Geologie en Mijnbouw **75:** 283–293, 1996.

The Geulhemmerberg Cretaceous/Tertiary boundary section (Maastrichtian type area, SE Netherlands); summary of results and a scenario of events

Jan Smit[1] & Henk Brinkhuis[2]
[1] *Institute of Earth Sciences, Department of Sedimentary Geology, Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, the Netherlands;* [2] *Laboratory of Palaeobotany and Palynology, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, the Netherlands*

Key words: K/T boundary, biostratigraphy, depositional model, geochemistry, sedimentology

Abstract

Integration of sedimentological, biostratigraphical, geochemical and paleomagnetic analyses of the recently discovered marginal marine Cretaceous/Tertiary (K/T) boundary section in the Geulhemmerberg caves (Maastrichtian type area, Limburg, SE Netherlands) resulted in a depositional model of the succession, placing the results in a global K/T boundary perspective. The proposed depositional scenario involves 1) deposition of marginal marine Upper Maastrichtian calcarenites and formation of a paleo-relief (proto-hardground, Berg en Terblijt Horizon), 2) deposition of latest Maastrichtian calcarenites, 3) K/T storm or hypercane-related 'washing' of the paleoshelf, and removal of latest Maastrichtian and earliest Danian sediments, including removal of an Ir-bearing layer, and 4) storm-induced filling of the paleodepressions in the Late Maastrichtian paleorelief by calcarenites and K/T boundary clays during early P0 Zone times of decreasing storm intensity.

Only the distributions of calcareous nannoplankton and ammonites do not fully match this scenario, since early Tertiary nannofossils have been reported from below the Berg en Terblijt Horizon and, at a nearby outcrop, ammonites from just above it. Their distribution patterns across the K/T boundary in the area require further study. We conclude that there is an unprecedented expanded earliest Tertiary succession in Limburg, containing a wealth of information about the first hundreds of years following the mass-extinction event at the K/T boundary.

Introduction

Known sections across the Cretaceous/Tertiary (K/T) boundary in a marginal marine setting above wave base are incomplete, with a hiatus of variable magnitude at the K/T boundary. As discussed in other contributions to this issue, such a situation was also envisaged in the type area of the Maastrichtian Stage in the SE Netherlands, where the boundary is traditionally positioned at the Vroenhoven Horizon, separating the Maastricht and Houthem formations (Felder 1975). The typical K/T boundary clay layers, known e.g. from nearby Stevns Klint in Denmark, were never reported from the area. It came therefore as a pleasant surprise that in November 1992 clay layers were discovered near the boundary in man-made caves in the Geulhemmerberg, 7 km ENE of Maastricht (Figures 1, 2; see also Brinkhuis and Smit, this issue).

The Geulhemmerberg was quarried for a specific 3 m-thick layer of the Meerssen Member of the Maastricht Formation, unit IVf-6 of Felder (1975), suitable for building materials. This unit is topped by a hardground, the Berg en Terblijt Horizon of Felder and Bosch (1996) which is visible in the ceiling of the caves. Above this hardground, in unit IVf-7 of Felder (1975), the topmost unit of the Meerssen Member, thin clay layers occur throughout the caves. At measuring point 251, the cave exposes several well-developed clay layers. This point is now known as the Geulhemmerberg 'main site' (Brinkhuis and Smit, this issue).

Scientists from different disciplines investigated splits of samples taken at this location, where the sec-

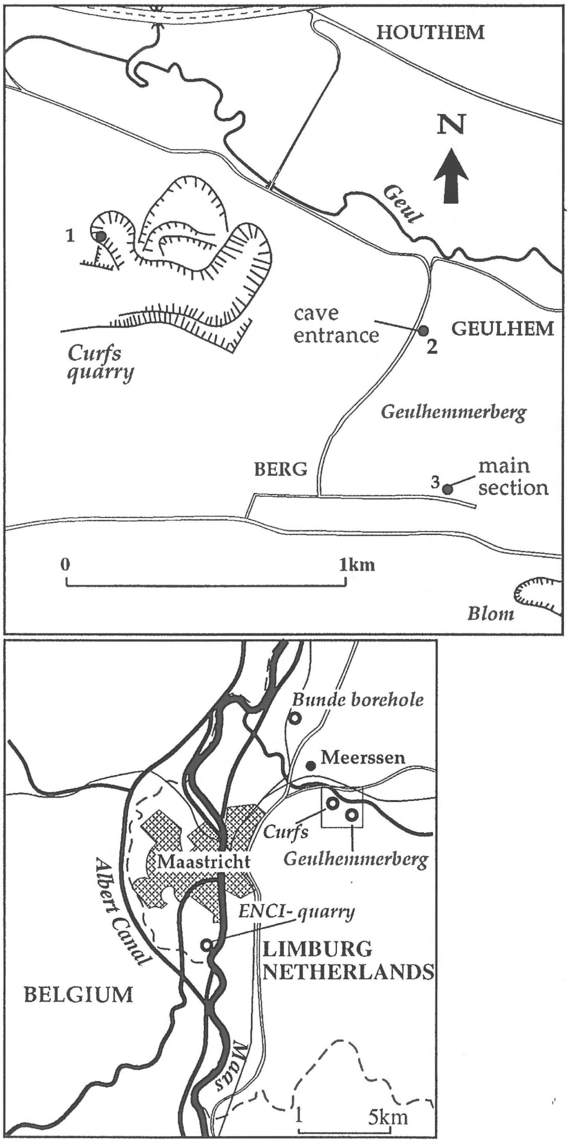


Figure 1. Location map of the Deep Dark Hole research area.

