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Microfacies analysis of Cretaceous/Tertiary boundary sections in the quarries Geulhemmerberg and Curfs, SE Netherlands

J.J.P. Zijlstra[1], M.H.M.P. Brouwers[1,2,3], H. Brinkhuis[2] & P.L. de Boer[1]
[1] *Institute of Earth Sciences, P.O. Box 80.021, Utrecht, the Netherlands;* [2] *Laboratory of Palaeobotany and Palynology, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, the Netherlands;* [3] *present address: Shell Internationale Petroleum Mij, P.O. Box 162, 2501 AN The Hague, the Netherlands*

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Abstract

Detailed thin-section microfacies analysis reveals the temporal and spatial variation of the depositional and early-diagenetic conditions of the upper part of the Meerssen Member of the Maastricht Formation, now considered to span the Cretaceous/Tertiary (K/T) boundary, at Geulhemmerberg and Curfs (Maastrichtian type area, SE Netherlands). The precession-induced cycles of the Meerssen Member have been formed due to periodic variations of hydrodynamic energy and of deposition rate. Their genesis is similar to that of other precession-induced cycles encountered in the underlying Maastrichtian and Campanian carbonates. The microfacies distribution shows that the calcarenitic Geulhemmerberg sediment has been deposited under higher hydrodynamic energy conditions and in deeper water than the coeval sediments of quarry Curfs. The microfacies is locally characterised by dissolution features that may have been produced by percolating meteoric water during syn-sedimentary exposure. We propose that the intercalated clay layers, despite their open marine microfossil assemblage, were deposited under conditions of very low wave energy in very shallow marine depressions that were only affected during storms.

Introduction

As a part of the multidisciplinary analysis of the recently discovered, presumably relatively complete Cretaceous/Tertiary (K/T) boundary section in the Geulhemmerberg caves (Maastrichtian type area, SE Netherlands, see Brinkhuis and Smit, this issue), the present study reports on an investigation of this succession by means of thin-section microfacies analysis. Furthermore, for comparison the coeval interval as exposed in the nearby quarry Curfs (Jagt et al., this issue), i.e. unit IVf-7, the uppermost part of the Meerssen Member of the Maastricht Formation (Felder 1975a, b) has also been investigated. Thus, we aim to increase the understanding of the temporal and spatial variation of the depositional and early-diagenetic conditions during the K/T transition in the area. The macroscopic lithostratigraphy and the biostratigraphy of these sequences is described in extenso elsewhere (Roep and Smit, Smit and Brinkhuis, this issue). In this contribution, some sedimentological aspects are summarised and attention is focused on the distribution of bioclasts and authigenic minerals in thin sections and on the interpretation of the microfacies distribution, following a model of the sedimentology of chalk (Zijlstra 1994, 1995).

Lithological overview, samples

Quarry Curfs

For location and stratigraphic details on quarry Curfs, reference is made to Jagt et al. (this issue). The Meerssen Member, as presently exposed in this quarry, consists of a fining-upward succession of porous, glauconitic and pyritic (partly oxidised) calcarenites and calcisiltites, with an upward increasing mud (smectite) content. Lithified layers occur at the top of partly eroded fining-upward sequences, some of which are laterally continuous, while others are laterally restricted

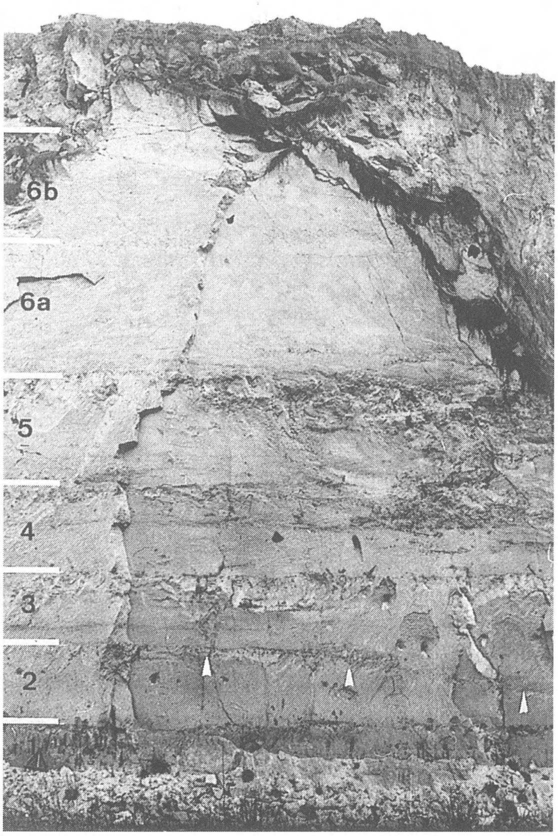


Figure 1. About 14-m-thick succession of the Meerssen Member (Maastricht Formation) exposed along a fracture in quarry Curfs. The exposure shows seven cycles (IVf-1 to IVf-7, Figure 27) with planar or sigmoidal (arrows) erosive bases and more or less lithified tops.

and pinch out against large-scale, low-angle, sigmoidal erosion surfaces (Figure 1).

In the lowermost part of the Meerssen Member the well-lithified layers occur at the top of relatively thin and coarse-grained, wavy-bedded, asymmetric, truncated (cf. Einsele et al. 1991) fining-upward cycles. These thin cycles are covered by thicker, finer-grained, more symmetric grain-size cycles with nodularly and weakly cemented layers.

The macrofossil assemblage of the lower part of the Meerssen Member at Curfs is characterised by coarse-grained fossil-grit layers with mainly dentiform serpulids (*Sclerostyla*; Jäger 1988), turitellid gastropods, clasts of large irregular echinoids (*Hemipneustes striatoradiatus*) and thin-shelled cusp-shaped oysters (*Pycnodontae vesicularis*). Very coarse-grained lithified bioclastic rubble, preserved in pockets in the eroded lithified layers, moreover contains moulds of colonial corals (Umbgrove 1925), coralline algae (Umbgrove, 1927) and the remains of large radiolitid rudists (Van de Geijn 1940). The consolidated and lithified sediments at the tops of the cycles contain *Thalassinoides* burrow networks. Locally the lithified layers have partly been eroded and developed into hardgrounds (Voigt 1959, 1974) that were bored by mussels and sponges (*Cliona*) and encrusted by oysters, brachiopods (*Crania*), bryozoa, serpulids and barnacles.

The fine- to medium-grained calcarenites in the middle parts of the lower cycles and at the bases of the finer-grained upper cycles, contain mainly large imperforate benthic foraminifera (amongst others *Lepidorbitoides minor, Siderolites calcitrapoides*; Hofker 1966; Sprechmann 1981), bifoliate and/or ramose bryozoa, oysters and echinoderm clasts.

The finest-grained sediments at the tops of the lower cycles and in the middle to upper parts of the upper cycles, contain a diverse association of small benthic foraminifera mixed with planktonic foraminifera and calcispheres (Villain 1975). In the lower half of the Meerssen Member, this lithified sediment contains well-preserved *Hemipneustes* tests and moulds of flat-based, mud-substratum, solitary corals (*Cyclolithes*). In the finer-grained upper part of the member, the lithified layers contain lenses with moulds of ammonites (*Sphenodiscus, Scaphites*) and the lightweight remains of pelecypods (*Pinna, Inoceramus*). The uppermost lithified layer at the top of the Meerssen Member, directly below the Vroenhoven Horizon, has a very poor fossil assemblage of low diversity with mainly the remains of small burrowing pelecypods (*Glycymeris*).

In this quarry the uppermost 3 m of the Meerssen Member, unit IVf-7 of Felder (1975a, b), with the Berg en Terblijt Horizon at the base (Felder and Bosch 1996), was sampled at irregular intervals of on average 30 cm (Figure 2), aiming at the recording of maximum facies contrast with minimal sample density. The sampled interval is characterised by very large-scale, slightly dipping, (sub)planar to weakly wavy erosion surfaces, covered by decimetre-thick, sparsely bioturbated, laminated layers, locally with a rather high smectite content. Most recent biostratigraphic information indicates an early Danian age for the sampled interval (Jagt et al., Smit and Brinkhuis, this issue).

Quarry Geulhemmerberg

For detailed descriptions of the locality, macroscopic lithostratigraphy and sedimentology of the Geulhem-

