basiplana/spiniger* Zone and yielding the early form of *B. woodi*;

The section between 17 and 29 m above the base of the member corresponds to the Weybourne2-3 Chalk, representing the upper *roemeri* Zone and yielding the late form of *B. woodi*.

At present, it cannot be determined whether the uppermost metre of the Zeven Wegen Member at the CPL SA quarry correlates with the topmost Weybourne3 Chalk (Catton Sponge Bed, *polyplocum* Zone) or not. As the index ammonite *Nostoceras (Bostrychoceras) polyplocum* (Roemer, 1841) has not been found yet it is assumed that the *polyplocum* Zone is not represented, at least for the time being.

Judging from recent data supplied by Robaszynski & Christensen (1989) and Robaszynski (1995), the Zeven Wegen Member is correlatable with the uppermost 'Craie de Trivières', the 'Craie d'Obourg' and the 'Craie de Nouvelles' in southern Belgium (Mons Basin).

Ammonoids of correlative value recorded from the Zeven Wegen Member (mainly from the Haccourt-Lixhe area) currently include *Patagiosites stobaei* (Nilsson, 1827) (sensu Giers, 1964, and revised by Kaplan et al., 1996), *Pachydiscus (P.) haldemsis* (Schlüter, 1867), *Trachyscaphites s. spiniger* (Schlüter, 1872), *Scaphites (S.) gibbus* Schlüter, 1872, and *Neancyloceras*? *phaleratum* (Griepenkerl, 1889). These enable correlations with the Mons Basin (Kennedy, 1993a; Robaszynski, 1995), with the Hannover-Braunschweig area and eastern Niedersachsen (Schmid & Ernst, 1975; G. Ernst et al., 1979; G. Ernst & Wood, 1996; Niebuhr, 1995, 1996; Niebuhr & Ernst, 1991; Niebuhr et al., 1997), with southeast Münsterland (Giers, 1964; Kaplan et al., 1996), with Austria (Kennedy & Summesberger, 1984), with southwestern France (Hancock & Kennedy, 1993; Hancock et al., 1993), with the Wisła valley in central Poland (Błaszkiewicz, 1979, 1980), with the Russian Platform (Naidin, 1979), with southern Sweden (Kennedy & Christensen, 1997), and with the United States (Cobban & Scott, 1964; Klinger & Wiedmann, 1983; Cobban & Kennedy, 1992).

G. Ernst et al. (1996) pointed out that two distinct incursions of 'Scandinavian' faunal elements in northern Germany occurred during transgressions, which they named the *mucronata* and *spiniger* transgressions. These can thus also be recognised in the Haccourt-Lixhe (Liège) and Zeven Wegen (southern Limburg) areas.

In northern Spain, Küchler & Kutz (1989) noted the FAD of *T. spiniger* in association with *P. haldemsis* to lie above the FAD of *Hoplitoplacenticeras marroti* (see above: Vaals Formation), which corresponds well with the situation in southern Limburg and adjacent areas.

Other macrofossils of correlative value comprise irregular echinoids [*Galeola papillosa basiplana* G. Ernst, 1971, *Echinogalerus*? *hemisphaericus* (Desor, 1842), *Cardiotaxis heberti* (Cotteau, 1860), *Echinocorys* gr. *conica/lamberti*, *Micraster* gr. *schroederi/glyphus*, and *M. stolleyi* Lambert, 1901], which allow the Zeven Wegen Member to be correlated with other northwest European localities (Norfolk, northern France and northwest Germany) (see G. Ernst, 1971; Schulz, 1985). A species of the bizarre holasterid genus *Hagenowia* may also prove to be biostratigraphically important. Schulz (1978) recorded from the *stobaei/basiplana* (= *basiplana/spiniger*) Zone in northwest Germany what he called *H. b. blackmorei*, a species previously known only from the Early Campanian of England (G. Ernst et al., 1971; Gale & Smith, 1982). This form may turn out to be conspecific with material from Haccourt (Liège) (Jagt, in prep. b) from the Zeven Wegen Member and from the middle Weybourne Chalk in Norfolk [Whittlesea's (1996a) *Hagenowia elongata*; see also Wood (1988), who noted that comparable forms occur in the Beeston Chalk].

Next in line are goniasterid asteroids of the lineage *Nymphaster studlandensis* - *N. alseni* - *N. peakei* (Schulz & Weitschat, 1971, 1975; Gale 1987b, 1989; Breton, 1992). *Nymphaster studlandensis* was originally described from the *mucronata* Zone of Studland Bay (Dorset, England) (Schulz & Weitschat, 1975), and has subsequently been recorded from the early Late Campanian of Germany and northeast Belgium (Gale, 1987b). *Nymphaster alseni* is from the 'middle Upper Campanian' (*roemeri* Zone) of northwest Germany, and is also known from the Weybourne Chalk (S/R flint interval) of Norfolk (Gale, 1987b). *Nymphaster peakei* of Gale (1987b, 1989) is the youngest member of the lineage, occurring in the Catton Sponge Beds and ranging into the Beeston/Paramoudra Chalks of Norfolk.

Although *N. studlandensis* is unknown from Norfolk, the type locality of that species (Gale et al., 1987; Mortimore, 1986, 1987) is stratigraphically (biozones and strontium isotopes) well correlatable with the Norfolk sections (McArthur et al., 1993b). The species' range in northeast Belgium corresponds well to that seen in England and Germany. In addition, since the echinoid *Galerites (Pironaster) roemeri* (Desor, 1847) does not occur in the Zeven Wegen Member, *N. alseni* may be used as an alternative index for (part of) the *roemeri* Zone (see Schulz, 1978).

Other asteroid species which may be considered to index taxa include *Crateraster favosus* (Spencer, 1913) and *Metopaster decipiens* Spencer, 1913 (Schulz & Weitschat, 1981; Gale, 1987a, b). Breton's (1992) interpretation of the latter species differs from that of other authors (see Jagt, in prep. c).

Finally, stratigraphically valuable macrofossil assemblages from the Zeven Wegen Member comprise various brachiopod species [e.g. *Cretirhynchia* gr. *woodwardi* (Davidson, 1853), *C.* gr. *lentiformis* (Woodward, 1833), *Kingena pentangulata* (Woodward, 1833), and rare isocraniids, compare H. Ernst, 1984], but it should be noted that the study of the micromorphic species has only just started (Simon, work in progress). This is expected to yield additional stratigraphic data, so that correlations with Norfolk (Johansen & Surlyk, 1990) and northwest Germany (Johansen, 1988a) may be established. The larger species assemblage compares well with Polish records (Bitner & Pisera, 1979; Popiel-Barczyk, 1988).

A few bivalve species may also be cited for interregional correlations, e.g. the pectinids '*Camptonectes*' *striatissimus* (von Hagenow, 1842), *Mimachlamys mantelliana* (d'Orbigny, 1847) and inoceramids, but the latter are invariably poorly preserved.

The Froidmont Hardground with underlying chalkstone (sensu Bromley & Gale, 1982) caps the Zeven Wegen Member, and represents a hiatus encompassing the late Late Campanian (*polyplocum* Zone) to late Early Maastrichtian (*cimbrica* and *fastigata* zones).