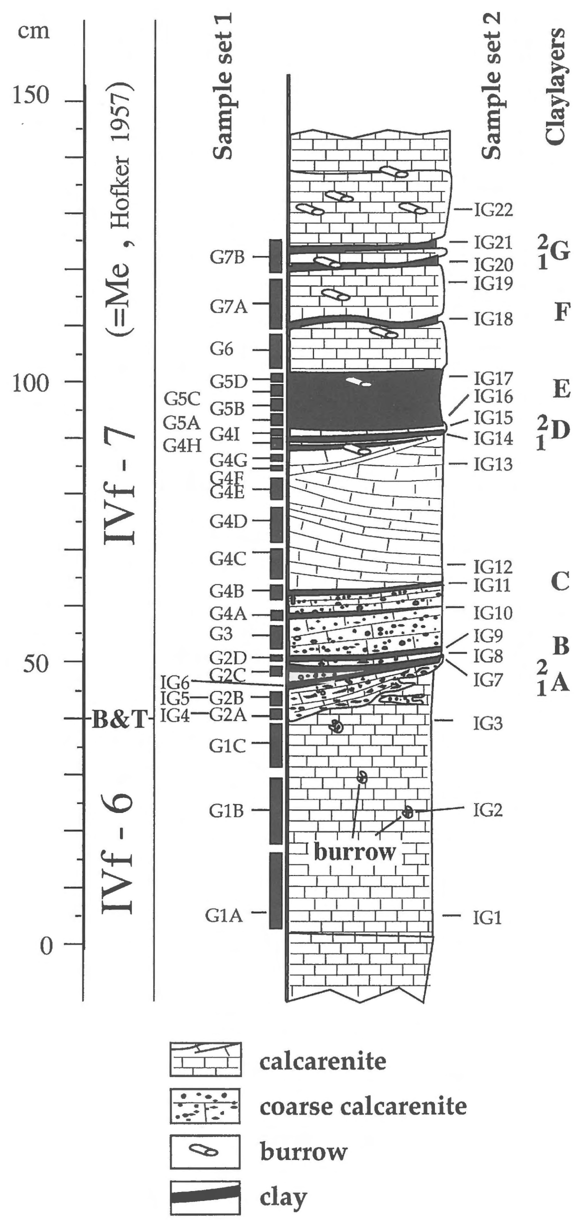


Figure 2. Lithologic column of the main K/T section as exposed in the Geulhemmerberg caves. B&T = Berg en Terblijt Horizon. Lithologic subdivision after Felder (1975) and Felder and Bosch (in press).

tion appeared most complete. The results of this 'Deep Dark Hole Project' are presented in this issue. At the main site, the exposed succession of calcarenites and clays measures some 125 to 150 cm (Figure 2). Above the Berg en Terblijt Horizon, in unit IVf-7, up to seven clay-layer complexes have been identified, labled A to G. Notably the E clay is well-developed. For location and sampling details the reader is referred to Brinkhuis and Smit (this issue).

The multidisciplinary analysis of the Geulhemmerberg section has resulted in new insights in many aspects of the K/T transition in mid-latitudes in a marginal marine setting. In this paper we review the more salient observations and results, and we present a scenario in which we place these in a global K/T boundary perspective.

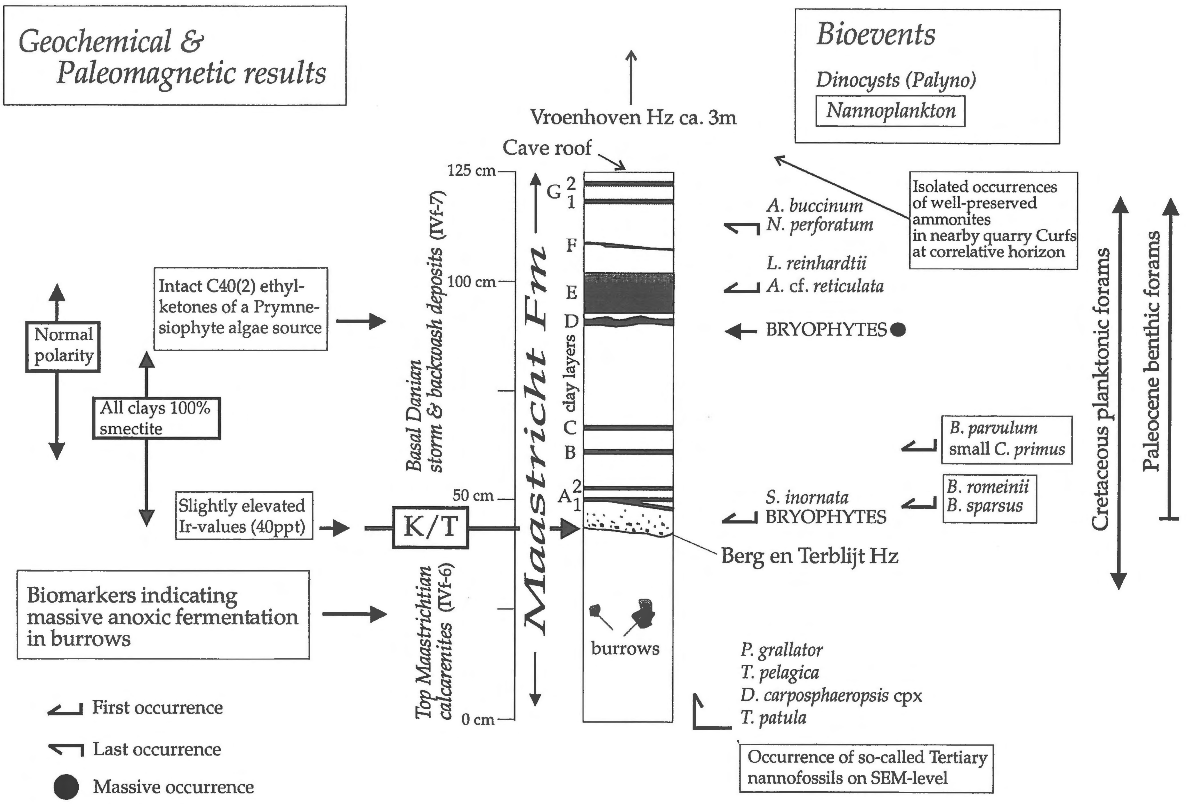


Figure 3. Overview of the principal results of the Geulhemmerberg Deep Dark Hole Project as reported in this issue. The K/T boundary is drawn at the Berg en Terblijt Horizon.

Summary of results

An overview of the findings and interpretations is depicted in Figure 3. The results may be subdivided in 1) a sedimentological, 2) a (micro) paleontological–biostratigraphical, and 3) a geochemical and paleomagnetic part. The integration of the results forms the basis of an age and paleoenvironment interpretation, of correlations to other K/T boundary sites, and of a scenario for the depositional history at K/T times.

Sedimentology (Roep and Smit, Zijlstra et al.)