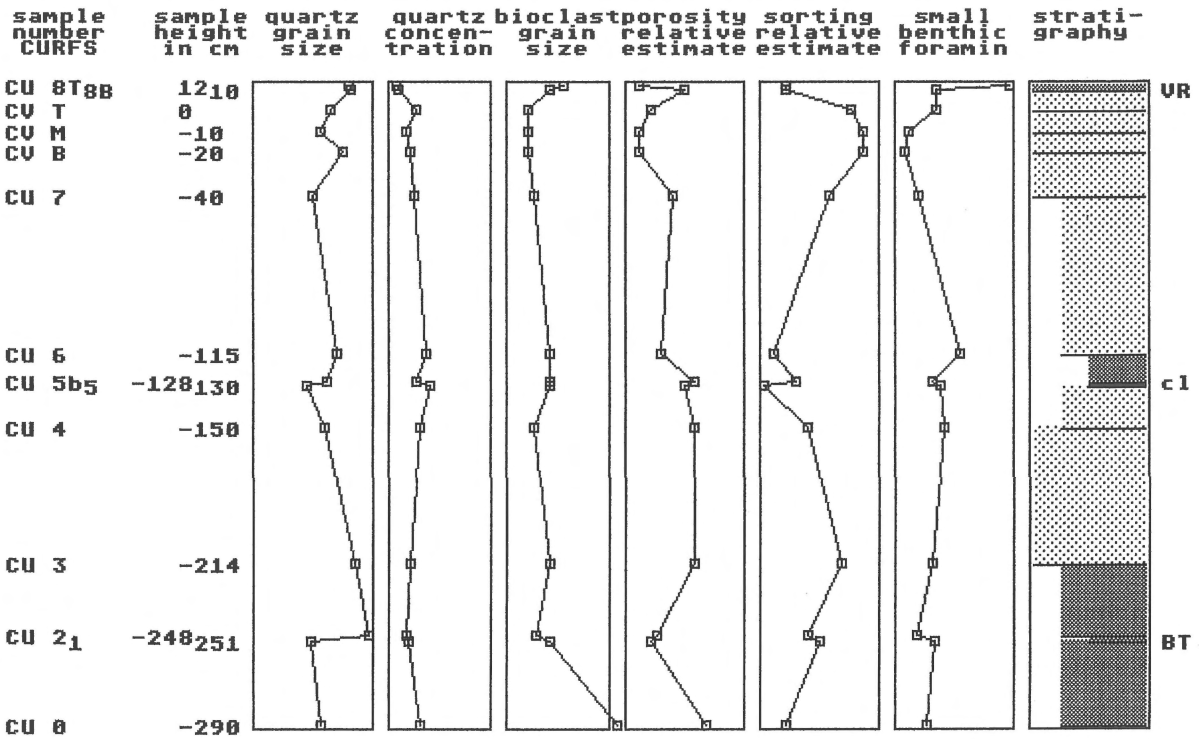
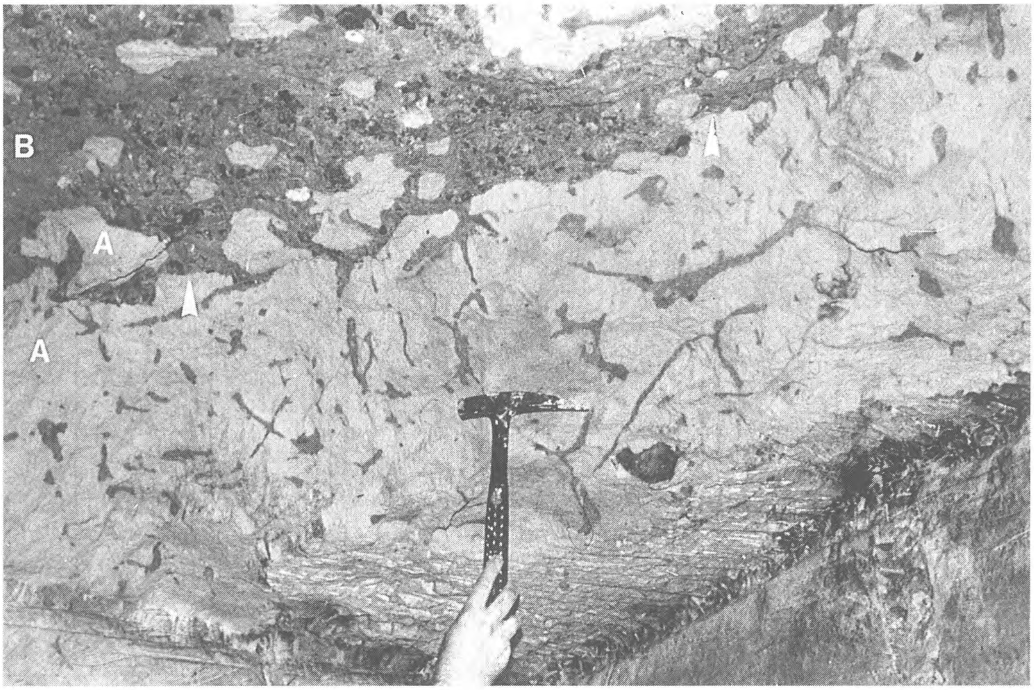


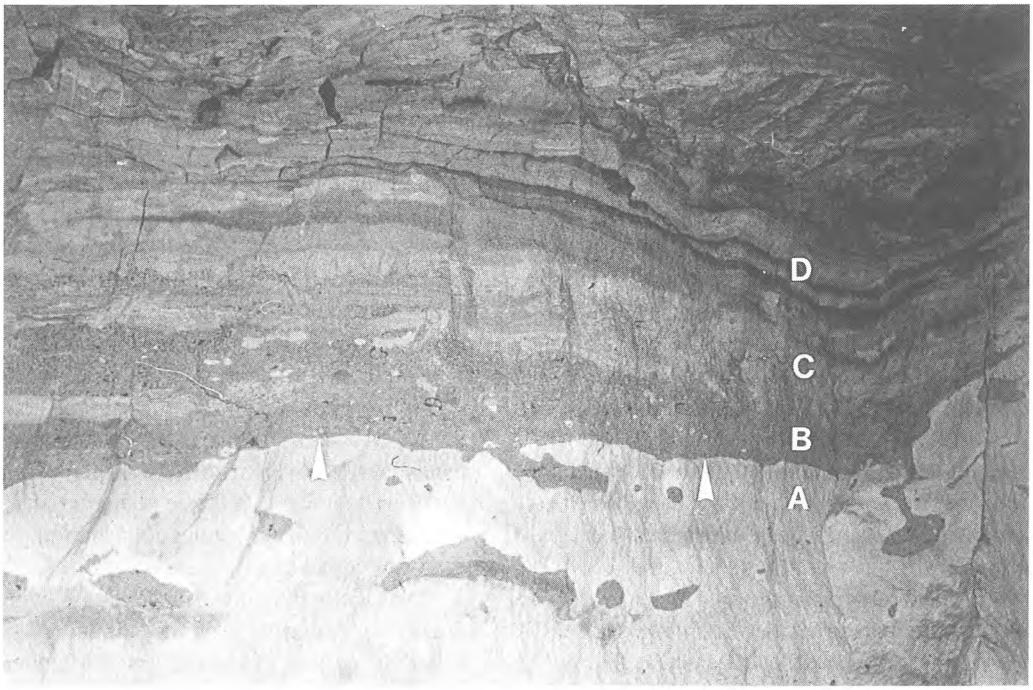
Figure 2. Results of the semi-quantitative analysis of the samples from quarry Curfs. Relative variations of counted numbers with lowest values to the left and highest values to the right. Stratigraphic column depicts the degree of glauconite oxidation (light = oxidised, grey = partly oxidised, black = non-oxidised) and the degree of lithification (left = well-lithified, right = non-lithified). VR = Vroenhoven Horizon, cl = clay layer, BT = Berg en Terblijt Horizon.

merberg 'main section' at measuring point 251 the reader is referred to Brinkhuis and Smit and Roep and Smit (both this issue). The homogeneous thick cycles of the upper part of the Meerssen Member (uppermost Maastrichtian; IVf-6a, b of Felder 1975a, b) have been excavated in the subterranean Geulhemmerberg quarry. The quarry ceiling is formed by a lithified layer that is considered equivalent to the layer directly below the Berg en Terblijt Horizon in quarry Curfs (Brinkhuis and Smit; Jagt et al.; Smit and Brinkhuis, this issue). The lithified layer, of which the top is thought to represent the K/T boundary (Smit and Brinkhuis, this issue), has been capriciously eroded and contains more or less enlarged *Thalassinoides* burrow networks, but no borings or encrustations. The erosion surface is undulating and several metre-wide and decimetre-deep irregular depressions occur, that have been filled with fining-upward layers of glauconitic and pyritic, bioclastic calcarenites and (smectitic) clays (Roep and Smit, this issue; Figures 3a, b, c). Immediately above the erosion surface, the sediment is a poorly sorted, well-bioturbated, coarse-grained, graded calcarenite. Repeatedly, the calcarenites grade into centimetre-thin bioturbated, (smectitic) mudstone layers (e.g. the A clay). The coarse-grained calcarenites are covered by sparsely bioturbated, large-scale, wavy-laminated, medium- to fine-grained calcarenites, with rather thick smectitic clay layers at the top (E clay). The uppermost smectitic layers immediately above the E clay have been extensively bioturbated and bioclastic silt has been admixed. The succession is widely considered equivalent to the sampled Meerssen unit IVf-7 in quarry Curfs (see e.g. Jagt et al., this issue), and, judged from the various contributions to this issue, early Danian in age.

The Geulhemmerberg succession is, with respect to the macro- and mesofossil content, indeed very similar to the upper part of the Meerssen Member in quarry Curfs. One may distinguish a coarse-grained poorly sorted calcarenitic facies with abundant *Orbitoides, Siderolites*, bifoliate and/or ramose bryozoa, thin-shelled oysters and echinoid clasts, a sorted medium-



a



b

c

Figure 3. Geulhemmerberg, upper part of the Meerssen Member (IVf-6, IVf-7). Arrows indicate the erosion surface of the Berg en Terblijt Horizon. All figures have the same scale (hammers are 30 cm long). a) Interval, about 1 m thick, near the top of the exposed sequence with bioturbated, lithified and eroded medium- to fine-grained calcarenites (A, Microfacies 1), covered by coarse-grained, poorly sorted, glauconitic and pyritic calcarenite (B). b) The depression has been filled with poorly sorted, coarse-grained calcarenites (B, Microfacies 2), covered by laminated, well-sorted, medium- to fine-grained calcarenites (C, Microfacies 3) and smectitic clay layers (D, Microfacies 4). c) Laterally, the lithified layer has been less eroded, pyrite was oxidised around burrows (light-coloured halos) and smectitic clay layers were deposited directly on top of the erosion surface of the Berg en Terblijt Horizon.

to fine-grained calcarenitic facies with small benthic foraminifera, and a fine-grained, smectitic, calcisiltitic to lutitic facies with planktonic foraminifera and calcispheres. In quarry Geulhemmerberg, about 1 m of sediment of unit IVf-7 has been sampled at average intervals of 10 cm (Figure 4).

Methods

Slides for thin-section analysis have been prepared according to standard techniques at the Institute of Earth Sciences, University of Utrecht. Based on thin-section analysis, the intervals top IVf-6 and IVf-7 at Geulhemmerberg and Curfs have been divided into microfacies-types, described below (for sample positions see Figures 2, 4).