Beutenaken Member

That the biostratigraphy of this member, which apparently corresponds to the 'Craie de Spiennes' in southern Belgium (Robaszynski & Christensen, 1989), was poorly known until recently is explained by the lack of exposures. Current age assignments rely primarily on calcareous nannofossils and coleoid cephalopods. Verbeek (1983) assigned the Beutenaken Member to the *Quadrum trifidum* Zone, and in so doing assigned a Late Campanian age to this member. This in contrast to Albers & Felder (1979), Robaszynski et al. (1985) and Slimani (1994, 1996), who considered the unit to be of Early Maastrichtian age. Macrofossil corroboration of Verbeek's (1983) views came when Keutgen & van der Tuuk (1991) showed the Beutenaken Member to yield typically Late Campanian coleoid cephalopods. Subsequently, Keutgen (1996) worked out the biozonation of this member in more detail, and data below are taken from his work.

Recorded by Keutgen from the Beutenaken Member are many specimens of *Belemnitella najdini* Kongiel, 1962 and *B. minor* sensu Christensen, 1995. The former species occurs in the Beeston Chalk Member in Norfolk (Christensen, 1995), and is probably confined to the late Late Campanian. The other species, however, ranges from the Late Campanian into the early Early Maastrichtian. Christensen (1995, 1996) recorded three successive evolutionary stages from Norfolk:

minor I occurs in the Catton Sponge Bed, Beeston Chalk Member and the lower part of the Paramoudra Chalk Member (= *polyplocum* and lower *langei* zones of Schulz, 1978; Schulz et al., 1984);

minor II occurs in the Paramoudra Chalk Member (= upper *langei* and *grimmensis* zones of Schulz, 1978);

minor III occurs in the early Early Maastrichtian (*lanceolata* to *obtusa* zones of Schulz, 1979).

In the extended type area of the Maastrichtian Stage, *B. minor* first occurs in the

Beutenaken Member, early forms (= *minor* I) being known from Teuven (northeast Belgium). Material from Bovenste Bos, Slenaken and Pesaken-Crapoel was referred to *minor* II or *minor* III by Keutgen (1996). These two 'subspecies' cannot be separated clearly in the area, which means that latest Campanian and earliest Maastrichtian cannot be documented precisely.

Keutgen (1996) noted that the presence/absence of *B. najdini* appears to be facies controlled, and on coleoid evidence he was able to demonstrate that the onset of Beutenaken sedimentation was diachronous in the area, going from Teuven to Pesaken-Crapoel.

The Beutenaken Member comprises two facies types (P.J. Felder, 1996), the greensand facies being well known from the margins of the member's areal extent. This facies may have been deposited in shallower settings and/or higher energy environments, comparable to the conditions prevailing during deposition of the Vijlen Member (see below).

Keutgen (1996) referred the major portion of the Beutenaken Member to his *Belemnitella minor* Zone, with *minor* I from the lower part corresponding to populations from the upper Beeston Chalk Member or basal Paramoudra Chalk Member in Norfolk (Christensen, 1995). The uppermost part of the Beutenaken Member is of Early Maastrichtian age, which means that Keutgen's *minor* Zone corresponds to the *langei*, *grimmensis/granulosus* and basal *lanceolata* zones of the NW German standard section (Schulz, 1979, Schulz et al., 1984; Schönfeld et al., 1996b). This implies that Beutenaken sedimentation started in the upper nannofossil zone CC22C [= Burnett's (1990) zone CC/B22 or *Eiffellithus eximius* Partial Range Zone]. Keutgen's *Belemnella inflata* Zone is represented in the uppermost Beutenaken Member; it corresponds roughly to the *lanceolata* and *pseudobtusa* zones. This means that the Campanian/Maastrichtian boundary in the type area of the Maastrichtian Stage is situated within the *minor* Zone, i.e. in the upper Beutenaken Member. The *inflata* and *obtusa* zones in the area are characterised by periods of low sedimentation rates.

Apart from the above-mentioned nannofossil and coleoid taxa Beutenaken Member strata have not yet yielded any other age-diagnostic (macro)fossils. This, together with the fact that in the area *B. minor* II and III cannot be distinguished unequivocally, explains why the critical latest Campanian/earliest Maastrichtian interval (Burnett et al., 1992a) cannot be recognised to date. Typical indexes such as the heteromorph ammonites *Nostoceras (N.) hyatti* Stephenson, 1941 and *Jeletzkytes nodosus* (Owen, 1852) (see Kennedy et al., 1992; Odin, 1996), which, in combination with strontium isotope stratigraphy, allow direct numerical calibration for the base of the Maastrichtian Stage (71.3/71.4 Ma; see McArthur et al., 1994; compare Clauser, 1994), are unknown.

For the Münsterland Basin (Germany), Kaever & Lommerzheim (1995) noted in the latest Campanian (*polyplocum* Zone and higher) a short-lived palaeotemperature increase, which earlier had been postulated for northwest Germany and Poland as well. A number of thermophilic benthic foraminifera are recorded from this interval. According to these authors this latest Campanian warm water pulse was probably a stratigraphically significant eco-event in central Europe, spanning cycles 4.3 and 4.4 of the sequence stratigraphic scheme. From the data for the Beutenaken Member presented above, it is clear that this member represents exactly this interval, the sequence

4.3/4.4 boundary probably corresponding to the boundary between the two facies types of the Beutenaken Member (P.J. Felder, 1996). In this respect, it is even more unfortunate that typical 'Tethyan' taxa such as the heteromorph ammonite *Nostoceras polyplocum* are unknown from the area.

Vijlen and Lixhe members

As summarised 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. Yet again, coleoid cephalopods constitute the best correlation tools. 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. Schulz (1979) mentioned also middle *obtusa* Zone belemnites from the Beutenaken area, while Keutgen (1996) in addition recorded *Belemnella (B.) lanceolata* (von Schlottheim, 1813) and *Belemnitella minor* Jeletzky, 1951 (sensu Christensen, 1995), an association typical of the lower *obtusa* Zone sensu Schulz (1979). Mean values for 'populations' of *B. (P.) obtusa* corroborate this age assignment (Keutgen & van der Tuuk, 1991).

Keutgen (1996) presented the most detailed biozonation to date, and data below are taken from his work. His *Belemnella obtusa* Zone characterises the lowermost Vijlen Member (= interval 0 of P.J. Felder & Bless, 1994), thus apparently corresponding to the 'Craie phosphatée de Ciply' in southern Belgium (Robaszynski & Christensen, 1989). The *Belemnella sumensis* Zone ranges from the base of interval 0 to within interval 5; from it *Belemnella (B.)* cf. *praearkhangelskii* Naidin, 1964 has been collected, corroborating correlations between the NW German standard section and southern Limburg (Keutgen, 1997). The *Belemnella cimbrica* Zone encompasses intervals 5 and 6, corresponding to the northwest German *cimbrica* and *fastigata*, the index taxon [*B. (B.) fastigata* Schulz, 1979] of the latter zone being unknown from the area. The presence of the scaphitid ammonite *Acanthoscaphites varians* (Łopuski, 1911) allows the lower boundary of the *fastigata* Zone to be drawn roughly near the base of interval 6. The LAD of *Belemnella (P.) cimbrica* Birkelund, 1957 is used to situate the Lower/Upper Maastrichtian boundary within the uppermost Vijlen or lowermost Lixhe members.