In this issue, Roep and Smit and Zijlstra et al. describe and interpret the sedimentology of the Geulhemmerberg section in detail. The analysed section consists of a succession of shallow-water calcarenites of variable composition, deposited above wave base and containing intercalated clay layers up to 15 cm thick. The section can be correlated to coeval deposits in the nearby quarry Curfs (Figure 1). One of the most striking features of the succession is an unusual undulating hardground in heavily burrowed calcarenites. The hardground contains depressions of up to 1.5 m deep. This hardground, the Berg en Terblijt Horizon of Felder and Bosch (1996), changes laterally into a less conspicuous, flat, burrowed surface in the Curfs quarry where it was originally defined. It marks a (brief) period of non-deposition. The Berg en Terblijt Horizon is unusual, because it preserves delicate sedimentary features that normally would not survive in the high-energy surf-zone. Sediments overlying the Berg en Terblijt Horizon, filling the depressions in the irregular relief, are interpreted as a thinning-up and fining-up sequence (Roep and Smit), culminating in the 10 to 15-cm-thick E clay. Sediments, mainly fine calcarenites, above the E clay indicate a shoaling up to the overlying Vroenhoven Horizon. This horizon, separating the Maastricht and Houthem formations, occurs some 3 m further up-section and is here interpreted as a third-order sequence boundary (Da-1 of Hardenbol 1994). The underlying Meerssen units IVf-6 and IVf-7 are here regarded to represent latest Maastrichtian to earliest Danian third-order highstand deposits. The Vroenhoven Horizon is visible at the entrance of the Geulhemmerberg caves and also at measuring point 278 in an air-shaft nearby measuring point 251. Micropaleontological and palynological information indicates that the Vroenhoven Horizon represents a considerable hiatus (A.J.T. Romein personal communication; Brinkhuis personal observation).

Roep and Smit attribute the erosion at the Berg en Terblijt Horizon to bio-erosion, and interpret the horizon as a submarine hardground. Furthermore, these authors regard the upward thinning of the overlying coarse layers and the fining-up of these layers up to the E clay to indicate deepening, or alternatively to a changeover to a more 'shielded' position. The clay layers, notably the E clay, could be deposited only during low-energy conditions. The dominant sedimentary processes are wave-transport or wave-induced ripcurrents, related to episodic stormwave activity. Zijlstra et al. also envisage the formation of the more continuous clay layers, notably the E clay as the result of decreasing 'hydrodynamic storm energy', probably a result of increased dampening of wave energy. Bioturbation is conspicuously reduced in the sediments directly overlying the Berg en Terblijt Horizon. Roep and Smit link this phenomenon to the 'Strangelove ocean' conditions (Hsu et al. 1982) following the mass-mortality at the K/T boundary.

Biostratigraphy

The bulk of the contributions to this issue describe the distribution of the various (micro)fossil groups, and their stratigraphic and paleoenvironmental significance. Below, a summary of the principal conclusions is presented.

Planktic foraminifera (Smit and Zachariasse)
No Tertiary taxa have been recorded in any of the clay layers between the Berg en Terblijt and Vroenhoven horizons in the Geulhemmerberg section. The excellently preserved planktic foraminiferal assemblages from these clay layers contain exclusively Cretaceous taxa, but nevertheless probably belong to (but are not younger than) the earliest Danian P0 Zone, based on low-diversity and low-abundance faunas and on the assumption that the E clay is chronostratigraphically virtually equivalent to the K/T boundary clay elsewhere (Smit and Romein 1985). Interestingly, the planktic/benthic foraminifer ratio in the E clay is about one. This may be interpreted to indicate a deep-water environment, which however seems unlikely in this case.

Benthic foraminifera (Witte and Schuurman, Kuhnt)
Witte and Schuurman report scarce Paleocene benthic foraminifers from just above the Berg en Terblijt Horizon. Furthermore, on the basis of general trends in the benthic foraminiferal assemblages, they infer an increase of paleo-waterdepth towards the E clay. Kuhnt addresses the paleoecologicl significance of changes within the benthic foraminiferal communities. He subdivides the section into a lower part, characterized by low and/or intermittent nutrient supply, and an upper part characterized by more enhanced nutrient availability.

Calcareous nannoplankton (Romein et al.)
The results of the calcareous nannoplankton analysis are not easy to interpret. SEM-studies suggest attribution of the entire section, including the calcarenites below the Berg en Terblijt Horizon, to the *Cruciplacolithus primus* Subzone of the NP1 Zone, or even to the middle NP1 Zone, because of the presence of small *Neobiscutum romeinii, N. parvulum* and extremely small forms of *C. primus*. These taxa are thus far known exclusively from the Danian. On the other hand, in light-microscope (LM) analysis these small forms are overlooked, and then the calcarenites below the Berg en Terblijt Horizon are attributed to the Late Maastrichtian *Nephrolithus frequens* Zone. In LM analysis the IVf-7 section above the Berg en Terblijt Horizon belongs to the NP1 *Biantholithus sparsus* Zone. In the latter case a small hiatus exists at the horizon, encompassing the basal NP1 *N. romeinii* Subzone. The SEM results are at odds with the other biostratigraphic data, which indicate that the sediments are latest Maastrichtian below, and basal Danian above the horizon.

Calcareous dinoflagellate cysts (Willems)
Too little is known about Cretaceous and Tertiary calcareous dinoflagellate cysts to even recognize the K/T boundary. Willems interprets changes in the diversity of the recovered assemblages in terms of relative sea-level changes, with maxima in the clay layers, notably in clays A, B, C and E. The most conspicuous change

in the assemblages, a spectacular increase in number of species immediately above the Berg en Terblijt Horizon, may be linked to the K/T event(s).

Palynology (Brinkhuis and Schiøler)
The stratigraphically diagnostic dinoflagellate cysts suggest that the succession below the Berg en Terblijt Horizon represents the latest Maastrichtian, and that above the horizon the early Danian. This is primarily based on the first occurrence (FO) of *Senoniasphaera inornata* just above the horizon. The Geulhemmerberg palynomorph assemblages point to a relatively marginal marine, probably inner-neritic depositional setting, with a significant terrestrial input. The terrestrial palynological elements (simple spores) are considered to be almost all derived from Bryophytes (mosses). These palynomorphs increase anomalously in numbers above the Berg en Terblijt Horizon. Their sudden proliferation may be associated with increased transport from the coastal plain, and/or it may reflect a major change in the terrestrial ecosystem. Quantitative changes in the palynomorph distribution are interpreted to be primarily caused by differences in hydrodynamical conditions, possibly combined with (slight) variations in waterdepth or the influence of restricted marine conditions. This interpretation is compatible with sedimentation regulated by decreasing (storm) wave activity above the Berg en Terblijt Horizon. Marine optima, based on highest relative numbers of *Spiniferites* spp., are inferred immediately above this horizon, and in the E clay.