Results; qualitative description of the thin-section microfacies

Geulhemmerberg

Microfacies 1. The homogeneously bioturbated, sorted, lithified, medium- to fine-grained calcarenites below the Berg en Terblijt Horizon (samples GRA 1, 2 and 3, Figure 4) consist of well-sorted, subangular (micritised) bioclasts with a highly diverse association of small benthic foraminifera. Few *Orbitoides* and *Siderolites* float in the matrix (sample GRA 2, Figure 5). Earliest-diagenetic micritisation and blackening (pyritisation) of part of the particles are common. Glauconite occurs as detrital peloidal grains, in bioclasts and in the pore space between bioclasts. Most glauconite is orange-coloured and oxidised; however, green-coloured, non-oxidised glauconite is still present. Pyritised particles are common, but all pyrite has been oxidised to iron (hydr)oxide. Pores have been dissolution-enlarged and in particular the particles

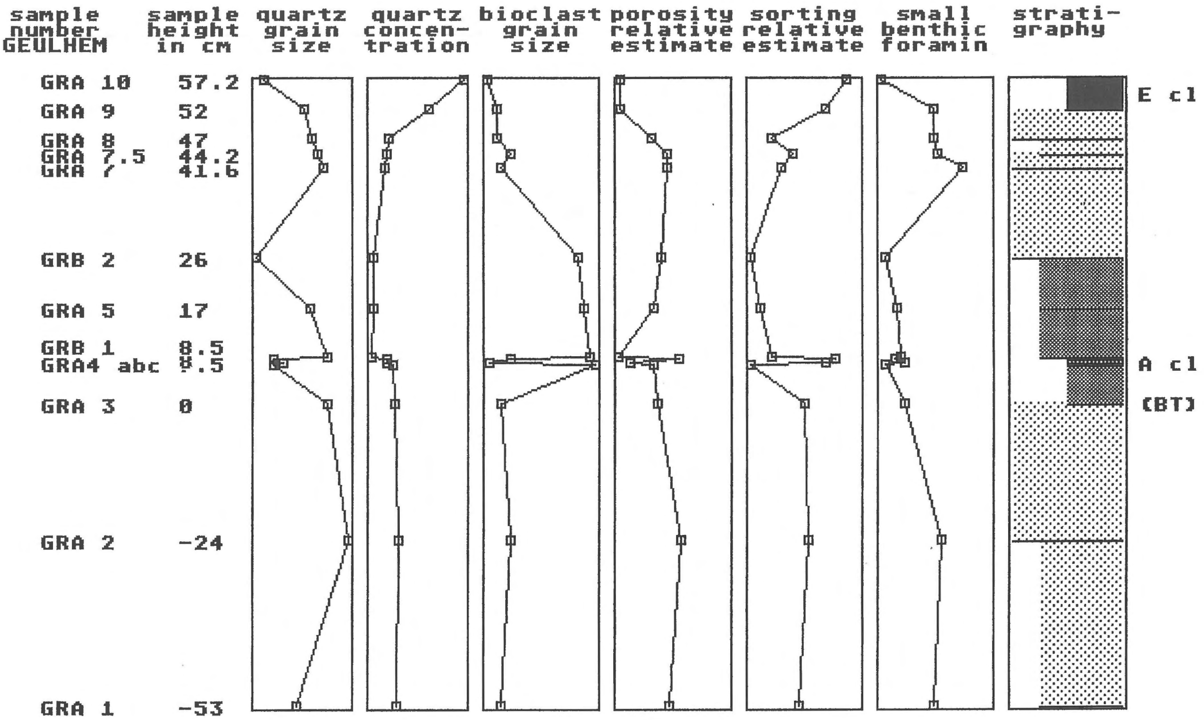


Figure 4. Results of the semi-quantitative analysis of the samples from the Geulhem(merberg) galleries. E cl = E clay (see Brinkhuis and Smit, this issue), A cl = A clay. For further explanation see Figure 2.

adjacent to pores are lined by a very fine-crystalline fibrous calcitic rim cement. Poikilotopic, syntaxial cement is common and mainly surrounds echinoid clasts, and incorporates adjacent particles and earlier rim cement.

Microfacies 2. The poorly sorted, coarse-grained, calcarenites that cover the erosion surface of the Berg en Terblijt Horizon (samples GRA 4, 5 and GRB 1, 2), consist of locally well-bioturbated, poorly sorted, rounded, broken and mineralised (glauconitised, pyritised) bioclasts. The matrix consists mainly of silt-sized, micritised peloids and bioclasts. The bioclasts are locally imbricated and may grade, within a centimetre, into calcisiltite and smectitic calcilutite with planktonic foraminifera and abundant calcispheres (sample GRA 4, Figure 6). The fine-grained tops of the deposits have been eroded and the sharply bounded, wavy erosion surfaces have been covered by medium-grained calcarenites with reworked calcilutite clasts. Storm deposition is suggested by the common occurrence of shelter voids below large bioclasts (sample GRB 2, Figure 7).

Figure 5. GRA 2 – Very porous medium-to fine-grained calcarenite with small *Lepidorbitoides* (1) filled with oxidized glauconite and/or ironhydroxide and with blackened pellets and bioclasts (b). Particles are commonly enveloped by syntaxial cement with undulating, dissolved margins. Locally patches of relict micrite and some large euhedral calcite crystals (arrow) occur. Width of view = 1.4 mm.

Besides few, well-preserved fossils (sample GRA 4c, Figure 8), bioclasts consist, moreover, of poorly preserved, rounded, broken, partly dissolved and glauconitised and/or pyritised remains of echinoderms,

Figure 6. GRA 4abc (height 4 cm, top left, large arrow) – Imbricated (small arrows) and graded coarse bioclastic sandstone, with bioturbated mudstone (Figure 10) in the middle and with medium- to fine-grained calcarenite at the top.

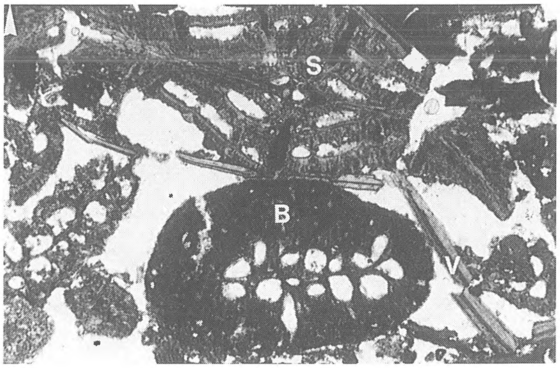


Figure 8. GRB 2 – Coarse-grained calcarenite with *Siderolites* (S), ramose bryozoa (dominantly restricted marine species; B) and thin-shelled oyster valves (V). Bioclasts have been blackened (pyritised), probably *in situ*, and were broken during compaction. Width of view = 3.4 mm.

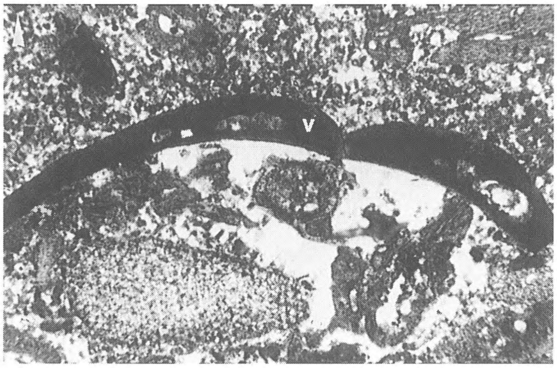


Figure 7. GRB 2 – Poorly sorted coarse-grained calcarenite with matrix of peloidal silt. Large blackened and/or dissolved (formerly silicified) (oyster) valve (v) shelters void with coarse bioclasts against fine-grained sediment above. Width of view = 3.4 mm.

thin-shelled oysters, ramose and/or bifoliate bryozoa, small benthic foraminifera and abundant large benthic imperforate foraminifera (sample GRB 2, Figure 9). Micrite-filled burrows of soft-substratum deposit feeders, i.e. *Chondrites* and *Zoophycus*, have been preserved *in situ* in the finest-grained sediment (A clay, sample GRA 4b, Figure 10) or they have been reworked and redeposited as muddy clasts in the coarser-grained calcarenites.

Micritisation and blackening of bioclasts is common, and may have affected the entire sediment (sample GRB 2, Figure 9). The clasts have been very well glauconitised and pyritised. Most of the iron minerals have been oxidised. Interparticle glauconite and pyrite in the pore space are rather rare. However, *in-situ* glauconitisation and pyritisation is well developed at the top of the coarse-grained calcarenites, below the muddy laminae (A clay, samples GRA 4, GRB 1, Figure 11).

Fine-crystalline rim cement has been mainly preserved in the intragranular pores (sample GRA 5, Figure 12). Syntaxial cement is common and well-developed, in particular at the lower side of echinoderm clasts (sample GRA 5, Figure 13). Often, micrite, bioclasts (sample GRA 4c, Figure 14) and cement have been strongly dissolved, have been scantily covered by iron (hydr)oxides, and have moreover been covered by a subhedral second-phase syntaxial cement.

The bioclastic sand has been well compacted after syntaxial cement precipitation as is witnessed by planar to interpenetrating grain contacts and by the absence of syntaxial cement at fracture boundaries of *in situ* broken bioclasts (sample GRB 2, Figure 9).

Microfacies 3. The medium- to fine-grained, sorted and laminated calcarenites that form the middle part of the depression-infill succession (samples GRA 7, 7.5, 8), are composed of well-sorted, sand-sized bioclasts with small benthic foraminifera and thin-shelled oyster remains. Upwards, the concentration of micrite increases. Clay clasts and millimetre-thin, centimetre-long burrows, filled with micritic calcisiltite, are commonly observed in the thin sections of the laminated fine-grained calcarenites (sample GRA 7, Figure 15).

Oxidised intragranular glauconite and pyrite are common in the clean calcarenites. The clay samples (GRA 8) contain, furthermore, non-oxidised detrital glauconitic peloids and partly oxidised, intra- and intergranular glauconite and pyrite. Fine-crystalline rim cement and syntaxial cement are common in the intra-

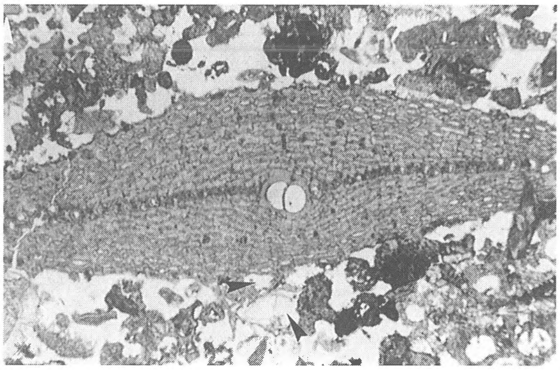


Figure 9. GRA 4c – *Lepidorbitoides* and matrix around dissolved clasts below this large benthic foraminifer (small arrows). Width of view = 3.4 mm.