Keutgen (1996) also proposed a regional ammonite zonation, based on the scaphitids *Acanthoscaphites tridens* (Kner, 1848), *Hoploscaphites constrictus* (J. Sowerby, 1817) and *A. varians* (Łopuski, 1911), as follows:

The *tridens* Zone comprises interval 0 (upper part, *sumensis* Zone) to interval 3, but it should be noted that the species ranges into interval 4 (Jagt et al., 1992; Jagt, Deckers et al., 1995; Keutgen, 1996).

The *constrictus* Zone comprises intervals 4 and 5 (except uppermost part), the index, however, extending up to the K/T boundary. A significant increase in numbers of *H. constrictus* in Denmark in the upper *sumensis* Zone appears to correspond to the FAD and acme of this species in the Aachen-Limburg area. The zonal species is otherwise considered an index for the Maastrichtian Stage (Hancock et al., 1993; Odin, 1996).

The *varians* Zone, with the FAD of the index in the uppermost part of interval 5, and inclusive of interval 6 at the CPL SA and CBR-Lixhe quarries. This corresponds to the upper *cimbrica* Zone, which means that the base of the *varians* Zone (= roughly base of interval 6) more or less matches the base of the *fastigata* Zone in northwest Germany.

For the CPL SA and CBR-Lixhe quarries, Keutgen (1996) noted that the Vijlen Member exposed there (thickness: c. 14.5 m) comprised relatively soft, greyish white marly chalks with few light grey flints, and, especially at the base, some glauconite. *Belemnitella junior* Nowak, 1913 is the sole coleoid species recorded in situ from this member at the CPL quarry, and representatives of *Belemnella sumensis/cimbrica* are restricted to burrow fills in the chalkstone underlying the Froidmont (= Slenaken) Horizon. From the CBR-Lixhe quarry, Schmid (1959) and Schulz & Schmid (1983a) recorded *B. cimbrica* from the basal metre of the Vijlen Member there. Correlation with the *Belemnella*-free portion of the Vijlen Member at Wilkensberg and Mamelis shows that the entire Vijlen Member as exposed at the CPL and CBR quarries should be referred to interval 6, and to Hofker's (1966) benthic foraminifer zone D. The Froidmont Horizon would then correspond to a hiatus comprising intervals 0-5.

Of interest is the FAD of the *Belemnitella junior* group in the Aachen-Limburg area. Following Jeletzky (1951) this group has generally been considered to mark the Early/Late Maastrichtian boundary (Christensen, 1990, 1996, 1997). However, Keutgen (1996) noted that the first representative had been collected c. 1 m above the base of the Vijlen Member at the Bovenste Bos quarry, which means *sumensis* Zone. For this reason, Keutgen noted that *B. junior* cannot be used as an index for the (early) Late Maastrichtian in the area. Christensen (1996) accepted Keutgen's data and recorded *B*. ex gr. *junior* from the Early Maastrichtian, restricting *B. junior* s. str. to its original use as Late Maastrichtian index. Detailed biometric studies of the *B. junior* group from various northwest and northeast European localities are still outstanding.

As noted above, coleoids allow the Vijlen Member to be correlated with southeast England (Norfolk), northern Germany (Schulz 1979, 1982; Herrig et al., 1996) and southern Germany (Schulz & Schmid, 1983b; Schönfeld et al., 1996a). A transatlantic correlation has recently been suggested on ammonoid evidence. The scaphitid *Jeletzkytes dorfi* Landman & Waage, 1993, originally described from the *Hoploscaphites birkelundi* Zone of Wyoming and South Dakota (Landman & Waage, 1993), was recorded by Jagt & Kennedy (1994) from the Vijlen Member (= interval 6) at the CPL SA quarry. These authors assumed this occurrence to lie in the lower *Belemnitella junior* Zone (i.e. to be of early Late Maastrichtian age) and on the basis of this record suggested the correlate the base of that zone with the base of the North American *birkelundi* Zone. This would then date the Early/Late Maastrichtian boundary in northwest Europe at slightly younger than 69.42 ± 0.37 Ma, which is the age of bentonites in the underlying *Baculites clinolobatus* Zone in the Western Interior. Now that the Vijlen Member at the CPL SA quarry has been dated (Keutgen, 1996) as equivalent to the *fastigata* Zone (= late Early Maastrichtian) this correlation has to be reconsidered.

Other ammonite species of correlative value include *Baculites knorrianus* Desmarest, 1817 (Birkelund, 1993; Kennedy, 1993a; Jagt, Deckers et al., 1995; Keutgen, 1996) and, recently recorded (Kennedy & Jagt, 1998) from interval 6 at the CPL SA and CBR quarries and from Snouwenberg (Voer, Belgium), *Trachybaculites columna* (Morton, 1834) (= *Baculites*(?) sp. 2 of Keutgen, 1996). This is an otherwise exclusively North

American species from the Maastrichtian of Alabama, Mississippi, South Dakota, Texas, and California (Cobban & Kennedy, 1995). With regard to the scaphitid *Acanthoscaphites varians* it appears that the type of this species from central Poland is considerably younger (Machalski, 1996) than the other records from Denmark (Birkelund, 1993), northwest Germany and Belgium (Jagt & Kennedy, 1989). There are obvious differences in ornament in this multituberculate species, and it may turn out to be necessary to split it at (sub)specific level (Machalski, 1996; Jagt et al., 1999). Amongst ammonites collected recently from the upper Vijlen Member at the CBR-Lixhe quarry are two fragmentary specimens of the pachydiscid *Pachydiscus neubergicus* (von Hauer, 1858), which is generally considered to be a good marker for the Maastrichtian Stage (Odin, 1996; Ward & Orr, 1997).

Of inoceramid bivalves, Keutgen (1996) recorded various representatives of the genus *Trochoceramus* from the Vijlen Member, viz. *T. nahorianensis* (Kotsubinsky, 1968) and *T. radiosus* (Quaas, 1902), both from interval 6. The FAD of this genus has recently been shown to roughly mark the Campanian/Maastrichtian boundary (Walaszczyk, 1996; Walaszczyk et al., 1996). However, species concepts appear to vary according to author. Despite these difficulties, this genus allows correlation with the Early Maastrichtian of Tercis (southwest France: Dhondt, 1993; Hancock et al., 1993). In addition, Keutgen documented *Spyridoceramus tegulatus* (von Hagenow, 1842), an important marker species (Dhondt, 1983, 1992; Schulz & Schmid, 1983a) from Vijlen Member intervals 2, 3, 5, and 6.

Biozones based on micromorph brachiopods are widely used in the northwest European white chalk facies, and can occasionally be correlated with 'Tethyan' regions (Surlyk, 1970, 1982, 1984; Surlyk & Dieni, 1988; Johansen & Surlyk, 1990). Keutgen (1996) noted that Surlyk's zonation cannot be applied to the Aachen-Limburg area, with the exception of the base of the *tenuicostata-semiglobularis* Zone. At Hemmoor (northwest Germany) and in Denmark the base of this zone roughly corresponds to the base of the *cimbrica* Zone, and marks the LAD of *Gisilina gisii* (Roemer, 1841) (see also Simon, 1994). The youngest specimen known in the area is from slightly below the upper limit of the *sumensis* Zone, which means that the species disappears simultaneously in Aachen-Limburg (base of interval 5), northwest Germany and Denmark. This allows the boundary between the *sumensis* and *cimbrica* zones to be drawn in the Aachen-Limburg area. Other medium- and large-sized species are currently under study, and comprise many species recorded from the Late Campanian to Late Maastrichtian elsewhere (Simon, 1993, work in progress).