Macrofossils (Jagt, Zijlstra et al.)
Jagt reviews the stratigraphically important macrofossils, among others the coleoid (belemnites) and ammonoid cephalopods, the inoceramid bivalves, and the echinoderms, of the calcarenites in the Maastrichtian type area. On ammonite and belemnite evidence, the Meerssen Member (the uppermost member of the Maastricht Formation), including unit IVf-7, belongs to the uppermost Maastrichtian *Belemnella gr. casimirovensis* Zone. Sediments from above the Vroenhoven Horizon correlate with the early Danian *oedumi* and *abildgaardi* echinoid zones in Denmark. The sediments between the Berg en Terblijt and Vroenhoven horizons in the Curfs quarry, contain exquisitely preserved, and therefore possibly *in situ*, inoceramids (*Tenuipteria*) and ammonites (*Baculites* and *Scaphites*). They are correlated with the lower Danian 'Cerithium Kalk' known from Denmark from just above the K/T boundary clay or 'Fishclay'. This suggests that the recovered ammonites are 'survivors' of the K/T boundary event(s).

In summary, the distributions of most analysed fossil groups suggest the K/T boundary to occur at the Berg en Terblijt Horizon, in particular when supplemented with sedimentological evidence such as the presence of a distinct 'boundary clay'. However, the interpretation of the biostratigraphy of the Geulhemmerberg and Curfs quarries is certainly not unequivocal when compared to the most recent, generally accepted biostratigraphic zonations (Berggren et al. 1985, 1995; Berggren and Miller 1988; Gradstein et al. 1994). Most of the biostratigraphic evidence suggests that the basal part of the Geulhemmerberg section below the Berg en Terblijt Horizon is latest Maastrichtian. Benthic foraminiferal, nannofossil and palynological evidence suggest that unit IVf-7 overlying the Berg en Terblijt Horizon may be dated as early Danian, with possibly the earliest Danian missing. The planktic foraminiferal assemblages appear to exclude an age younger than the basalmost Danian P0 Zone. Surprisingly, the calcareous nannoplankton distribution suggests that also the exposed part of unit IVf-6 of the Meerssen Member, below the Berg en Terblijt Horizon, is Danian in age. Furthermore at odds with the planktic foraminiferal and palynobiostratigraphy, the nannofossil assemblages between the Berg en Terblijt and Vroenhoven horizons indicate a middle Danian age. On the other hand, the ammonite finds (if those are not survivors) point to a latest Maastrichtian age of the same interval.

The depositional environment(s) of the succession are invariably regarded as marginal marine. Paleodepth estimates differ, however, from shoreface (Zijlstra et al.) or 20–40 m (Roep and Smit) on sedimentological evidence, to outer shelf based on benthic foraminifers (Witte and Schuurman). The quantitative distribution patterns of the various microfossil groups analysed all point to deepening towards the E clay, followed by shoaling above it.

Geochemical, stable-isotope and paleomagnetic results

Stable isotopes (Schmitz and Speijer)
The $\delta^{13}C$ analyses from selected benthic and planktic foraminifers, mainly from the clay layers, do not reveal significant trends across the K/T boundary at the Berg en Terblijt Horizon. The drop in $\delta^{13}C$ values, recorded

globally at low latitudes just above the K/T boundary, apparently has not been found at Geulhemmerberg, in agreement with the data from the Danish Stevns Klint and Nye Kløv sections (Keller et al. 1993). Strong differences in diagenesis (Vonhof and Smit), however, prevent firm conclusions on these data.

Strontium isotopes (Vonhof and Smit)
The $^{87}Sr/^{86}Sr$ analyses of the entire Late Maastrichtian to early Danian interval of the ENCI and Curfs quarries reveal a strong scattering due to diagenetic Sr exchange. Nevertheless, the resulting $^{87}Sr/^{86}Sr$ profile is comparable to the Late Maastrichtian reference curves, and yields an age model that is consistent with the available biostratigraphic evidence. The sedimentation rate of the mainly Late Maastrichtian Meerssen Member (excluding unit IVf-7) estimated from the $^{87}Sr/^{86}Sr$ curve is about 10 cm/kyr. The $^{87}Sr/^{86}Sr$ ratios from the well-preserved *Heterohelix* planktic foraminifer specimens within the E clay appear well buffered from diagenetic overprint. These ratios are high and compatible with global, basal Danian seawater $^{87}Sr/^{86}Sr$ ratios. They also support a P0 Zone age for the interval between the Berg en Terblijt and Vroenhoven horizons. The high $^{87}Sr/^{86}Sr$ ratios further strengthen the hypothesis that the Cretaceous taxa in the E clay are survivor species rather than reworked specimens.

Inorganic geochemistry (Smit and Rocchia)
None of the trace elements analysed across the K/T boundary shows anomalous enrichments. Some siderophile elements show enhanced values at the Berg en Terblijt Horizon. Iridium does not have anomalous concentrations at any level, although the Th-normalized profiles hint at some down-section diffusion of Ir and Cr into the top of the Maastrichtian below the Berg en Terblijt Horizon. Most of the profiles can be explained by the variations in insoluble residue content. The negative correlation of Sr to Ca is remarkable, and may be explained by strong diagenesis of the porous calcarenites. The low La/Ce ratios of the clay layers may indicate dysoxic conditions during deposition of the clays.

Organic geochemistry (Yamamoto et al.)
A $C_{40:2}$ ethyl ketone dominates in all clay-layers of the Geulhemmerberg succession. This compound is probably derived from a specific, highly abundant non-coccolithophorid Prymnesiophyte alga which may have already been present in Late Maastrichtian times. Furthermore, fatty acids as well as their randomly oxidized hydroxy- and keto-counterparts are also abundant. These compounds probably indicate bacterially transformed biochemical components of terrestrial origin, although they are probably not derived from the Bryophyte (moss) spores abundantly present in the sediments. Their distributions are, however, strikingly similar to those of fatty acids in Antarctic soils. 16-, 17-, and 22-hydroxy- and keto-fatty acids with a clear even over odd carbon number preference are probably of marine origin. The biochemical relationships between these compounds and the $C_{40:2}$ ethyl ketone indicate that they originate from the same alga. The presence of these diverse, easily extractable, highly functionalized organic compounds demonstrates an extreme immaturity and therefore a pristine preservation of the clay layers of the Geulhemmerberg K/T boundary section.