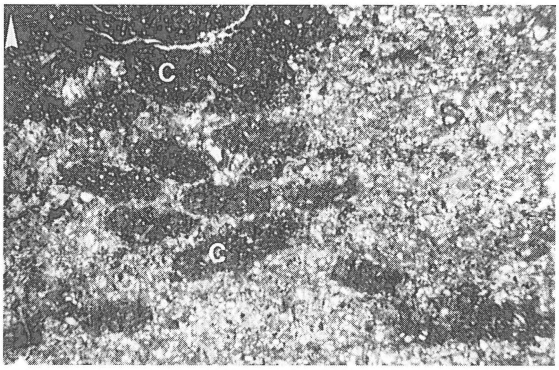


Figure 10. GRA 4b – Muddy calcisiltite with small benthic foraminifera and with a cluster of compacted *Chondrites* burrows (C) that have been filled with silty calcilutite (see also Figure 6). Width of view = 3.4 mm.

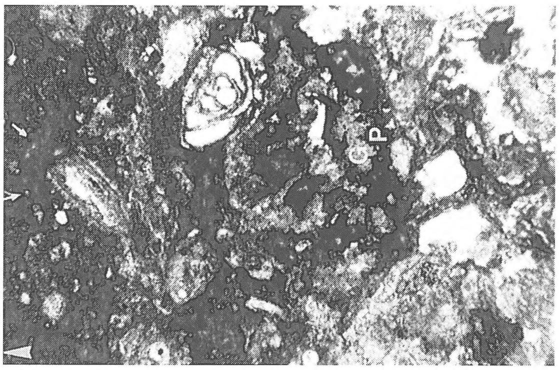


Figure 11. GRB 1 – Boundary between coarse-grained calcarenite and calcilutite (A clay). The bioclasts of the calcarenite have been mineralised by glauconite (G) and pyrite (P). Bioclasts and matrix have been partly dissolved. The calcarenite is covered by a layer of smectitic calcilutite with peloids and bioclasts. This wackestone has been pyritised at the basis and consists upwards of calcilutite laminae that drape conformably over extruding bioclasts (small arrows). Top is at left (large arrow). Width of view = 1.4 mm.

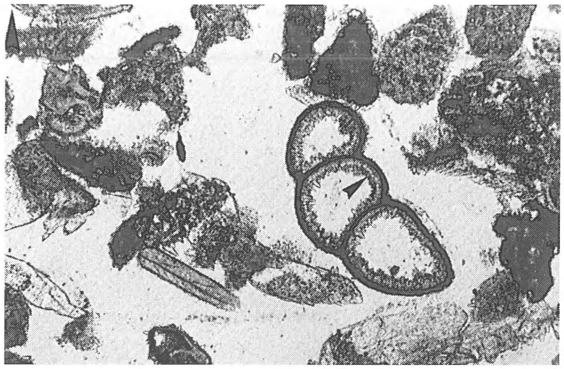


Figure 12. GRA 5 – Very porous, medium- to fine-grained calcarenite with small blackened benthic foraminifer with intraparticle, two-phase, thin, fibrous rim cement (arrow). Width of view = 1.4 mm.

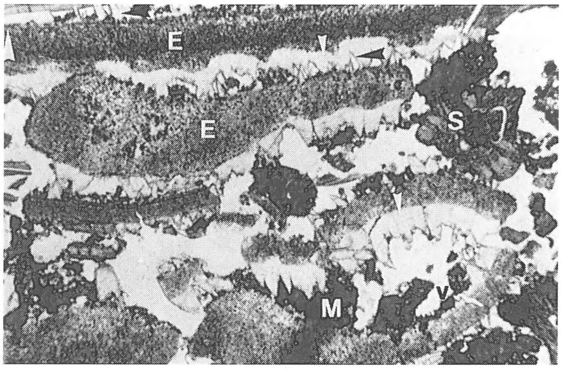


Figure 13. GRA 5 – Parallel-oriented, platy echinoid (E) and oyster clasts with mineralised broken *Siderolites* (S). Interparticle pore space consists partly of dark-coloured, mineralised, peloidal mudstone with dissolved margins (M) and partly of large vuggy pores (v). Typical syntaxial rim cement occurs commonly around echinoid clasts. The upper surfaces of the clasts have been covered by mudstone or by (isolated) euhedral (bridging) calcite crystals (black arrows). The lower surfaces of the clasts, moreover, have been covered by relatively thick rims of continuous undulating syntaxial cement, grading into euhedral, skalenohedral or 'pseudopodic' extrusions, locally enveloping underlying syntaxial crystals that grew on the upper surfaces of bioclasts (white arrows). Width of view = 3.4 mm.

and intergranular pores, in particular in the lithified samples (GRA 7, 7.5).

Microfacies 4. The smectitic clay layers at the tops of the fining-upward sequences are composed of muddy bioclastic-peloidal calcisiltite (sample GRA 9, Figure 16) and smectitic calcilutite (sample GRA 10, Figure 17). The peloidal calcisiltite is very well sorted, strongly compacted and contains mainly small echinoderm clasts, abundant small benthic foraminifera of low diversity, planktonic foraminifera and calci-

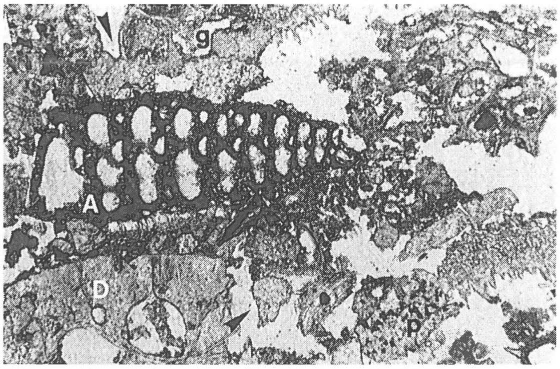


Figure 14. GRA 4c – Large (not dissolved) agglutinating benthic foraminifer (A) and restricted marine epiphytic bryozoa (D). Bioclasts have been strongly dissolved (lacy structure, black arrows). Inter- and intraparticle glauconite or ironhydroxyde coatings (g) and intraparticle pyrite (p) fill are common. Width of view = 1.4 mm.

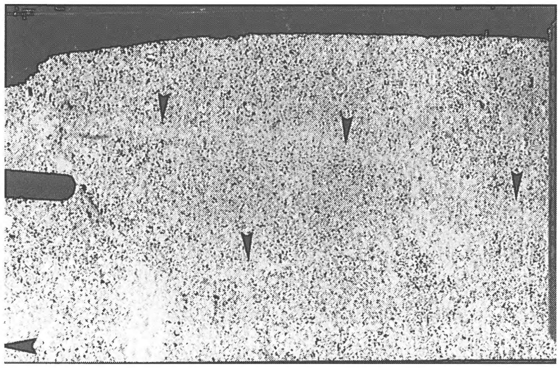


Figure 15. GRA 7 (height 4 cm, top is at left) – Muddy, medium to fine-grained, laminated calcarenite with traces of bioturbation (arrows).

spheres. The calcilutite contains only rare planktonic foraminifera.

The peloidal calcisiltite has been very well glauconitised *in situ*. Silt-sized patches of oxidised glauconitised clasts, surrounded by diffuse glauconitised halos, are concentrated in depositional laminae. Detrital peloidal non-oxidised glauconite is common. Some post-depositional vuggy dissolution has been encountered.

Curfs

Microfacies 1. The homogeneously bioturbated, sorted and lithified fine-grained calcarenites found near the basis of the Geulhemmerberg section, below the Berg en Terblijt Horizon, have not been observed in

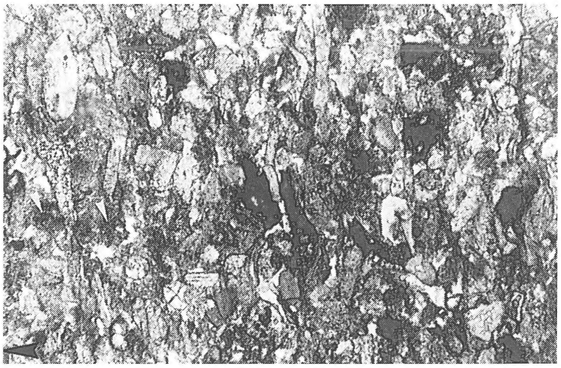


Figure 16. GRA 9 – Well-sorted, well-compacted, laminated calcisiltite with bioclasts and deformed intraclasts. Locally, the sediment has been glauconitised in patches with diffuse boundaries (arrows). Top is at left. Width of view = 1.4 mm.

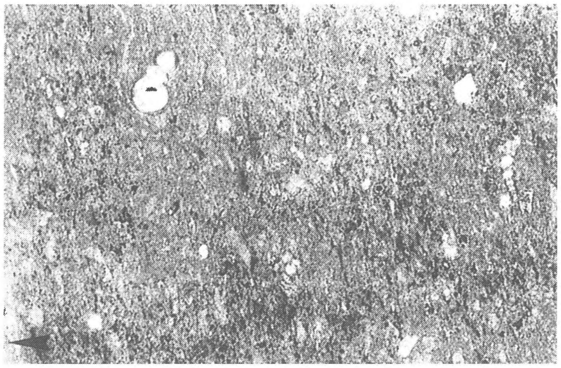


Figure 17. GRA 10 – Smectitic (laminated) claystone (basis E clay) with well-preserved small benthic foraminifera, planktonic foraminifera and calcispheres. Top is at left. Width of view = 0.9 mm.

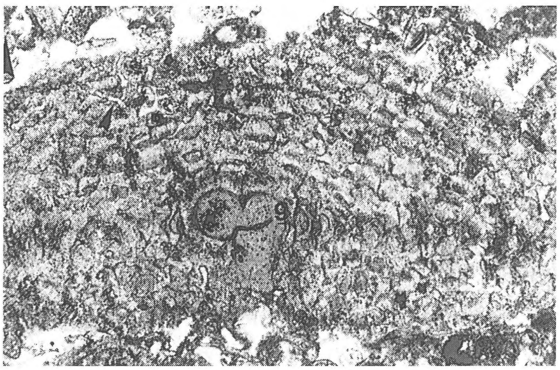


Figure 18. CU 5 – Porous, medium- to fine-grained calcarenite with rounded, (oxidised) glauconitised (g), bored (small arrow) *Lepidorbitoides*. Width of view = 1.4 mm.