Echinoids, and *Galerites (G.) stadensis* (Lambert, 1911) in particular, are stratigraphically important as well. Schulz (1985) demonstrated that this species evolved from *G. (G.) abbreviatus* Lamarck, 1816 in the middle/upper *sumensis* Zone. Jagt, Deckers et al. (1995) and Keutgen (1996) recorded *G. stadensis* from coeval intervals of the Vijlen Member at Altembroeck (northeast Belgium) and the Aachen-Limburg area, respectively. The species ranges into the Late Maastrichtian (Lixhe Member).

With the exception of the Lixhe Member in the Aachen-Mamelis area (van der Ham & van Birgelen, 1992), echinoid faunas of this member are still poorly known, but have a definite boreal/temperate aspect. The holasterid genus *Echinocorys* is very common and most specimens appear to be assignable to the group of *E. conoidea*

(Goldfuss, 1829). In the Lixhe 3-Lanaye members interval this group is ousted by representatives of the holasterid genus *Hemipneustes*, which is a 'Tethyan' genus known from southern Europe, north Africa and the Middle East. Whether or not there is overlap in the ranges of these genera remains to be determined.

Of benthic foraminifera the following may be noted: the presence of *Bolivinoides australis* (mean pustule value 5.4), the absence of species of *Belemnella* and the record of *A. varians*, allows the Vijlen Member at the CPL SA quarry to be correlated with the upper c. 9 m in the Mamelis section (P.J. Felder & Bless, 1994), corresponding to their interval 6. Keutgen (1996) noted the FAD of *Reussella cimbrica* (Troelsen, 1937) to lie in the basal Lixhe 1 Member (see Robaszynski et al., 1985). This species is characteristic of Hofker's (1966) benthic foraminifer zone E (dated as early Late Maastrichtian), and is the index of the '*Pseudouvigerina cimbrica* Zone' in Denmark. On this evidence, Keutgen proposed to place the Early/Late Maastrichtian boundary at the base of the Lixhe 1 Member, to coincide with the Wahlwiller Horizon.

Nannofossil assemblages from the Vijlen Member and most of the Lixhe members comprise typical *Reinhardtites levis* Zone (CC24) or lower *Arkhangelskiella cymbiformis* Zone (CC25a) taxa, and thus correspond well with the belemnite data. In the higher Lixhe members zone CC25b (FAD of *Lithraphidites quadratus* Bramlette & Martini, 1964) is documented.

In a sequence stratigraphic context (Keutgen, 1996; P.J. Felder, 1996), the following can be stated about the Vijlen Member. Keutgen (1996) noted that rhythmic changes in palaeo-waterdepth could be noted which might have sequence-stratigraphic value, cycles of 4th to 6th orders being interpreted as short-lived sea-level fluctuations (Haq et al., 1988), 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 (compare P.J. Felder, 1996), 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 (palaeo-waterdepth to a maximum of 40 m). Intervals 1-5 of the Vijlen Member possibly correspond to the highstand phase of cycle 4.4 (palaeo-waterdepths between 80-100 m), and the base of interval 6 could well be the maximum flooding surface at the 4.4/4.5 cycle boundary (compare P.J. Felder, 1996). Interval 6 and the basal Lixhe 1 Member could then be interpreted as lowstand deposits of cycle 4.5 (palaeo-waterdepth to a maximum of 60 m). Lower order cycles may either be climate controlled, or be the result of synsedimentary regional tectonic processes (P.J. Felder & Bless, 1994). It has been demonstrated on numerous occasions that inversion tectonics had a considerable impact on the Late Cretaceous sedimentation in the type area of the Maastrichtian Stage (see e.g. Bless et al., 1987; Rossa, 1987; Bless, 1991a, b; Geluk et al., 1994; Gras, 1995; Bless & Fernández Narvaiza, 1996). In this light there are obvious similarities with the Mons Basin in southern Belgium (Vandycke & Bergerat, 1990; Vandycke et al., 1991).

On the basis of a quantitative palynological analysis of a section in the Lixhe 3 Member at the ENCI-Maastricht BV quarry, Streel et al. (1995) recorded an obvious relationship between pollen content of the sediment and short-term climatic changes (cooling trends), as based on oxygen isotopes.

Lanaye Member

Albers & Felder (1979) noted the occurrence in this member of the benthic foraminifera *Reussella cimbrica*, *Coleites reticulosus* (Plummer, 1926) and *Bolivinoides decorata gigantea* Hiltermann & Koch, 1950, which assigned an unequivocal early Late Maastrichtian age to this unit, corresponding to Hofker's (1966) zone F and Koch's (1977) *Gavelinella danica* Zone.

Coleoid cephalopods are common and comprise representatives of *Belemnitella junior* only. Ammonites are extremely rare, poorly preserved phosphatised baculitids being the only taxa known to date. Neither of these groups allow precise correlations with sections abroad to be established.

Tegulated inoceramid bivalves, and *Tenuipteria argentea* (Conrad, 1858) in particular, are potentially of more importance stratigraphically (Dhondt, 1983, 1992; Landman & Waage, 1993). Based on the correlation proposed by Schulz & Schmid (1983a) of the flint maxima in the Maastrichtian type area and Hemmoor in conjunction with the FAD of the nannofossil taxon *Nephrolithus frequens* in the middle *argentea/junior* Zone at Hemmoor, the first representatives of *T. argentea* in the Maastrichtian type area could be expected in the Lanaye Member. So far only poorly preserved specimens have been collected from the upper Lanaye Member at Eben Emael (CBR-Romontbos quarry, northeast Belgium). These cannot be identified to species with certainty; this matter will be discussed further below.

Nannofossil assemblages are held to be indicative of the *Lithraphidites quadratus* Zone (Cepek & Moorkens, 1979; Verbeek, 1983; Robaszynski et al., 1985); van Heck's (1979) record of *Nephrolithus frequens* from this member could not be substantiated by Verbeek (1983).

Planktonic foraminifera (Moorkens, 1971; Bellier & Villain, 1975; Robaszynski et al., 1985; Robaszynski, 1988) include *Globotruncana contusa* Zone taxa, confirming a Late Maastrichtian age, but not suitable for detailed correlations.

Maastricht Formation

Lithostratigraphy and facies interpretation

Valkenburg Member

Stratotype — Disused quarry (exposure 62A-207) east of Valkenburg aan de Geul (southern Limburg), co-ordinates 318.520/186.770.

In the western part of southern Limburg this member comprises a 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 are not distributed everywhere. Where they do occur, they are crumbly, light grey flint nodules. Total thickness increases from west to east. At the ENCI Nederland BV quarry it amounts to c. 2.5 m, while at Valkenburg-Schaelsberg it is c. 45 m.

Zijlstra (1994) noted the occurrence of several tens of metres wide and decimetre deep depressions 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. This member (= Valkenburg) is 2.5 m thick, 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-Maastricht BV 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

Stratotype — Quarries Wijngaardsberg and Varkensgat at the Riesenberg east of Gronsveld, exposures 62A-424 and 62A-159, respectively, co-ordinates 314.050/180.150.

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 sediment at the top. The upper part of this member consists of well-sorted bioclastic fine sand with low-angle, large-scale wavy lamination (hummocky stratification), with flint nodules forming laterally restricted curvi-planar layers.