Subsequent organic geochemical studies on samples from samples just below the Berg en Terblijt Horizon revealed the presence of a C_{17} cyclopropyl fatty acid. This ‘molecular fossil’ has probably been formed by bacteria during massive anoxic fermentation. The fermentation probably took place in large accumulations of organic matter on the seafloor, as a result of a mass mortality in the marine ecosystem. The same molecular fossil has also been recorded in the El Kef section and is there restricted to a few centimetres of clay directly above the K/T boundary. It is therefore proposed as a ‘biomarker’ for the K/T boundary (K. Ficken et al., in preparation). A basal clay layer containing this K/T boundary biomarker has not been found in the Geulhemmerberg section, and may have been eroded before the deposition of unit IVf-7 in the depressions in the paleorelief.

Magnetostratigraphy (Langereis)
The samples analysed for the clay layers between the Berg en Terblijt and Vroenhoven horizons all reveal a normal paleomagnetic inclination (polarity). This is interpreted as a (viscous) recent overprint component, rather than a true residual normal inclination. The normal polarity would be at odds with most of the biostratigraphic results, and with the interpretation that the Geulhemmerberg clays are the equivalent of the K/T boundary clays elsewhere, which all show a reversed paleomagnetic polarity.

In summary, the most prominent results from the chemical and physical studies of the Geulhemmerberg succession are: 1) the absence of Ir-enriched layers, although slight Th-normalized elevations below the Berg en Terblijt Horizon suggest syn-sedimentary removal of an Ir-rich layer, 2) the absence of significant fluctuations in the stable-isotope composition, 3) an early Danian $^{87}Sr/^{86}Sr$ ratio of the clay layers, 4) an extreme immaturity of the clay layers, regarding the presence of highly functionalized organic compounds, and 5) the presence of the C_{17} K/T boundary 'biomarker' in burrows below the Berg en Terblijt Horizon. These results are compatible with the various paleontological studies, which all report an excellent preservation of microfossils in the clay intervals.

Discussion

Age assessment; where is the K/T boundary?

As discussed above, the various paleontological analyses result in a controversy between: 1) the nannofossil results, 2) the ammonite distribution, and 3) the conclusions from other fossil groups. Results from the latter place the K/T boundary at the Berg en Terblijt Horizon. Positioning of the K/T boundary at this horizon is further supported by the presence of detrital clays just above it, unique in the entire Late Maastrichtian–Danian succession in Limburg. A similar 'boundary clay' is invariably present immediately above the K/T boundary in the most complete sections known, such as Caravaca, Zumaya and Agost in Spain, El Kef in Tunisia, Woodside Creek in New Zealand, and Stevns Klint and Nye Kløv in Denmark. If the latter correlation is accepted, the absence of an Ir anomaly is puzzling, as the Geulhemmerberg clays represent the only K/T boundary clay known in the world which lacks a marked Ir anomaly at its base. But on the other hand, this absence should not be too surprising, because the Berg en Terblijt Horizon was above (storm) wave base at K/T time. The high $^{87}Sr/^{86}Sr$ ratio further points to an early Danian age for the clay-bearing interval.

If the positioning of the K/T boundary at the Berg en Terblijt Horizon is accepted, then it should be realized that 1) some nannofossil index taxa such as *N. romeinii, N. parvulum* and *C. primus* already occur in the Late Maastrichtian, and that 2) some ammonites (*Baculites* and *Scaphites*) and the inoceramid-like *Tenuipteria* possibly survived the K/T boundary event for a short time, together with a few planktic foraminifers.

A scenario of K/T boundary events in the south of Limburg

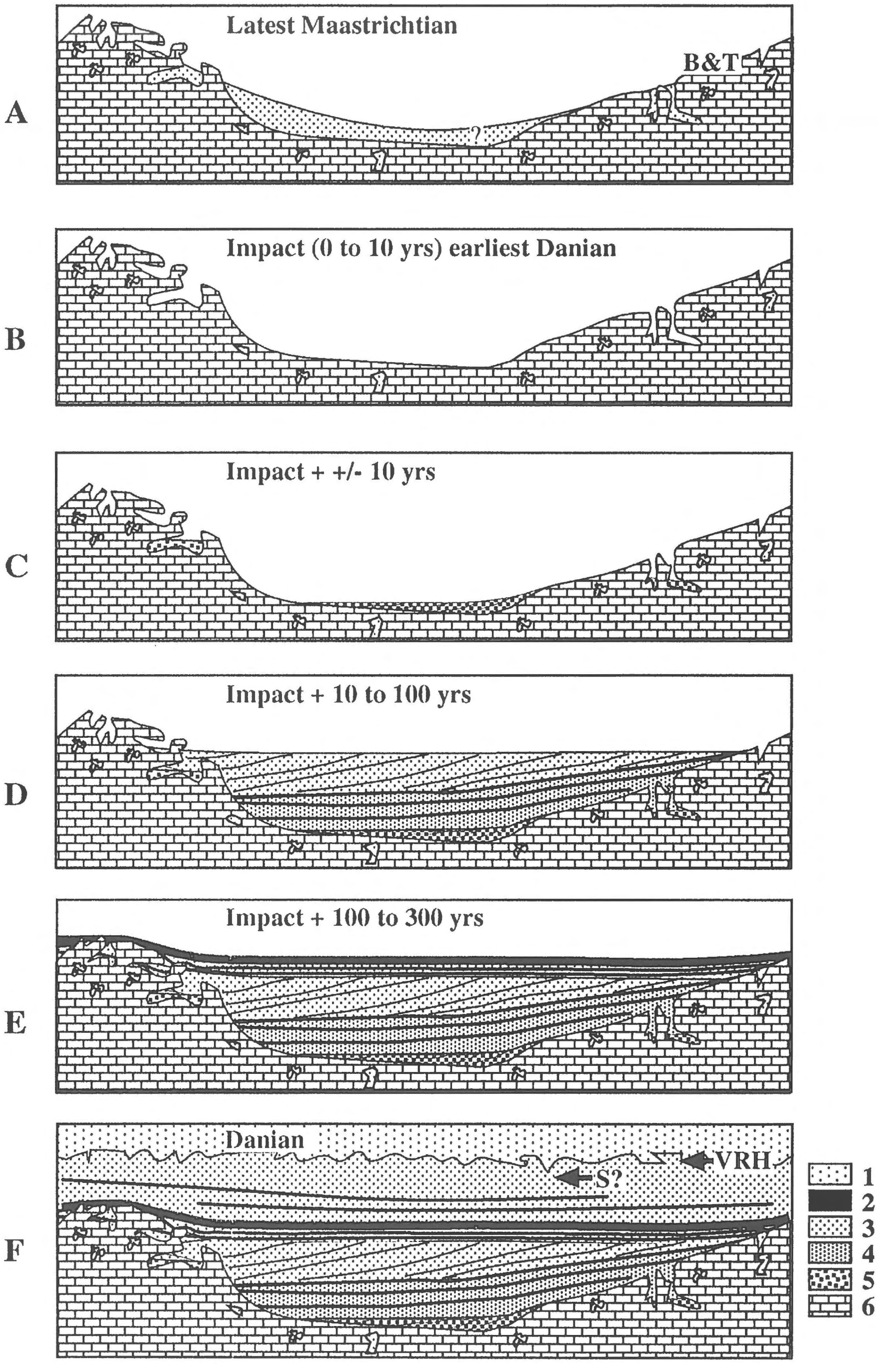
With the K/T boundary positioned at the Berg en Terblijt Horizon, the findings may be linked to the well-established K/T bolide impact on Yucatan, Mexico. More specifically, the following depositional scenario relates the Geulhemmerberg succession to the impact's possible immediate and longer-term environmental consequences, and to interacting eustatic sealevel changes and vertical tectonic movements in the south of Limburg during K/T boundary time (Figure 4):