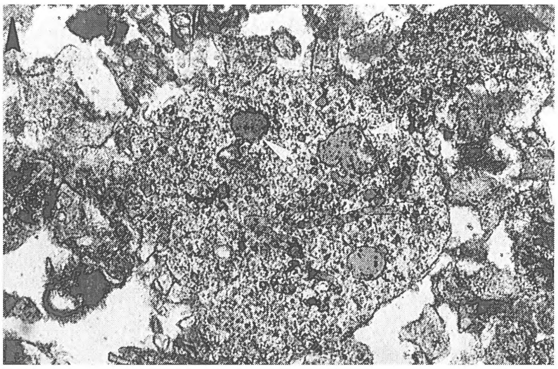


Figure 19. CU 4 – Porous, medium- to fine-grained calcarenite with rounded, partly dissolved, bored echinoid clast. The borings have been filled with (non-oxidised) glauconite and tiny pyrite framboids (small arrows). Width of view = 1.4 mm.

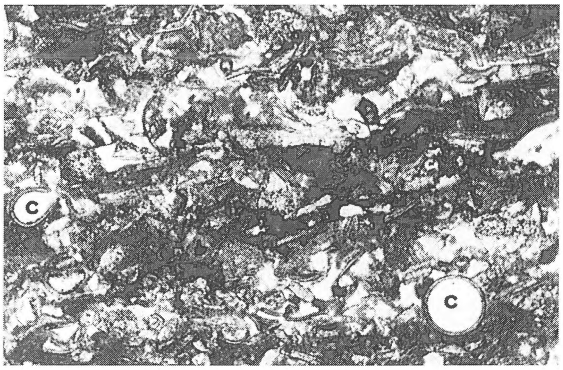


Figure 20. CU 5 – Laminated, muddy calcisiltite with (pithionellid) calcispheres (c) and abundant thin-shelled remains of calcispheres, benthic foraminifera or possibly ostracods. Lamination is formed by muddy pyritised layers, that alternate with porous (micrite dissolution) layers. Width of view = 1.4 mm.

the thin sections sampled below this horizon in quarry Curfs.

Microfacies 2. The coarse-grained, poorly sorted calcarenites above the Berg en Terblijt Horizon in quarry Curfs are, as compared to the Geulhemmerberg equivalent, less well sorted and on average finer-grained. The bioclasts are much more rounded, bored and glauconitised and/or pyritised (samples CU 5, 4, Figures 18, 19). The samples CU 0, 1, 5, 6 and to a lesser extent CU 4 and 5B are characterised by the common occurrence of larger bioclasts, which occur randomly oriented in the finer-grained matrix. The bioclasts are comparable to those of the Geulhemmerberg and are mainly remains of echinoderms, large imperforate benthic foraminifera and, less commonly, the remains of ramose and/or bifoliate bryozoa and thin-shelled oysters.

Microfacies 3. The medium- to fine-grained calcarenites of Curfs quarry (samples CU 2, 3 and 7) are less sorted than those of the Geulhemmerberg and consist of rather well micritised bioclasts and common to abundant small benthic foraminifera.

Microfacies 4. The calcisiltites of Curfs quarry (sample CU 5, Figure 20; CV B(ottom), M(iddle) and T(op)) are characterised by abundant calcispheres and common planktonic foraminifera. The fine-grained calcarenites directly below (sample CU 8B) and above (sample CU 8T) the Vroenhoven Horizon contain respectively common and abundant peloids and small benthic foraminifera.

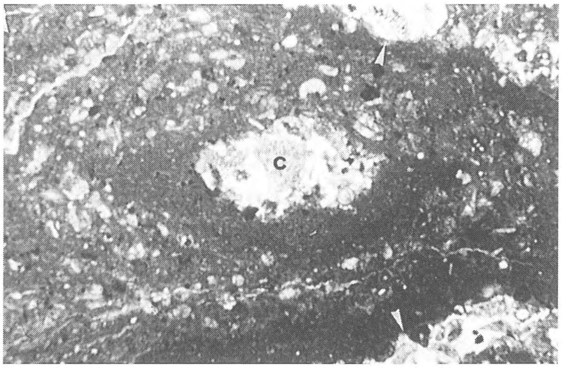


Figure 21. CU 0 – Cross-section through large muddy 'Spreiten' burrow in porous muddy calcarenite. The central tube (c) is well visible and surrounded by a muddy margin that contains bioclastic laminae. Locally a slight penetration of bioclasts into the burrow margin (arrows) can be observed. Width of view = 3.4 mm.

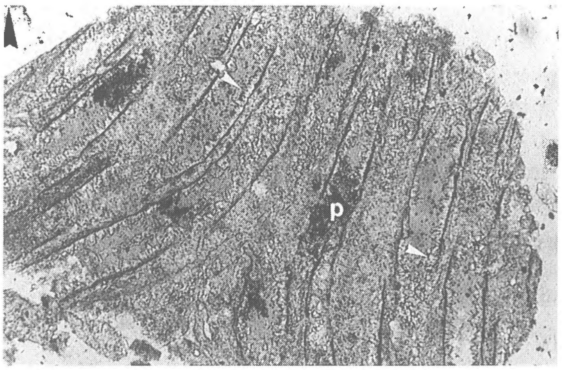


Figure 22. CU 1 – Bryozoan clast with intragranular chamber walls that have been covered by poorly ordered, small euhedral calcite rim cement (arrows) that does not occur at the outer margin of the clast. The inner parts of the chambers have been filled and the calcite crystals have been covered by glauconite. Locally, the glauconite has been pyritised (p) and the carbonate cement partly dissolved. Width of view = 0.9 mm.

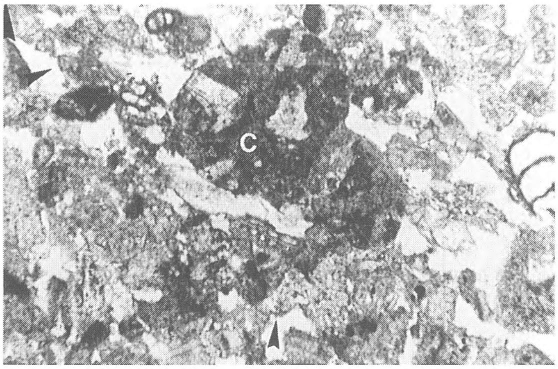


Figure 23. CU 4 – Porous, medium- and fine-grained calcarenite with (non-oxidised) glauconitised and pyritised intraclast (C) and dissolution-enlarged pores of which the margins are lined by (iron-hydroxide) clay minerals, suggesting early dissolution before clay-mineral genesis (arrows). Width of view = 1.4 mm.

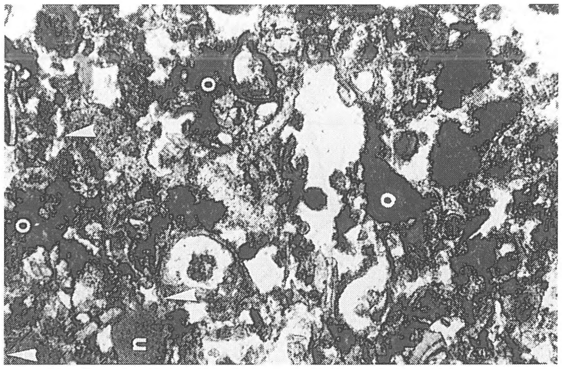


Figure 24. CU 8 – Medium- to fine-grained calcarenite. Boundary between Meerssen and Geulhem Members (Vroenhoven Horizon, small arrows). Simultaneous occurrence of *in situ*, (oxidised) glauconitised bioclasts (o) and younger, well-preserved, detrital (non-oxidised) glauconitised peloids (n). Top is at left. Width of view = 1.4 mm.

All samples of quarry Curfs contain *in-situ* micrite-filled *Chondrites* and *Zoophycus* burrows, which are particularly well preserved in sample CU 0 (Figure 21). Bioturbative mixing is indicated by curly lamination and by reworked burrow-fills which are commonly found as fine-grained clasts.

Glauconite is common and occurs in particular as intragranular fill of larger bioclasts (sample CU 1, Figure 22), in glauconitised intraclasts (sample CU 4, Figure 23), and as peloidal detrital glauconite. Rarely, interparticle pore space has been glauconitised. The upper part of the lithified layer directly below the Vroenhoven Horizon has been dissolved and contains orange-coloured, oxidised glauconite. It is covered by peloidal calcarenites of the Geulhem Member with well-preserved, green-coloured, non-oxidised glauconitic peloids and orange-coloured oxidised reworked glauconitic clasts (sample CU 8, Figure 24). Pyrite is often associated with glauconite or occurs as cloudy precipitates in fine-grained burrow-fills (sample CV B, Figure 25).

Rim and syntaxial carbonate cement are common, but most of the sediment of the top of the Meerssen Member in quarry Curfs is not (samples CU 1, 5, 5b) or rather poorly lithified (samples CU 0, 2, 4, 6). The samples CU 3, 7 and 8B are well, and the samples CV B, M and T very well lithified. The latter three samples of the lithified layer below the Vroenhoven Horizon are characterised by a typical fine-crystalline equant carbonate cement, that fills the pore space, and by moulds of small aragonitic or high-Mg-calcitic bioclasts and burrowing pelecypods, that were dissolved before early-diagenetic pyrite precipitation occurred

Figure 25. CV B – Fine-grained burrow fill (F) with sharply bounded cloudy pyritisation and fine-crystalline rhombic (dolomite) carbonate crystals. Adjacent, porous bioclastic siltstone with fine-crystalline equant calcite cement. Width of view = 1.4 mm.

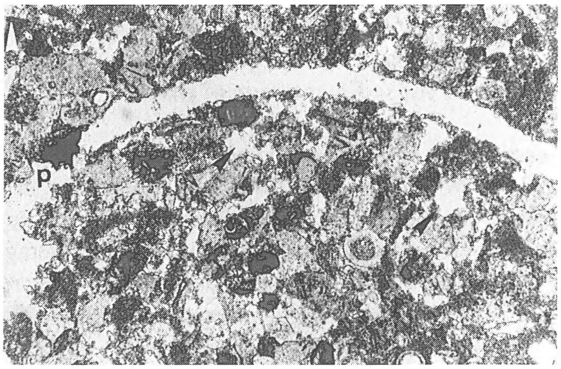


Figure 26. CV M – Muddy calcisiltite with few. slightly dissolution-enlarged pores, probably coinciding with moulds of dissolved (aragonitic, high Mg-calcitic) clasts (arrows). Large (early-diagenetic) mouldic pore, locally filled with early-diagenetic pyrite (p) after dissolution of pelecypod shell. Common (poorly visible) equant, fine-crystalline cement. Width of view = 1.4 mm.