Schiepersberg Member

Stratotype — Disused Schiepersberg quarry (exposure 62A-26) at Cadier en Keer, co-ordinates 315.880/182.680.

In the west this unit comprises 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

Stratotype — Marnebel quarry at Emael (Bassenge, Liège; exposure 61H-7), co-ordinates 310.850/175.050.

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 Heerlen 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, 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 palaeodepths of 20 to 40 m, and free from oceanic influence. Sediment reworking resulted in homogenisation of sediments 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.

Seagrass is known to influence and stabilise accumulating sediments (Voigt & Domke, 1955; Brasier, 1975; Boardman et al., 1992), but Ivany et al. (1990) stressed that little is yet known of the evolutionary development of seagrass-animal interactions or of the ecological role of seagrass communities through time. This is related to the extreme rarity of well-preserved fossil seagrasses.

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. Especially in glauconite-rich portions cross-bedding has been demonstrated, and bioturbation occurs commonly. 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. 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, slightly less diverse biocoenoses. Ostracod faunas suggest decreased hydrodynamics in a lagoon-like setting near a flat coastline and a low hinterland.

Nekum Member

Stratotype — Disused de Tombe quarry, Sint Pietersberg, south of Maastricht (exposure 61F-8), co-ordinates 315.130/175.350.

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 the echinoid *Hemipneustes striatoradiatus* (Leske, 1778) and the ostreid bivalve '*Pycnodonte vesicularis*' auct. (non Lamarck, 1806). 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 resting upon the Laumont Horizon an indurated calcarenite. Zijlstra (1988) described the flint nodules occurring in the lower part of this member (the highest in situ occurrence of flints in the type Maastrichtian) as having a crypto/microcrystalline texture. Often nodules are associated with concentrations of large skeletal grains, and nodules are tubular when related to bioturbation. The upper part of the member comprises porous, fine 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 very coarse bioclastic sand.

Meerssen Member

Stratotype — Curfs-Ankerpoort quarry at Geulhem, southeast of Meerssen (exposure 62A-13), co-ordinates 320.120/182.100.

This member comprises in the west 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, thus 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, a bored and 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 sediments 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 those traces that could be ascribed to endolithic algae, documented 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 follows: 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 active biochemical cycle in the formation of exo- and endoskeletons.

Biostratigraphy

In recent years it has been demonstrated on numerous occasions that lithostratigraphical correlations in the 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-Maastricht BV quarry and the CBR-Romontbos quarry (Eben Emael) is straightforward for the Lanaye Member (Gulpen Formation), but problems arise especially in the lower part of the overlying Maastricht Formation. Duffin & Reynders (1995) assumed shallower depths of deposition for the Eben Emael area to account for some of the discrepancies between both sections. A multidisciplinary approach, including geochemistry, sequence stratigraphy, sedimentology, taphonomy, and micro- and macropalaeontology, along the lines proposed by Brett (1995), would ultimately result in a detailed characterisation of the type Maastrichtian. Such studies have only just started, and refinements of the picture presented here (which, of necessity, is brief as it is) are to be expected in the (near) future.

Recent collecting efforts have concentrated on the upper Meerssen Member as exposed at the ENCI-Maastricht BV 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; Fraaye, 1996a-c). 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).

Coleoids 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 base of section IVf-4 of the Meerssen Member onwards (Jagt, 1996). Van der Tuuk & Bor (1980) noted that 'populations' of this species in the Maastricht type area consisted mainly of juvenile and subadult specimens, an observation confirmed by subsequent studies. Christensen (1996, 1997) showed the distribution of *B. 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 latest Maastrichtian at Hemmoor (Schulz & Schmid, 1983a), 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, 1983a; Christensen, 1996) and that the uppermost six metres of the section exposed have not yielded any belemnites.

The FAD of *B. kazimiroviensis* in the type Maastrichtian apparently coincides with the demise of rudistid bivalves and the majority of 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/T boundary, if one accepts Vonhof & Smit's (1996) estimate of c. 10 cm/ka sedimentation rate, could have resulted in deeper waters and an increased sedimentation rate.

Representatives of the *B. kazimiroviensis* group range to the K/T boundary (= Berg en Terblijt Horizon, following Smit & Brinkhuis, 1996) and dominate coleoid assemblages there. Reworked, but otherwise fairly well-preserved, specimens have been collected from the base of section IVf-7 at the Ankerpoort-Curfs quarry (Geulhem) and at the Geulhemmerberg section, where 'battlefields' of the 'resedimented accumulate type' of Doyle & Macdonald (1993) occur. This suggests time-averaging to have taken place at this horizon (Fürsich & Aberhan, 1990; Kidwell, 1991; Kidwell & Bosence, 1991). Heavily abraded and bored specimens have been collected from the base of section Va-1 of the Geulhem Member, resting directly on the Vroenhoven Horizon. Unit IVf-7 of the underlying Meerssen Member has not yielded any specimens, despite the fact that it contains other typically latest Maastrichtian macrofossils (see below).

It has recently been noted in the literature that ammonite ranges in the type Maastrichtian are considerably preservation biased (Jagt & Kuypers, 1994). 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'. Silicified faunas collected from the lower Maastricht Formation have been shown to comprise ammonites otherwise known exclusively from the upper Maastricht Formation.

The pachydiscid *Menuites terminus* (Ward & Kennedy, 1993) is amongst the stratigraphically most important species. To date two specimens are known from the middle/upper Meerssen Member (Jagt, 1995a, b, 1996; Machalski & Jagt, 1998). In the Bay of Biscay sections of southwest France and northern Spain (Ward & Kennedy, 1993) this short-ranging species is the index of the latest Maastrichtian *terminus* Zone, its FAD lying 30-40 m below the K/T boundary at Zumaya, Hendaye and Bidart. Analyses of nannofossil assemblages (Burnett et al., 1992b) documented for these sections the (sub)zones CC25B (top), CC25C [FAD of *Micula murus* (Martini) Bukry, 1973] and CC26 [index *Nephrolithus frequens*, and associated *Micula prinsii* Perch-Nielsen, 1979]. *Menuites terminus* is also known from Denmark (Birkelund, 1993; Kennedy, 1993b), where it occurs in brachiopod zone 10 *stevensis-chitoniformis* (sensu Surlyk, 1984), or in coleoid terms, '*casimirovensis* Zone', and from the latest Maastrichtian of Bulgaria (Ivanov, 1995). Ward & Kennedy (1993) also considered material from Azerbaijan (undifferentiated Maastrichtian) to be conspecific. Recently published material from the latest Maastrichtian of central Poland (Marcinowski & Radwanski, 1996) is not conspecific, as noted by Machalski (1996). However, the species does appear to occur in Poland based on material currently under study (Machalski & Jagt, 1998).

Another species, *Sphenodiscus binckhorsti* J. Böhm, 1898, which first occurs in the basal Nekum Member, ranges to the Berg en Terblijt Horizon. It is fairly common in the upper part of section IVf-6 at the Ankerpoort-Curfs and Blom quarries, and also known from coeval horizons at the ENCI-Maastricht BV quarry and at Vroenhoven-Riemst (Albertkanaal sections) where it is extremely rare. In the literature there are records of this species from the Late Maastrichtian of Bulgaria and Poland (Machalski & Walaszczyk, 1988). Should future studies demonstrate that Late Maastrichtian records of species of *Sphenodiscus* refer to a single, variable taxon, as suggested by Kennedy (pers. comm. 1993), this genus could well turn out to be a valuable marker in transatlantic correlations.