Pre-Impact

Fossiliferous calcarenitic limestones are deposited in latest Maastrichtian times in the area of south Limburg, above (storm) wave base in a marginal, shallow, warm, (sub) tropical sea. Sedimentation rates were high (10 cm/kyr) because of the rapid subsidence of the area in the Late Cretaceous (Gras 1995). Perhaps as a consequence of the (third-order) sea-level fall in latest Maastrichtian times (Hardenbol 1994), or of Milankovich-cyclicity-related processes (cf. Zijlstra et al., this issue), or of decreased sedimentation as a result of rapid subsidence, or of a combination of these processes, the Berg en Terblijt hardground develops on the seafloor. The hardground locally shows a considerable relief of about 2.5 m at least. Lithified, bored mounds protrude above the seafloor. Those would normally be eroded in such a wave-swept environment, and therefore such structures have not been found at any of the other commonly occurring hardgrounds in the Maastrichtian of south Limburg. The unique preservation of these bored mounds is one of the reasons to infer that these structures were fossilized as a result of the K/T events. Possibly, some uppermost Maastrichtian non-lithified sediment and fossils may have been deposited on the Berg en Terblijt Horizon prior to the K/T boundary event.

Impact and aftermath

The 180 to 240 km-diameter Chicxulub crater in Yucatan, Mexico (cf. Hildebrand et al. 1991; Sharpton et al. 1993; Smit et al. 1992) is the largest known impact crater on earth. The evidence supporting the interpretation of the crater as a remnant of the K/T meteorite impact is convincing and growing. Moreover, the crater is within a small error (± 50 kyr; Swisher 1992) of K/T boundary age. It is the most likely candidate for the K/T



impact event, and may be related to the biotic changes at the K/T boundary. The results presented in this issue indicate that the Geulhemmerberg succession may be regarded as a key-section for clarification of the effects of such an impact on the biosphere in a marginal marine setting.

We assume that the Berg en Terblijt Horizon with its associated relief existed on the seafloor at the moment of impact, because the burrows below the depressions

←

Figure 4. Proposed scenario of the depositional and erosional history across the K/T boundary in the Geulhemmerberg section.
A) Latest Maastrichtian. Formation of the Berg & Terblijt (B&T) hardground on top of burrowed calcarenites as a submarine relief, loosely (?) filled with highstand-tract carbonate sand.
B) Impact on Yucatan and worldwide deposition of fallout of the impact. The impact leads to mass-mortality, and to massive bacterial fermentation of organic material. These deposits and the loose carbonate sands have been removed in the Geulhemmerberg by 'hypercane' storms, and/or a sealevel drop, induced by the 'Impact winter'.
C) Sealevel rise (melting?), and first storm deposits (coarse calcarenites) in the lows.
D) Episodic infilling in the lows, periods of deposition of calcarenites and clays. The fining upward trend indicates waning storms or increased shielding; the clays represent periods of quiescence.
E) Deposition of the D and E clays; waterdepth increasing to 20–40 m. The E clay drapes also over the highs. In all depression fills, bioturbation has markedly decreased. Blooms of bryophyte spores and proliferation of dinoflagellates in the clays.
F) Continued episodic infilling of calcarenites and clays, with increased bioturbation, followed by the formation of the Vroenhoven hardground (VRH), representing the early Danian sequence boundary, and then deposition of the Geulhem Member glauconitic calcarenites (transgressive systems tract). Some survivor ammonite species (S?) occur just below the VRH in the Curfs quarry.
Lithologic symbols: 1) glauconitic calcarenite, 2) clay layers, 3) fine, laminated calcarenites, 4) intermediate calcarenites, 5) coarse calcarenites, 6) calcarenites of unit IVf-6 of the Meerssen Member.

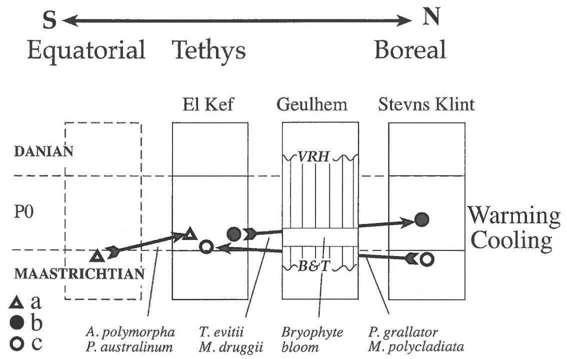


Figure 5. Schematic illustration of the dinoflagellate (cyst) migrations at K/T times. a) Tropical, b) Tethyan, c) Boreal species.

in the hardground are filled with glauconite and coarse quartz grains, quite unlike the first preserved sedimentary filling (unit IVf-7) of the depressions. It is furthermore assumed that the fall-out of the Chicxulub impact, usually found in Europe as an a-few-millimetres-thick clay layer containing small micro-krystites, shocked mineral grains and very fine-grained vaporized remains of the bolide itself (Ir-rich dust), has settled in a matter of weeks (Smit et al. 1992; Smit et al. in press). However, since such ejecta have so far not been found on the Berg en Terblijt Horizon, they have probably been swept off from its surface. The only traces remaining of these swept-off ejecta may be the slightly enhanced Th-normalized Ir values in, and just below the horizon.