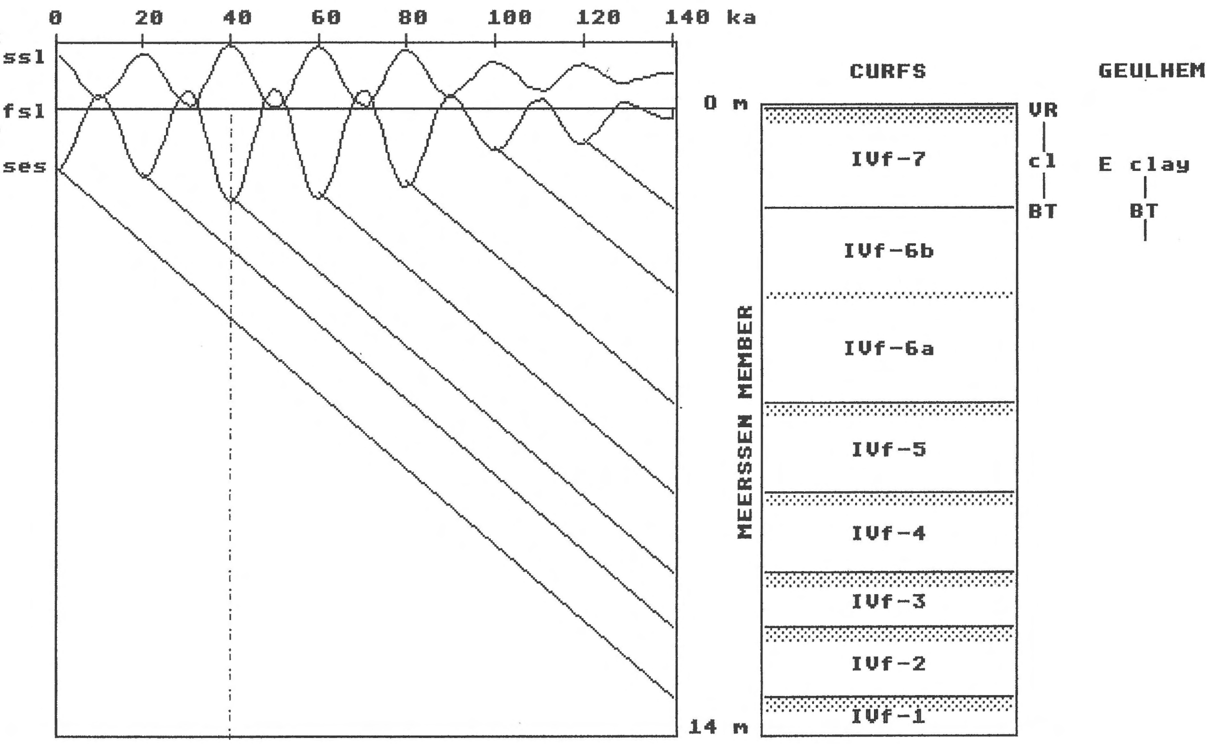


Figure 27. Interpretation of the cycle succession and calculation of the precession-induced storm energy variations according to a model of the sedimentology of chalk (Zijlstra 1995). The erosion surfaces are connected through lines, which reflect constant subsidence, to the intersection point with the schematic 20-ka precession time lines. These points represent the relative maximum depths of storm reworking below the fair-weather sea-level (for example fsl–ses = appr. 2 m at 40 ka). The amplitudes of the average storm-induced sea-level (ssl) and the storm erosion surfaces (ses) have been schematically depicted relative to the constant fair-weather sea-level (fsl), which level coincides with the presumably emerged lithified layer below the Vroenhoven Horizon (VR). The sampled intervals of Curfs and Geulhem(merberg) are indicated. BT = Berg en Terblijt Horizon.

in the shallow sub-oxic redox zone of iron reduction (sample CV M, Figure 26).

A model of the sedimentology of chalk

According to a model of the sedimentology of chalk (Zijlstra 1995), one can distinguish in quarry Curfs seven cycles in the Meerssen Member, which have been deposited during precession periods of on average about 20 ka (Figure 27). These periods were characterised by an increase and then decrease of the average storm frequency and intensity, and consequently by a variation of the average hydrodynamic energy, of the maximum sea-level height during storms, and of the depth of reworking during storms.

During times of storm-energy increase, fines were winnowed. Consequently deposition rates decreased and sediment remained longer in various redox zones of bacterial metabolism and authigenic mineral genesis, below and parallel to the sediment surface (Berner 1980; Zijlstra 1987, 1989, 1995; Figure 28). Thus, the condensed, coarse-grained calcarenites were glauconitised in the shallow suboxic redox zone of bioturbation, hydrodynamic reworking and manganese reduction (Harder 1980; Odin and Matter 1981), and were pyritised in the zone of iron reduction below (Pyzic and Sommer, 1981). In the deepest redox zones of sulphate reduction, fermentation and carbondioxide reduction, sediment was lithified due to carbonate-cement precipitation (Raiswell 1987).

During storms, at times of maximum hydrodynamic energy and deepest reworking, the lithified layer became locally exposed and was partly eroded. Commonly it was covered by a fining-upwards storm layer. Only in the highest energy environments, the lithi-

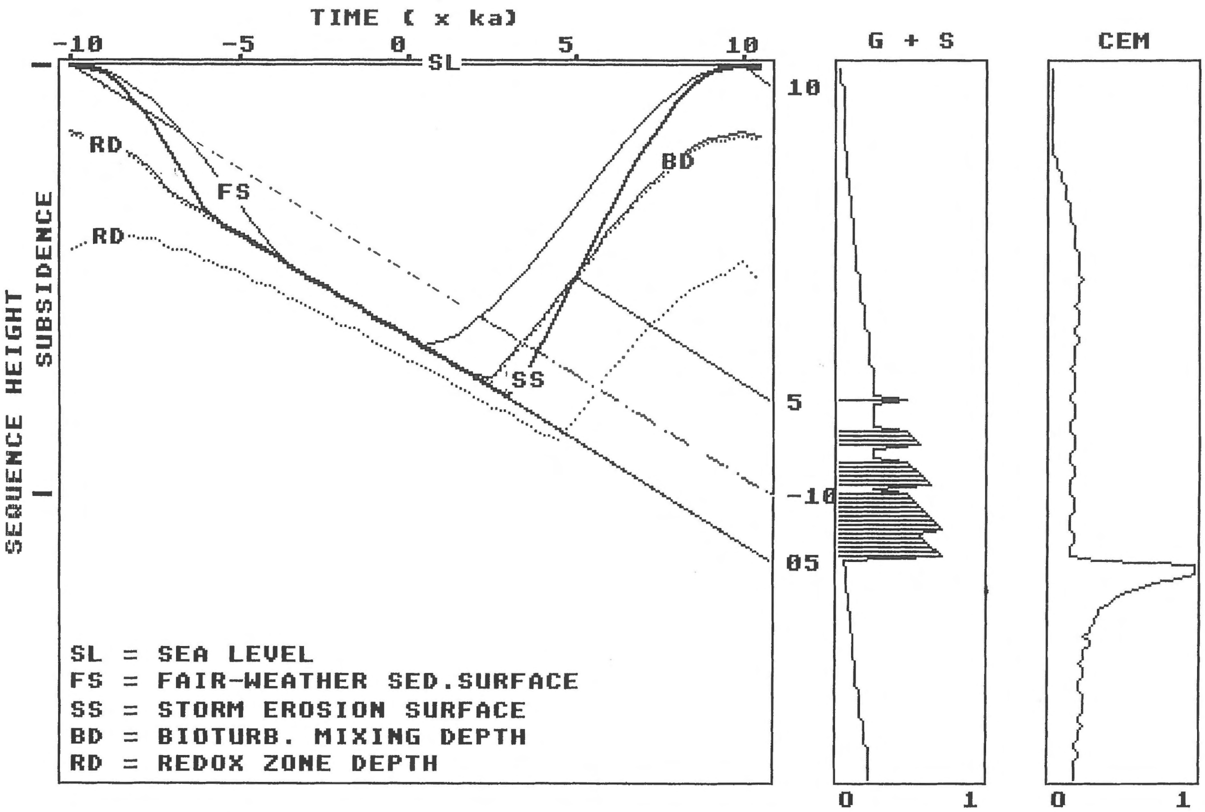


Figure 28. The genesis of a tempestite cycle during a precession period of increasing–decreasing storm intensity. Subsidence rate is constant. The fair-weather surface (FS) coincides with the storm erosion surface (SS) during the minus 5 to 0 ka period, and a hardground forms on top of the exposed redox zone (RD-RD) of lithification. Lamination is preserved as long as depth of storm erosion (SS) exceeds depth of bioturbation (BD, 0 to 5 ka). Right-hand boxes: Grain-size profile (G) and structures (S). Laminated sediment is hatched and homogeneously bioturbated sediment is blank. The concentration of carbonate cement (CEM) is depicted on the right (after Zijlstra 1995).

fied layer remained exposed during subsequent fair-weather conditions, was bored and encrusted, and developed into a hardground.

During the subsequent decrease of average storm energy, a fining-upward sequence of amalgamated fining-upward storm layers was deposited upon the coarse-grained, condensed, and mineralised sediment or on the hardground. The degree of erosion of previously deposited storm layers decreased, and the thickness and average grain size of the subsequently deposited storm layers decreased as well.

After redeposition, the uppermost part of the laminated storm layers became bioturbated, and was commonly eroded during the next storm. However, during periods with low storm intensity, most of the homogeneously bioturbated top parts of the precession-controlled tempestite cycles are preserved.

The variation of storm intensity during subsequent precession periods was modulated by the approximately 100-ka eccentricity cycle (Zijlstra 1995). The resulting rhythmic successions of four to six beds, deposited during a 100-ka eccentricity period, therefore grade from relatively thin, coarse-grained cycles with well-mineralised layers to thicker, finer-grained cycles with less mineralised layers (Figures 27, 28).