The scaphitid *Hoploscaphites constrictus* has often been cited as valuable marker species for the Maastrichtian, and the forma *crassus* Lopuski (1911) for the latest Maastrichtian. However, as noted by Radwanski (1996), interpretations of this morphotype have varied widely amongst previous authors. In fact, Machalski (1996) showed it to represent the end of a continuum in 'populations' from central Poland. That author also proposed a correlation of the upper Kazimierz Opoka in Poland with the lower part of the '*casimirovensis* Zone' in Denmark, while the lower Kazimierz Opoka could correspond to the upper *junior* Zone in Denmark. This then suggests the lower limit of the '*casimirovensis* Zone' to be diachronous between these two areas (see also Christensen, 1996).

The occurrence of well-preserved baculitid ammonites in the upper part of section IVf-7 (in the chalkstone underlying the Vroenhoven Horizon) (Jagt, 1996) is reminiscent of records of baculitids and scaphitids from the 'Cerithium Kalk', up to within 20 cm from the base of the Danian, by Rasmussen (1971). Birkelund (1993) subsequently considered these specimens to have been reworked, despite the fact that ammonite survivor species have also been recorded from elsewhere (Zinsmeister et al., 1989).

The range of the stratigraphically important inoceramid bivalve *Tenuipteria argentea* in the type Maastrichtian is still rather poorly known. Undoubted specimens are known from the entire Meerssen Member, with an acme near the top of section IVf-6. However, a coquina-like concentration of what appears to be the equivalve inoceramid *Spyridoceramus tegulatus* is known from the upper Nekum Member (Jagt, 1995a). In this respect, it is quite possible that the poorly preserved tegulated inoceramids that are currently known from the middle/upper Lanaye Member to the top of the Nekum Member represent in fact this species, and not *T. argentea*. The range of the latter would then more or less correspond to its range in Poland (Abdel-Gawad, 1986), being confined to the '*casimirovensis* Zone'. Alternatively, these two species may have overlapping ranges in the Maastrichtian type area, but poor preservation often precludes definite specific assignment. In the Bay of Biscay sections (MacLeod, 1994), *T. argentea* is restricted to the Late Maastrichtian and ranges through part of the *fresvillensis* Zone and the entire *terminus* Zone (sensu Ward & Kennedy, 1993). In northern Germany, *T. argentea* ranges lower, being typical of the *argentea/junior* and *danica/argentea* zones (Schulz & Schmid, 1983a; Schulz et al., 1984).

Amongst echinoids there are very few taxa that can be used for interregional correlations; Jagt (in prep. b) is referred to for details. Although psychocidarine echinoids are now also known to occur in the type Maastrichtian (entire Meerssen Member), such forms are more typical of the overlying Geulhem Member (Houthem Formation) of Early Palaeocene age. The fact that occasional finds of abraded spines, all apparently assignable to *Tylocidaris (T.) hardouini* (Desor, 1855) (see below), are known from the top of the Meerssen Member at the ENCI Nederland BV and 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 and often ill preserved, and do not allow precise age assignments. Amongst the rich benthic assemblages, large 'Tethyan' forms predominate especially in the Meerssen Member (Bignot & Neumann, 1991), although some species first occur lower in the section [e.g. *Omphalocyclus macroporus* (Lamarck, 1816) in the basal Gronsveld Member, pers. obs.]. In the literature, such forms have also been recorded from further north in Europe, at the southern limit of the deeper water white chalk facies (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 type Maastrichtian should be used with caution (see also Dhondt et al., 1996).

The shallow-water, hardground-/seagrass-dominated depositional setting of the uppermost Maastricht Formation is renowned worldwide for its exquisitely preserved bryozoan faunas (e.g. Voigt, 1956, 1959, 1979, 1981, 1983, 1987b). It appears that a few species, e.g. *Pergensella geniculata* (von Hagenow, 1851), can be used for interregional correlations. Weitschat (1974) equated the higher *Belemnitella junior* Zone at Hemmoor with part of the Md (= Meerssen Member) and remarked that records of this species from the Kunrade Limestone facies suggested that at least part of this facies extended into the Md. This interpretation has not been followed by subsequent authors.

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 (compare e.g. Case & Cappetta, 1997).

The 'Tethyan' pulses apparently have a (? combined) North African/South European as well as a North Atlantic origin (Bless, 1991a; Malchus, 1996). In this respect it is of note that Haslett (1994) noted a palaeoceanographic change for the Bay of Biscay sections from a Tethyan to a North Atlantic dominated setting during the latest Maastrichtian. A gradual decrease of temperature during the Late Maastrichtian has been documented by many authors (e.g. Wiedmann, 1996), and for the North Sea Basin Stenvall (1995) noted that any transgression and regression induced a change in palaeoceanographic conditions. He proposed to use the FAD of *Nephrolithus frequens* rather than the M 900 marl layer at Hemmoor (≈ FAD of *Belemnitella junior*; Schulz et al., 1984) to define the Lower/Upper Maastrichtian boundary. Christensen (1996) noted that this marl layer might represent a chronostratigraphic horizon, being also recorded at the same stratigraphical levels in Denmark and Rügen. Stenvall (1995), however, considered this layer to be no more than a regional event, the result of an interaction between the Early Maastrichtian regression and the incoming of North Atlantic water into the basin which was otherwise dominated by a Tethyan influx.

Schönfeld & Burnett (1991) noted that the warm water outflow from the northwest European epicontinental seas through the Channel could well have been a dominant factor in separating the Boreal and Tethyan bioprovinces on the western European shelf. They also considered that the palaeoceanographic 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 (see also Stenvall, 1995; Mortimore et al., 1996), 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 reach the northwest European epicontinental seas. These authors noted that the biogeographical separation between the boreal/temperate and Tethyan realms was not only the result of limited faunal/floral exchange through narrow marine straits.

Nannofossil zonal assignments for the Maastricht Formation have varied according to authors (e.g. van Heck, 1979; Čepek & Moorkens, 1979; Verbeek, 1983, 1986; Romein et al., 1996). However, there seems to be a general consensus about referring the entire formation to zone CC26 (*N. frequens*). Romein et al. (1996) noted the absence of *Micula murus* and *M. prinsii* (but see their pl. 1, fig. 5 !) from the uppermost Meerssen Member in the Geulhemmerberg section. This absence hampers correlations with other occurrences, for which Henriksson (1993) has recently suggested that the *M. prinsii* Zone could be useful in determining the presence of complete terminal Maastrichtian sequences.

Brinkhuis & Schiøler (1996) have recently shown the uppermost Meerssen Member in the Geulhemmerberg section to contain, amongst other species, *Thalassiphora pelagica* (Eisenack, 1954) Benedek & Gocht, 1981 and *Palynodinium grallator* Gocht, 1970. This assemblage enables a correlation with the latest Maastrichtian in other parts of the North Sea Basin (Hultberg & Malmgren, 1986; Schiøler, 1993; Schiøler & Wilson, 1993). It suggests that the type Maastrichtian is more complete than the section in central Poland. Machalski (1996) cited H.J. Hansen et al.'s (1989) work showing that the upper Kazimierz Opoka in central Poland corresponded to the lower part of the *P. grallator* Zone, and that the upper two subzones of this zone (J.M. Hansen, 1977, 1979; Hultberg & Malmgren, 1986, 1987) were absent. When compared with Danish sections, this shows that between 5 and 10 m of sediment are missing in Poland (Machalski, 1996). A dinoflagellate biozonation and sequence-stratigraphic interpretation of the Maastrichtian stratotype section has recently been proposed by Schiøler et al. (1997). These authors documented a change from open marine to marginal marine conditions to have taken place 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 (Haq et al.'s [1988] UZA 4.5, TA 1.1, TA 1.2 and a fourth of probably higher order) could be recognised at the ENCI-Maastricht BV quarry.