A key element in most K/T boundary impact scenarios and models, is the subsequent blocking of sunlight by stratospheric dust and aerosol loading (Alvarez et al. 1980; Toon et al. 1982; Turco et al. 1990). The dust is either directly deposited on the stratosphere after it is sent in a ballistic trajectory around the world due to the force of the expanding impact-explosion plume (Melosh 1991), and/or it is transported by means of the hypothesized so-called 'hypercanes', super-hurricanes supposedly capable of injecting large amounts of aerosols in the stratosphere (Emanuel et al. 1995). All these models predict a severe drop in global temperature. It has been suggested that the period of reduced solar radiation may have lasted between six months to more than a decade (Pope et al. 1994). The brief cooling-episode is envisaged to have been followed by a longer period of pronounced warming when the dust veil has lifted and an increase of CO_2 in the atmosphere has led to greenhouse conditions. The excess CO_2 is thought to be derived from limestone vaporized at the Chicxulub impact as well as from the large-scale mass-mortality and wildfires. The mass-mortality of the $CaCO_3$-secreting organisms in the oceans at the K/T boundary has prevented a quick recycling of the CO_2 and therefore this greenhouse phase may have lasted several thousands of years. This is supported by the duration of the negative anomalies in the $\delta^{18}O$ profiles at Caravaca and Agost in Spain (Romein and Smit 1981; Smit 1990). Some support for the cooling-followed-by-warming scenario can be found in the detailed dinoflagellate records of El Kef in Tunisia and Stevns Klint in Denmark (Brinkhuis et al., in preparation, Figure 5), and in $\delta^{18}O$ records elsewhere. At El Kef, one of the most expanded, continuous K/T boundary sections in the world (Late Maastrichtian sedimentation rate about 10 cm/kyr), dinocyst assemblages from the first centimetre of sediment above the ejecta layer contain Boreal 'immigrants'. These are not known in the Maastrichtian of the Tethyan realm but well known from the Maastrichtian of higher-latitude sites like Denmark. The assemblages containing Boreal elements are rapidly replaced by assemblages dominated by tropical dinocysts. This migration of 'warm' dinocysts into higher latitudes is also seen in Denmark, where warm-water Tethyan forms (e.g. *Trithyrodinium evittii*, never before observed in the Maastrichtian of the Boreal realm) occur just above the ejecta layer, interpreted to indicate a global warming. This warm period is also recorded in the δ^{18}O-profile in Agost and Caravaca in Spain, and lasted for several thousands of years (Smit 1990).

We speculate that besides having pronounced effects on (photosynthetic) life, this short-term cooling and darkening may have resulted in temporal storage of water on the continents, either as ice or as increased groundwater content in soils. This could have caused a very brief sea-level lowering of several metres. If linked to the Geulhemmerberg succession, we believe that 1) the specific preservation of the Berg en Terblijt Horizon, followed by 2) the rapidly decreasing grainsize in the depression infilling, combined with 3) the repeated, sudden change from coarse limestones to very-fine grained clay layers, may indeed be best explained by the influence of a sudden sea-level fall combined with repeated (hypercane) storm deposition of coarse material and eventual settling of the fine fraction. Furthermore, the absence of warm (Tethyan) dinocysts in the clay layers, and the 'spike' of bryophyte spores, possibly representing a moss-rich, almost tundra-like vegetation, suggest that the entire, > 1.4 m-thick depression infilling of calcarenites and clays, and possibly all of unit IVf-7 between the Berg en Terblijt and Vroenhoven horizons, occurred after deposition of the Ir-rich dust, but before the period of warming.

In conclusion, we suggest that the deposition of unit IVf-7 may have taken place in less than a hundred years after the K/T impact. If so, there is an unprecedented expanded earliest Tertiary succession in Limburg, containing a wealth of information about the first years following the mass extinction at the K/T boundary.

Acknowledgements

Stimulating discussions with all colleagues involved in the Deep Dark Hole Project and their efforts are gratefully acknowledged. D.A.J. Batjes is thanked for various suggestions for improvement of the manuscript. The second author acknowledges support from the Netherlands Foundation for Geosciences (GOA) and financial aid from the Netherlands Organization for the Advancement of Scientific Research (NWO) and the LPP Foundation. This is publication 960813 of the Netherlands Research School of Sedimentary Geology (NSG).

References

Alvarez, L.W., W. Alvarez, F. Asaro & H.V. Michel 1980 Extraterrestrial cause for the Cretaceous-Tertiary extinction – Science 208: 1095–1108

Berggren, W.A. & K.G. Miller 1988 Paleogene tropical planktonic foraminiferal biostratigraphy and magnetobiochronology – Micropaleontology 34: 362–380

Berggren, W.A., D.V. Kent, J.J. Flynn & J.A. Van Couvering 1985 Cenozoic geochronology – Geol. Soc. Am. Bull. 96: 1407–1418

Berggren, W.A., D.V. Kent, C.C. Swisher III & M.P. Aubry 1995 A revised Cenozoic geochronology and chronostratigraphy – In: W.A. Berggren, D.V. Kent, M.P. Aubry & J. Hardenbol (eds): Geochronology, Time Scales and Global Stratigraphic Correlation – Soc. Econ. Paleontol. Mineral., Spec. Publ. 54: 129–212

Brinkhuis, H. & P. Schiøler (this issue) Palynology of the Geulhemmerberg Cretaceous/Tertiary boundary section (Limburg, SE Netherlands)

Brinkhuis, H. & J. Smit (this issue) The Geulhemmerberg Cretaceous/Tertiary boundary section (Maastrichtian type area, SE Netherlands); an introduction

Emanuel, K.A., K. Speer, R. Rotunno, R. Srivastava & M. Molina 1995 Hypercanes: A possible link in global extinctions – J. Geophys. Res. 100: 13755–13765

Felder, W.M. 1975 Lithostratigrafie van het Boven-Krijt en het Dano-Montien in Zuid-Limbrg en het aangrenzende gebied. In: W.H. Zagwijn & C.J. van Staalduinen (eds): Toelichting bij geologische overzichtskaarten van Nederland, Rijks Geol. Dienst, Haarlem: 63–72

Felder, W.M. & H.W. Bosch 1996 Afzettingen uit het Boven-Krijt en Danien in Zuid-Limburg en omgeving – Geologie van Nederland (Rijks Geol. Dienst, Heerlen) (in press)

Gradstein, F.M., F.P. Agterberg, J.G. Ogg, J. Hardenbol, P. van Veen, J. Thierry & Z. Huang 1994 A Mesozoic timescale – J. Geophys. Res. 99: 24051–24074

Gras, R. 1995 Late Cretaceous sedimentation and tectonic inversion, southern Netherlands – Geol. Mijnbouw 74: 117–127