Thin, asymmetric precession-induced cycles in the lower part of the Meerssen Member reflect relatively strong erosion during subsequent increasingly higher-energy precession periods. They have been relatively strongly mineralised during relatively long periods of erosion and/or non-deposition. The thicker, more symmetrical cycles have been eroded less during subsequent precession periods in which the energy decreased, while the periodic variation of the depo-

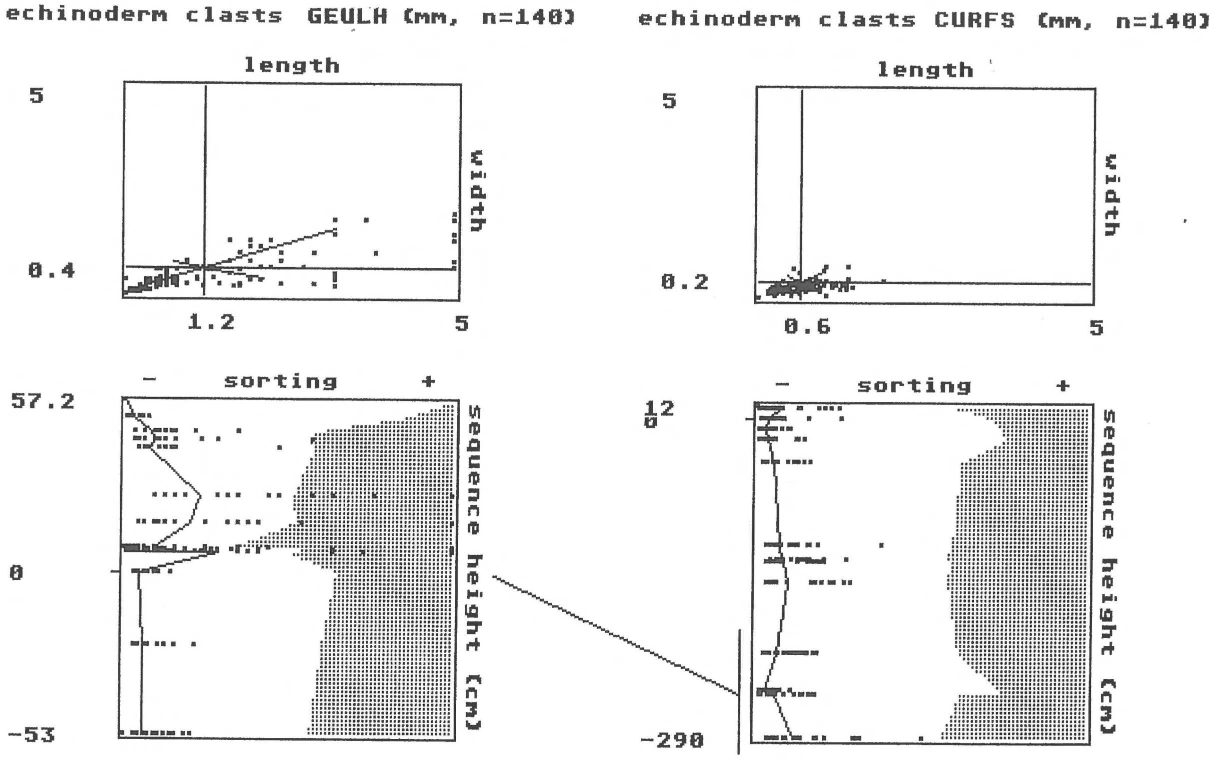


Figure 29. Results of the measurements of the maximum and minimum diameters of the ten largest echinoid clasts counted per thin section. Left = Geulhemmerberg and right = quarry Curfs. Sizes in millimetres. Note that the average width and length, depicted in the upper boxes, at Geulhemmerberg is twice that at Curfs and relatively variable in Geulhemmerberg due to the presence of relatively large clasts. The maximum diameter data have been depicted on the same scale in the lower boxes at their proper sample heights. Lines connect average diameter values of successive samples. The boundary between blank and shaded areas connects the normalised sorting values of successive samples. The 'correlation' line connects the Berg en Terblijt Horizons of Geulhemmerberg and Curfs (see Jagt et al., this issue). The vertical line at the right represents the interval of the sampled Geulhemmerberg sequence, at the same scale as the Curfs sequence.

sition rate was smaller, and long periods of non-deposition and strong mineralisation did not occur (Zijlstra 1995).

Thus, the relatively thin, asymmetric, coarse-grained, well-lithified cycles in the lower part of the Meerssen Member are interpreted as precession-induced cycles of increasing energy, and the relatively thick, more symmetric, fine-grained and poorly lithified cycles in the upper part of this member as precession-related cycles of decreasing energy. The 14 m-thick Meerssen Member with seven precession cycles has been deposited during approximately 140 ka at an average rate of 10 cm/ka, which is significantly higher than the general average deposition rate for NW European Maastrichtian chalk of 4 cm/ka (Van Hinte 1976).

Tentative interpretation and the sedimentary environment

The qualitative investigation of the microfacies provides insight into the depositional and early-diagenetic conditions that defined the sedimentary environment at the quarries Geulhemmerberg and Curfs at the end of the Maastrichtian. Additional information comes from a semi-quantitative analysis (Figures 2, 4) of the average detrital quartz grain size, detrital quartz concentration, bioclast grain size (with special attention for the length and width of echinoid clasts, Figure 29), the small benthic foraminifera concentration, the sorting and the porosity. However, the low number of samples hampers a sound statistical analysis of the semi-quantitative data and the preliminary investigation thus only allows a tentative interpretation of the similarly varying (positively correlated), mirrored (negatively correlated) and not or complexly correlated characteristics in the profiles of the quarries Geulhemmerberg and Curfs.

Hydrodynamics

The on average 2-m-thick precession-induced cycles, deposited during on average about 20-ka periods, imply that average deposition rates have been of the order of 10 cm/ka. Due to bioturbative mixing and storm reworking, grains may have remained several thousand years in the depositional environment and, even at low transport rates of several metres per year, grains may have been transported over distances of several tens of kilometres before they were finally buried. The poor preservation and the sorting of bioclasts according to fall velocity, reflect the low deposition rates in an environment characterised by intermittent stirring of the top of the sediment column during storms.

The size and concentration of the detrital quartz grains provide information about the hydrodynamic conditions. They appear to be negatively correlated (Figures 2, 4). Quartz seems to have been winnowed from the coarse-grained calcarenites (samples GRA 4, GRB 2, CU 2), which contain the lowest concentrations of the largest quartz grains, and was redeposited in the finer-grained sediments, that are characterised by the highest concentrations of smallest quartz grain sizes (samples GRA 9, 10).

The importance of hydrodynamic sorting is furthermore witnessed by the small benthic foraminifera, which are presumably hydrodynamically equivalent to medium-grained quartz; their concentrations correlate positively with this quartz grain-size fraction. Single storm events may have had only a minor influence on the distribution of quartz and small benthic foraminifera. For instance, in sample GRA 4abc, an event deposit with three layers of different average grain size is recognised (Figure 6). These layers have, however, similar quartz grain sizes and similar small benthic foraminifera concentrations. Thus, the quartz and benthic foraminifera distributions seem to have been a function of the long-term average hydrodynamic energy variations.

The bioclast grain size correlates positively with the quartz grain size and can also be used as an indication of hydrodynamic energy during deposition. Sorting and bioclast grain size correlate negatively, and sorting correlates positively with the porosity. Coarse-grained bioclasts, poor sorting and low porosity of the coarsest-grained calcarenites (microfacies 2) suggest that this is a condensed deposit of which part of the fines has been winnowed and of which another part of the fines was sheltered by the remaining coarse-grained clasts. The winnowed fines were redeposited, after wave reworking during storms, in the well-sorted, porous, medium- to fine-grained calcarenites and in the well-sorted, low-porosity calcisiltites and calcilutites.

Furthermore, the width and length distribution of echinoid clasts (Figure 29) has been measured in order to estimate the hydrodynamic conditions during deposition. Again grain size and sorting correlate negatively. The average size of the echinoid clasts in the Geulhemmerberg quarry is twice that in quarry Curfs, while the length/width ratio is equal. Apparently, mechanical break-down of echinoderm clasts has been dominant, and length is a function of test thickness and strength. The occurrence of the largest clasts and the higher average clast size at Geulhemmerberg with respect to Curfs, suggests that the average hydrodynamic energy was larger at Geulhemmerberg. The vertical variation of clast size is also highest in the Geulhemmerberg quarry, while sorting is better in quarry Curfs. Apparently, hydrodynamic energy varied more at Geulhemmerberg and fines were especially deposited at Curfs.

With regard to the depositional conditions, it is suggested that the microfacies grain-size distribution is in accordance with the hypothesis that the environment was characterised by short-term fluctuations of hydrodynamic energy during storm events and by long-periodic variations of average hydrodynamic energy as a result of climate variations. In quarry Geulhemmerberg these variations were strongest, and laminated deposits were preserved after deepest storm reworking. In quarry Curfs, just over 1 km away, the average hydrodynamic energy was lower and variations were weaker, while relatively thin storm layers were entirely mixed by bioturbation after storms, and thus lamination has been poorly preserved.

Early diagenesis

The high content of authigenic smectite and of the potassium-rich smectitic aggregate glauconite, reflects times of slow burial of sediment through the sub-oxic zone of manganese reduction and clay-mineral genesis (cf. Zijlstra 1995). Due to the low deposition rates, sediment was reworked many times before final deposition. Glauconitic bioclasts and peloids were deposited in the lower parts of the fining-upward storm layers, while the finer-grained and lighter smectite was deposited near the tops. Smectite was subsequently mixed with underlying glauconitic bioclastic sediment during bioturbation, and argillaceous calcisiltites and calcarenites formed like they occur in quarry Curfs. Smectic layers like those in the Geulhemmerberg quarry have escaped bioturbative mixing, either because bioturbation was absent, or because bioturbation only affected the uppermost parts of very thick smectitic storm layers that later were only partly reworked during subsequent weaker storms.