The strontium isotope profile for the type Maastrichtian (Vonhof & Smit, 1996) has been shown to be a useful chronostratigraphic tool in correlating the type section with Bidart and El Kef (Tunisia) (see Nelson et al., 1991; Clauser, 1994). These authors computed for the upper 30 m of the type Maastrichtian (= base Emael Member to top Meerssen Member) a sedimentation rate of ≈ 10 cm/ka, thus providing a valuable tool for estimating faunal changeover patterns in the Late (latest) Maastrichtian of the type area.

Houthem Formation

Lithostratigraphy and facies interpretation

Geulhem Member

Stratotype — Curfs-Ankerpoort quarry at Geulhem, southeast of Meerssen (exposure 62A-13), co-ordinates 320.120/182.100.

This unit comprises poorly indurated, light yellowish-grey, fine- to coarse-grained chalks with varying glauconite content. Irregularly distributed are more indurated chalk beds and nodules. Locally hardgrounds and fossil hash layers and lenses occur. Total thickness is up to c. 10 m.

The other members of the Houthem Formation, the Bunde Member (stratotype: borehole 61F-2 at Brommelen, municipality of Bunde, co-ordinates 324.630/179.050, depth 30-53 m, base not reached) and the Geleen Member (stratotype: shaft III of state mine Maurits at Geleen, borehole 60C-249, co-ordinates 331.440/184.800, depth 169.20-185.50 m), were characterised by Albers & Felder (1979) as follows:

The Bunde Member comprises poorly indurated light grey, fine- to coarse-grained chalks with irregularly distributed indurated chalk nodules. Locally thin hash beds and/or lenses occur. Total thickness varies between c. 10 and 25 m.

The Geleen Member comprises poorly indurated, light grey, coarse-grained chalks with irregularly distributed indurated chalk beds and nodules. Locally irregular fossil hash lenses occur. Total thickness up to c. 18 m.

Albers & Felder (1979) also noted that lithologically the Houthem Formation corresponded largely to the Maastricht Formation, in comprising biodetritus chalks and hardground phenomena, but that biocoenoses differed. They assumed the hiatus at the Vroenhoven Horizon to probably comprise the entire Early and Middle Danian, explained by a decreased sedimentation rate and/or submarine erosion.

Deposits correlative with the Houthem Formation have been recorded in the literature from the Belgian Campine area (Bless et al., 1993) and from northwest Germany (Hückelhoven-Erkelenz area; Anderson, 1973, 1974, 1975; Müller, 1988; Müller & Strauch, 1991).

Bignot (1992, 1993) and Bignot & Janin (1994) proposed correlations between the various northwest European occurrences of Danian and 'Montian' strata, notably in the Paris Basin, southern Belgium (Mons Basin), southern Limburg and the Danian type area (Denmark, southwest Sweden). These authors demonstrated the type Montian to be the time-equivalent of part of the Danian. In the Paris Basin two distinct units could be distinguished, viz. the Early Danian Mont Aimé-Vertus Formation and the Middle Danian (= Montian) 'Calcaire pisolithique' of Vigny, Meudon and Laversines. Two successive Danian transgressions were thus postulated, and deposition was assumed to have occurred in a shallow (30 m at the most), warm (18-20 °C for coolest month) marine environment distributed along a carbonate ramp.

On lithological features, the Geulhem Member as exposed at the Ankerpoort-Curfs quarry (Geulhem) can be subdivided into two, possibly three, units (Jagt et al., 1996). Biostratigraphic data (see below) suggests these to be of Early (earliest ?) and Middle Danian age, but exactly how these units relate to Bignot's (1993) two transgressive pulses remains to be determined. On current evidence, the Vroenhoven Horizon, formerly generally equated with the K/T boundary in the Maastrichtian type area (Jagt et al., 1996), is situated within the Early Danian portion of the section and may correlate with the top of the Danish 'Cerithium Kalk' (Brinkhuis & Smit, 1996). Two distinct horizons, packed with a low diversity external/internal bivalve mould fauna, corresponding to the base of section Va-2 and to section Va-3 in Jagt et al. (1996, fig. 7) apparently indicate periods of reduced sedimentation rate (higher-energy settings ?) and time-averaging.

For detailed descriptions of sedimentological aspects, microfacies analysis, stable isotope ($\delta^{18}O$, $\delta^{13}C$) records, palaeomagnetism and trace element analysis of the K/T boundary section as exposed in the combined Ankerpoort-Curfs and Geulhemmerberg sequences, reference is made to Roep & Smit (1996), Zijlstra et al. (1996), Schmitz & Speijer (1996), Langereis (1996), and Smit & Rocchia (1996). Smit & Brinkhuis (1996) summarised the results of multidisciplinary studies of this K/T boundary section and presented a possible scenario of events with reference to the Yucatán Peninsula impact.

Biostratigraphy

The combined sections exposed at the Ankerpoort-Curfs quarry and the Geulhemmerberg nearby have recently been shown to comprise the most complete K/T boundary interval in the Maastrichtian type area known to date (Brinkhuis & Smit, 1996). Most of the data presented below are taken from the various contributions contained in this thematic volume.

Previous zonal assignments of the Geulhem Member on nannofossil evidence was reviewed by Romein et al. (1996). These authors noted for the Geulhemmerberg section that results of light microscopy and scanning electron microscopy analyses of nannofossil assemblages differed significantly. They documented the Early Danian *Biantholithus sparsus* Zone, subdivided into the *Neobiscutum romeinii* and *N. parvulum* Subzones, for unit IVf-7 of the Meerssen Member as exposed at Geulhemmerberg. The lowermost sample (G2A), resting directly on the Berg en Terblijt Horizon, taken from this section was tentatively referred to the basal Danian *Obliquipithonella operculata* Subzone. The authors also noted that there were no acmes of *O. operculata* (Bramlette & Martini, 1964) Fütterer, 1987 and of *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947, used in sections elsewhere to mark the K/T boundary. Scanning electron microscopy analyses of the same samples, however, revealed the occurrence of *Cruciplacolithus primus* Perch-Nielsen, 1977, *N. parvulum* (Romein, 1979) Varol, 1989 and *N. romeinii* Perch-Nielsen, 1981 throughout the Geulhemmerberg section, i.e. also in the latest Maastrichtian part of it, dated on macro- and microfossil evidence. A comparison with the El Kef section showed, according to Romein et al. (1996), that the earliest Danian is missing in the Geulhemmerberg section and that Early Danian subzones are strongly reduced in thickness, which is assumed to have resulted from non-deposition rather than condensation.