Hardenbol, J. 1994 Sequence stratigraphic calibration of Paleocene and Lower Eocene continental margin deposits in NW Europe and the US Gulf Coast with the oceanic chronostratigraphic record – GFF 116: 49–51

Hildebrand, A.R., G.T. Penfield, D.A. Kring, M. Pilkington, A. Camargo, S.B. Jacobsen & W.V. Boynton 1991 Chicxulub crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatan peninsula, Mexico – Geology 19: 867–871

Hsu, K.J., Q. He, J.A. McKenzie, H. Weissert, K. Perch-Nielsen, H. Oberhanstli, K. Kelts, J. LaBreque, L. Tauxe, U. Krahenbull, S.R. Percival, R. Wright, A.M. Karpoff, N. Petersen, P. Tucker, R.Z. Poore, A.M. Gombos, K. Piscotto, M.F. Carman & E. Schreiber 1982 Mass mortality and its environmental and evolutionary consequences – Science 216: 249–256

Jagt, J.W.M. (this issue) Late Maastrichtian and Early Palaeocene index macrofossils in the Maastrichtian type area (SE Netherlands, NE Belgium)

Keller, G., E. Barrera, B. Schmitz & E. Mattson 1993 Gradual mass extinction, species survivorship, and long-term environmental changes across the Cretaceous Tertiary boundary in high latitudes – Geol. Soc. Am. Bull. 105: 979–997

Kuhnt, W. (this issue) Early Danian benthic foraminiferal community structures, Geulhemmerberg, SE Netherlands

Langereis, C.G. (this issue) Paleomagnetism of the Geulhemmerberg K/T boundary section, the Netherlands

Melosh, H.J. & A.M. Vickery 1991 Melt droplet formation in energetic impacts – Nature 350: 494–497

Pope, K.O., K.H. Baies, A.C. Ocampo & B.A. Ivanov 1994 Impact winter and the Cretaceous/Tertiary extinctions: Results of a Chicxulub asteroid impact model – Earth Planet. Sci. Lett. 128: 719–725

Roep, Th.B. & J. Smit (this issue) Sedimentological aspects of the K/T boundary at Geulhemmerberg, Zuid Limburg, the Netherlands

Romein, A.J.T. & J. Smit 1981 The Cretaceous/Tertiary boundary: calcareous nannofossils and stable isotopes – Proc. Kon. Ned. Akad. Wet. B 84 (3): 295–313

Romein, A.J.T., H. Willems & H. Mai (this issue) Calcareous nannoplankton of the Geulhemmerberg K/T boundary section, Maastrichtian type area, the Netherlands

Schmitz, B. & R.P. Speijer (this issue) Stable isotope ($\delta^{18}O$, $\delta^{13}C$) records across the Cretaceous/Tertiary boundary at Geulhemmerberg, southern Netherlands

Sharpton, V.L., K. Burke, A. Camargo-Zanoguera, S.A. Hall, D.S. Lee, L.E. Marin, G. Suarez-Reynoso, J.M. Quezada-Muneton & P.D.U.-F. Spudis-Jaime 1993 Chicxulub multiring impact basin; size and other characteristics derived from gravity analysis – Science 261: 1564–1567

Smit, J. 1990 Meteorite impact, extinctions and the Cretaceous-Tertiary boundary – Geol. Mijnbouw 69: 187–204

Smit, J. & R. Rocchia (this issue) Neutron activation analysis of trace elements in the Geulhemmerberg Cretaceous/Tertiary boundary section, SE Netherlands

Smit, J. & A.J.T. Romein 1985 A sequence of events across the Cretaceous-Tertiary boundary – Earth Planet. Sci. Lett. 74: 155–170

Smit, J. & W.J. Zachariasse (this issue) Planktic foraminifera in the Cretaceous/Tertiary boundary clays of the Geulhemmerberg (SE Netherlands)

Smit, J., A. Montanari, N.H.M. Swinburne, W. Alvarez, A.R. Hildebrand, S.V. Margolis, P. Claeys, W. Lowry & F. Asaro 1992 Tektite-bearing, deep-water clastic unit at the Cretaceous–Tertiary boundary in northeastern Mexico – Geology 20: 99–103

Smit, J., T.B. Roep, W. Alvarez, A. Montanari, P. Claeys, J.M. Grajales-Nishimura & J. Bermudez 1996 Coarse grained, clastic beds at the Cretaceous/Tertiary boundary around the Gulf of Mexico: Tsunami induced deposits from the Chicxulub impact? In: G. Ryder, D. Fastowski & S. Gardner (eds): Proc. Conf. New developments regarding the KT event and other catastrophies in Earth history – Geol. Soc. Am. Spec. Paper 307: (in press)

Swisher III, C.C., J.M.G. Nishimura, A. Montanari, E.C. Pardo, S.V. Margolis, P. Claeys, W. Alvarez, J. Smit, P. Renne, F.J.M.R. Maurasse, G. Curtiss & M. McWilliams 1992 Coeval $^{40}/Ar^{39}Ar$ ages of 65.0 million years ago from Chicxulub Crater melt-rock and Cretaceous-Tertiary boundary tektites – Science 257: 954–958

Toon, O.B., J.B. Pollack, T.P. Ackerman, R.P. Turco, C.P. McKay & M.S. Liu 1982 Evolution of an impact generated dust cloud and its effects on the atmosphere – Geol. Soc. Am. Spec. paper 190: 187–200

Turco, R.P., O.B. Toon, T.P. Ackerman, J.B. Pollack & C. Sagan 1990 Climate and smoke: an appraisal of nuclear winter – Nature 247: 166–176

Vonhof, H.B. & J. Smit (this issue) Strontium-isotope stratigraphy of the type Maastrichtian and the Cretaceous/Tertiary boundary in the Maastricht area (SE Netherlands)

Willems, H. (this issue) Calcareous dinocysts from the Geulhemmerberg K/T boundary section (Limburg, SE Netherlands)

Witte, L. & H. Schuurman (this issue) Calcareous benthic foraminifera across the Cretaceous/Tertiary boundary in the Geulhemmerberg (SE Netherlands)

Yamamoto, M., K. Ficken, M. Baas, H.-J. Bosch & J.W. de Leeuw (this issue) Molecular palaeontology of the earliest Danian at Geulhemmerberg (the Netherlands)

Zijlstra, J.J.P., M.H.M.P. Brouwers, H. Brinkhuis & P.L. de Boer (this issue) Microfacies analysis of Cretaceous/Tertiary boundary sections in the quarries Geulhemmerberg and Curfs, SE Netherlands