In-situ glauconitisation of sediment layers, like those found at the bases of clay layers (samples GRA 4a, GRA 9) and at the tops of lithified layers (sample CU 8B) is the result of prolonged residence in the sub-oxic redox zone of clay-mineral genesis. Due to the repeated erosion down to the glauconitised layer, followed by redeposition of the eroded sediment, young and instable smectite was repeatedly oxidised during reworking and provided the products for further growth of more stable glauconite during recurrence of sub-oxic conditions after coverage by the redeposited sediment. Such conditions occured when 1) the increase of storm energy and erosion depth was equivalent to the rate of subsidence or sea-level rise, 2) when the sediment was lithified and resisted further erosion (Vroenhoven Horizon), or 3) when the average hydrodynamic energy decreased instantaneously, and a coarse-grained sediment was repeatedly exposed and covered by a much lower-energetic, fine-grained sediment (clay layers).

The rare occurrence of interparticle glauconite in the coarse-grained calcarenites of the Geulhemmerberg reflects the continuous reworking during storms, while the rare occurrence of interparticle glauconite in the homogeneous sediment of quarry Curfs was presumably caused by continuous bioturbative mixing.

The co-occurrence of oxidised brown-coloured and non-oxidised, green-coloured glauconite either indicates that oxidation was a result of repeated reworking and contact with oxygenated seawater or that (syn-sedimentary?) selective oxidation occurred during contact with percolating oxygenated meteoric water.

The presence of gravitational cement (sample GRA 5, Figure 13), the dissolution of aragonitic bioclasts before early diagenetic pyrite precipitation (sample CV M, Figure 26) and the fine-crystalline equant calcite cement of the lithified layer below the Vroenhoven Horizon in quarry Curfs, are considered features that formed in a porefluid that was undersaturated with respect to the more soluble carbonates (aragonite) and that may have been caused by syn-sedimentary (?) meteoric water percolation.

Comparison of the Geulhemmerberg and Curfs quarries

The comparison between the Curfs and Geulhemmerberg successions is hampered by the fact that the sediment of the Curfs sequence has been strongly bioturbated and that its average grain-size is only half of that of the Geulhemmerberg sequence. Lithologic variations in the Curfs quarry thus became poorly pronounced. Comparing the microfacies of both successions (Figures 2, 4 and 29), the coarse-grained, poorly sorted smectitic, glauconitic, pyritic calcarenites of samples GRA 4 and GRB 1 seem equivalent to samples CU 0 and CU 1. Samples GRA 5 and GRB 2 with micritised and/or blackened bioclasts and with a peloidal silty matrix are equivalent to samples CU 2 and 3. The medium- to fine-grained calcarenites of samples GRA 1, 2, 3, 7, 7.5 and 8 are equivalent to the bioturbated medium- to fine-grained calcarenites of samples CU 3, 6 and 7. The glauconitic peloidal calcisiltite with abundant small benthic foraminifera of sample GRA 8 is very similar to the sediment of sample CU 8. The rather pure smectite of sample GRA 10 has no equivalent in quarry Curfs but may be compared with the smectitic samples CU 5 and 5b. The muddy lithified calcisiltite with plankton below the Vroenhoven Horizon has no equivalent among the samples of the Geulhemmerberg.

Discussion

The interpretation of the sedimentology of the K/T boundary sections in the type-area of the Maastrichtian is complicated due to the poor understanding of the lateral facies variation. It is presumed that the sediments have been deposited in an environment that was characterised by rather small and slow changes of sea-level. Contrary to most modern sediments that have been and still are deposited under conditions of an extremely rapidly varying sea-level, the chalk-like sediments are considered to have been continuously in equilibrium with the waterdepth and with the intrinsic hydrodynamic conditions.

Due to the relatively low deposition rates and strong wave activity, like they occur in shallow seas during storms today, sediment was mature and grains must have been transported intensively and possibly over considerable distances before they were finally buried. Therefore, in particular small and/or light-weight fossils may not primarily reflect the composition of the paleo-community at the site of deposition, but rather the processes of transport and hydrodynamic sorting.

For instance, the common occurrence of planktonic foraminifera in the smectitic clay layers and in the lithified sediments directly below the Vroenhoven Horizon is presumably not indicative of a deeper marine environment but rather a reflection of near-coastal lower energetic depositional conditions under which these fossils could accumulate after having been imported from the open sea.

The depth of deposition of chalk is still a matter of discussion. Mostly, very fine-grained chalk is considered the deepest hemi-pelagic facies (Håkansson et al. 1974). Consequently, the coarse-grained lower part of the Meerssen Member with hermatypic corals, that is intercalated between finer-grained sediments, is commonly considered to reflect a shallowing and an increased influence of storm waves as a result of a decrease of water depth.

However, low-angle unconformities in the NW European chalk suggest that relief was moderate and that the shelf and shore zone had a very low gradient. Thus, waves coming in from the open sea were effectively damped, much in analogy to the present-day situation of Shark Bay (W Australia; cf. Logan et al. 1970). Such damping of wave-energy might have been further enhanced by sea-grass vegetation. In such a case, the coarse-grained lower part of the Meerssen Member with hermatypic corals would represent relatively open marine conditions in a period with relatively deep water. A subsequent decrease of water depth, due to sediment accumulation, vertical tectonic movements, eustatic sea-level lowering or some combination of these, would have led to a decrease of wave energy and the deposition of fine-grained sediment at the Geulhemmerberg and Curfs sites.

Such a model of a low-gradient, shallow-marine environment in which wave action was damped, indeed explains the occurrence of smectitic K/T boundary clay layers on top of coarse-grained calcarenites. Furthermore, the near-horizontality of the paleo-seabed also prohibited a several tens of metres depth difference between Geulhemmerberg and Curfs (at a mutual distance of 1 km only), that would have been needed to produce the observed lateral difference of the average grain size as a result of a lateral variation of near-bottom wave activity on a deeper marine slope.

Compared to series of older precession-induced cycles in the Maastrichtian of the type-area, the upward thickening of such cycles is rather well pronounced in the Meerssen Member. A great thickness of latest Maastrichtian (precession-induced) cycles has been observed also in the chalk sequence of Stevns Klint (Denmark; Zijlstra 1995), the carbonate-marl sequence of Zumaya (Spain; Ten Kate and Sprenger 1993) and in continental deposits of southern France (personal communication I. Cojan). It is not clear yet what has caused the supra-regional, simultaneous, local increase of deposition rates. This might have been caused by a world-wide acceleration of tectonically induced subsurface motions, related to events like, for example, the massive Deccan Trap basalt outflow at the end of the Cretaceous (Voigt 1979; McLean 1985). Other possibilities, such as a gradual increase of subsidence rates and relief, or a climatically induced rapid increase of run-off and sediment production need further consideration.

Conclusions

The Meerssen Member of the Maastricht Formation contains 1) relatively high-energetic asymmetric precession-induced tempestite cycles that formed during times characterised by strongly varying, but relatively low, average deposition rates, deep reworking and well-developed mineralisation, and 2) relatively low-energetic, more symmetric precession-induced tempestite cycles, deposited at relatively high and only slightly varying rates, that have been less well mineralised and that were less deeply reworked during storms.

In general, the microfacies of the intervals top IVf-6 and IVf-7 of the Meerssen Member is characterised by a fossil assemblage of low diversity. Bioclasts have been sorted according to fall velocity and the coarser elements reflect the highest hydrodynamic conditions during storm-deposition. Poor preservation of fossils and a strong mineralisation of sediments reflect times of slow deposition. The microfacies distribution shows that the Geulhemmerberg sediment has been deposited under higher hydrodynamic energy conditions and in deeper water than the coeval sediments of quarry Curfs. It also confirms that the sampled part of the Geulhemmerberg sequence is equivalent to the upper part of interval IVf-6 and the lower half of the interval IVf-7 as exposed in quarry Curfs. The microfacies is locally characterised by dissolution features that may have been produced by percolating meteoric water (during syn-sedimentary exposure?).

The massive hermatypic corals in the lower part of the Meerssen Member at Curfs, which are typical for a well-agitated environment within the photic zone at a depth of the order of a few metres (Figure 27), indicate conditions of highest hydrodynamic energy which we relate to a shelf which was sufficiently steep to allow waves to approach this site. The finer-grained, lower-energy sediments in the upper part of the Meerssen Member (IVf-6, 7) are interpreted as shoreface deposits, possibly covered by sea-grass vegetation (Voigt and Domke, 1955) with epiphytic large-benthic foraminifera and epiphytic bryozoa. The low diversity of the fossil assemblage and the occurrence of thin-shelled, light-weight remains of molluscs in the finest-grained sediments of unit IVf-7 indicate very low-energetic, marine to continental conditions. The uppermost very well-lithified layer directly below the Vroenhoven Horizon, with equant microsparitic cement, with a dissolved and oxidised surface, and with a low-diversity burrowing pelecypod assemblage, may have been affected by paleo-karst and may represent a phase of emergence and sub-aerial lithification during the early Danian.

We propose that the clay layers, despite their open marine microfossil assemblage (Brinkhuis and Schiøler, Smith and Zachariasse, Witte and Schuurman, this issue), were deposited under conditions of very low wave energy in very shallow marine depressions that were only affected during storms. The E clay layer is thought to reflect such a period of low energy. It was preserved at Geulhemmerberg because it fills depressions and was only partly affected by reworking and bioturbation during a subsequent increase of storm intensity and deepening. The clay layer is absent in quarry Curfs, because 1) it has been eroded, or 2) because it has been mixed with bioclastic sediment by bioturbation, or 3) because the sediment surface was emerged, so that no clay could be deposited from suspension.

The precession-induced cycles of the Meerssen Member have been formed during and due to periodic variations of hydrodynamic energy and of deposition rate. Their genesis is similar to that of other precession-induced cycles encountered in the underlying Maastrichtian and Campanian carbonates (cf. Zijlstra, 1995). The cycles are exceptional as they are rather thick, very coarse-grained and well lithified. These characteristic features can be attributed to a rather high rate of relative sea-level rise, and the, on average, relatively high and strongly varying hydrodynamic energy, which led to deep storm reworking and well-developped authigenesis.

The exceptional and rapid, vertical thickness increase of the cycles in the Meerssen Member in the Maastricht area has also been observed in other uppermost Maastrichtian sequences in Europe. It is as yet not clear which mechanisms have caused the relatively rapid environmental changes during the last 150 000 years of the Maastrichtian that mark the end of the Cretaceous.

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