Hofker's benthic foraminifer zones P, Q and R correspond to the Geulhem, Bunde and Geleen members of the Houthem Formation, respectively. Within the (extended) Maastrichtian type area, zonal indicators have been successfully used in correlations (see Herngreen et al., 1986; Bless et al., 1993), but problems arise when trying to correlate interregionally. Amongst benthic foraminifera assemblages from section IVf-7 of the Geulhemmerberg section (Kuhnt, 1996; Witte & Schuurman, 1996) many Late Maastrichtian species have been recorded, in addition to Palaeocene marker species such as *Ceratobulimina tuberculata* Brotzen, 1948 and *Rosalina brotzeni* Hofker, 1961. Kuhnt (1996) noted that the presence of 'high-productivity' benthic foraminifer assemblages in the upper part of the sequence, together with the markedly increased numbers of certain calcareous dinoflagellate cysts, could well be an indication of an important recovery phase after the K/T boundary trophic collapse. Planktonic foraminifera from the same section were described by Smit & Zachariasse (1996). No genuine Early (earliest) Danian taxa were recorded, but a number of Cretaceous taxa were considered to have survived K/T boundary perturbations in the area. Comparison with other data (benthic foraminifera, dinocysts and nannofossils) and the overall lithological succession suggested the IVf-7 unit in the Geulhemmerberg to be referable to the basal Danian P0 planktonic foraminifer zone.

The remainder of the Geulhem Member is characterised by Danian planktonic foraminifera, which allow correlations with the type Danian (M. Meijer, 1959; Moorkens, 1982).

Dinoflagellates and other palynomorphs (Brinkhuis & Schiøler, 1996) showed the top of section IVf-6 in the Geulhemmerberg section to be of latest Maastrichtian (see above) and section IVf-7 to be of Early Danian age, mainly on the basis of *Senoniasphaera inornata* (Drugg) Stover & Evitt, 1978. The FAD of this species more or less corresponds to the K/T boundary, when calibrated against the P0 Zone. Two additional species which are important in documenting the Early Danian on a worldwide scale, viz. *Damassadinium californicum* (Drugg) Stover & Evitt, 1978 and *Carpatella cornuta* Grigorovich, 1969, have not been observed in the Geulhemmerberg section.

Of calcareous dinocysts from the Geulhemmerberg section Willems (1996) remarked that several 'events' could be recognised, but that, on the basis of current data on these fossils, it could not be determined whether or not they could be used as K/T boundary indicators.

The Geulhem Member, and especially its upper part as exposed in temporary exposures along the Albertkanaal near Vroenhoven-Riemst (northeast Belgium), has been shown to contain highly diverse echinoid faunas (van der Ham, 1988). These comprise a few elements in common with Early/Middle Danian echinoid faunas elsewhere in northwest Europe (Mons Basin, Denmark and southern Sweden). Of note are representatives of the psychocidarine genus *Tylocidaris*. Quite a number of successive species, based mainly on size and shape of primary spines, have been described from the Danian type area, where they have been used as zonal markers (Brotzen, 1959). J.M. Hansen (1977) showed these echinoid zones to be diachronous across the Danish Basin when compared with dinoflagellate distribution. However, Gravesen (1993) has recently put forward arguments in favour of their being used as zonal indexes. As observed by Jagt (1996), the first representatives of *Tylocidaris (T.) oedumi* Brünnich Nielsen, 1938 in Denmark (base of the Early Danian *oedumi* Zone; see Gravesen, 1993) are very close to *T. (T.) hardouini* (Desor, 1855) from the Maastrichtian type area, which ranges through sections Va-1 and Va-2 of the Geulhem Member. The FAD of the successor species in Denmark, *T. (T.) abildgaardi* Ravn, 1928 lies c. 3 m above the K/T boundary. Spines of this type are unknown from the Geulhem Member, which may suggest a hiatus within this unit. In situ spines from above section Va-3 (see Jagt et al., 1996, fig. 7) are closely comparable to the Danish Middle Danian *T. (T.) bruennichi* Ravn, 1928.

There is currently no echinoid evidence to suggest that sedimentation of the Geulhem Member continued into the Late Danian. Sediments of the overlying Bunde and Geleen members are known only from boreholes, and samples from cores are generally too small for macrofossil analyses.

At least two species of goniasterid asteroids appear to be reliable Early Danian markers as well, viz. *Metopaster spencerii* Brünnich Nielsen, 1943 and *M. kagstrupensis* Brünnich Nielsen, 1943 (Rasmussen, 1950, 1964, 1965, 1972). Both species have been recorded from the Early Danian *oedumi* and *abildgaardi* zones in Denmark (Brünnich Nielsen, 1943; Rasmussen, 1971) but their FADs still need to be determined. Section IVf-7 of the Meerssen Member as exposed in the Ankerpoort-Curfs quarry (Geulhem) has not yielded any specimens; the first examples are known from section Va-1 and correlatives elsewhere in the Maastricht area.

Similar to the Upper(most) Maastrichtian Meerssen Member, the (micromorphic) brachiopod faunas from the Geulhem Member cannot be compared in detail with zonations proposed for Denmark (Surlyk & Johansen, 1984; Johansen, 1987, 1988b, 1989). It is assumed that differences in substrate nature and microhabitats can explain these discrepancies. However, various species of cancellothyridid and megathyridid are quite common, and these may well turn out to include good stratigraphic markers upon closer inspection.

On ostracod evidence, Deroo (1959, 1966) correlated the Geulhem Member with the 'Tuffeau de Ciply' in southern Belgium and assigned a Late Danian age to this unit. However, it should be noted that he placed the 'Montien' above the 'Danien supérieur'. Subsequent authors (e.g. Bignot, 1992, 1993) have shown the Montian to correspond to the Middle Danian elsewhere in northwest Europe (see also Voigt, 1987a).

Elements amongst crustacean faunas, such as raninid crabs (Jagt et al., 1993) and brachylepadomorph barnacles (Jagt & Collins, 1988), and serpulid assemblages (Jäger, 1993) have also provided arguments for correlation of the Geulhem Member with the type Danian in Denmark and southern Sweden.

Until recently, the correlative potential of neoselachians in the Geulhem Member was not fully appreciated. Work underway suggests that various species can be used for interregional correlation and patterns of faunal exchange between North Africa and Europe. The record (Halter, 1989) from the basal Geulhem Member of the dasyatoid ray *Prosopodon assafai* Noubhani & Cappetta, 1995, originally described from the Danian of Morocco (Noubhani & Cappetta, 1995) is just one example; various others will be discussed by Reynders & Halter (work in progress).

On the basis of strontium isotope analyses of heterohelicid foraminifera from the Geulhemmerberg E clay, Vonhof & Smit (1996) confirmed the Early Danian age assignment of other studies. In the absence of an iridium spike (Smit & Rocchia, 1996; Smit & Brinkhuis, 1996) in the K/T boundary interval in the Geulhemmerberg section, the planktonic species *Heterohelix globulosa* (Ehrenberg, 1840) was assumed to have survived the K/T boundary for at least some 5-50 ka. This corresponds to the duration of deposition of the iridium-bearing boundary clay interval elsewhere (northern Spain and Tunisia).

Smit & Brinkhuis (1996) reported briefly on geochemical studies which had revealed the presence of 'molecular fossils' in samples from just below the Berg en Terblijt Horizon (= top section IVf-6). These are of a bacterial origin, having been formed during massive anoxic fermentation, and are a valuable marker for the K/T boundary, since they are also known to occur at El Kef in the basal boundary clay interval.

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