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A sequence of events across the Cretaceous-Tertiary boundary

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The lithological and biological sequence of events across the Cretaceous-Tertiary (K/T), as developed in thick and complete landbased sections and termed the standard K/T event sequence, is also found in many DSDP cores from all over the globe.

Microtektite-like spherules have been found in almost every core or outcrop with an iridium anomaly, forming a worldwide strewnfield. These "microtektites" are an excellent indicator of the K/T boundary level.

The basal Paleocene "*Globigerina*" *eugubina* Zone is now established in all major ocean basins. The difference in faunas between the Pacific and Tethys/Atlantic Oceans may point to different recovery of the oldest Paleocene planktonic foraminiferal assemblages in different ocean basins. Planktonic foraminifera and nannoplankton apparently show a different extinction-recovery pattern at the K/T boundary which suggests that the nannoplankton underwent final extinction later and recover later than planktonic foraminifera. These patterns may be important for the evaluation of the type and range of environmental stress resulting from the hypothesized impact(s) at the K/T boundary. Blocking of sunlight by the dust cloud still can account for the clear mass-mortality at the K/T boundary but seems less likely as explanation for the final nannoplankton extinction, as photosynthetic nannoplankton appear to survive 1000–10,000 years into the Tertiary.

1. Introduction

The best way to evaluate the environmental and biological stress after a major impact at the Cretaceous-Tertiary (K/T) boundary and the resulting evolutionary consequences, is the detailed analysis of extinction and renewal patterns of fossils which occur in abundance, in sections which are as complete as possible. These conditions eliminate most macrofossils and probably all terrestrial sections. In the predominantly pelagic marine sections where these conditions are met, a succession of lithologies can be recognized which is very similar from section to section.

To obtain a better idea how the evolution of the planktonic biota took place we have analysed the most complete DSDP cores that cross the K/T boundary from sites around the world (Fig. 1), and we have reviewed the existing documentation on these sections. A comparison is made with the most complete landbased sections, which have the advantage that stratigraphic and sedimentological details can be much better observed.

Smit and ten Kate [1] earlier hypothesized a sequence of K/T boundary events from the paleontology and lithology of the most complete

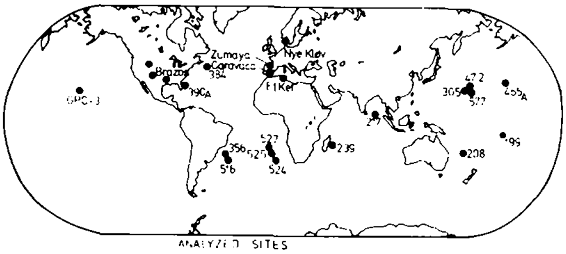

Fig. 1. Map showing the DSDP sites and landbased sections analysed in this paper.

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sections. Lithological and biological events show the same order in each section, and could be calibrated against each other through the exact coincidence of the mass-mortality level and the level with the maximum extraterrestrial component (ETC). The ETC-rich level is equivalent to the level with the iridium spike, but contains also numerous microtektite-like spherules [2]. Most of these spherules are best explained as the remains of microtekties, and have originated in the same way as tektites, but are highly altered diagenetically. As the term tektite is reserved for a glass object, and none of the K/T spherules contains glass, we prefer the term "microtektite"-like spherules. It is evident that the iridium anomaly and the microtektite-like spherules were produced by the same event as they invariably occur at the same level in each section, and have a high iridium content themselves [2]. We have found these "microtektites" also in a number of cores, where the iridium anomaly has not (yet) been found.

Fig. 2 shows the worldwide distribution of the microtektite-like spherules, which essentially overlaps the distribution of the known iridium anomalies. Three types of spherules can be recognized presently: sanidine spherules which are probably altered from quenched plagioclase or pyroxene; glauconite spherules, which may have formed from a basaltic glass precursor; and dark spherules with a very high iridium concentration [2] containing magnesioferrite/hercynite spinels, probably the only minerals not diagenetically altered since the impact event.

The purpose of this paper is to compare this sequence of events with additional sequences found in the newly analysed DSDP cores and landbased sections. Without exception the essentials of the K/T boundary event sequence could be found in the analysed sites, but only a few show a complete sequence of events. Because this event sequence can be applied so successfully to almost all pelagic sections, we will refer to it as the standard K/T boundary event sequence.

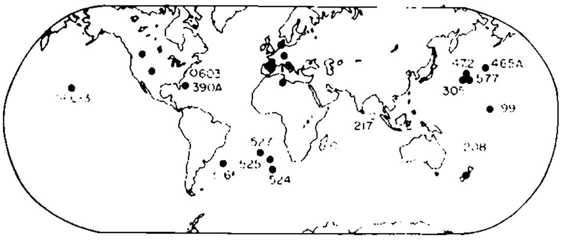

Fig. 2. Map showing worldwide distribution of microtektite-like spherules. Open circles questionable.

From several sites a comparison was made between species abundance profiles of planktonic foraminifera and nannoplankton [3] (Fig. 3). As can be seen from the species abundance plots, the change from dominantly Cretaceous to dominantly Tertiary nannoplankton taxa invariably takes place higher up section than for the planktonic foraminifera. This can be explained in different ways; it could be due to differential reworking of nannoplankton vs. planktonic foraminifera, but it can also be interpreted as indication that nannoplankton phytoplankton responded differently to impact-induced stresses than planktonic foraminifera do. However, both were clearly greatly reduced in numbers at the ETC-rich level. The K/T boundary as defined on nannoplankton is consequently usually drawn higher (see below) than the K/T boundary based on planktonic foraminifera. The nannofossil defined K/T boundary is also well above the mass extinction level, a definition for the K/T boundary which is used in this paper.

1.1. Biostratigraphy

The evolution of the topmost Cretaceous and basal Paleocene biozonation based on planktonic foraminifera shows progressively more detail since its inception in 1957 [7]. Originally, it shows a topmost Maastrichtian *Abathomphalus mayaroensis* Zone, followed in the Paleocene by the *Globorotalia trinidadensis* Zone. Later a *Globigerina pseudobulloides* (*Globoconusa daubjergensis*) zone was recognized below the *Gl. trinidadensis* zone. Luterbacher and Premoli Silva [5] separated the basal part of the *G. pseudobulloides* Zone in the "*Globigerina*" *eugubina* Zone, and a (slightly younger) *Eoglobigerina taurica* Zone was recognized by Russian authors [6]. Both are based on assemblages of extremely small but slightly differ-

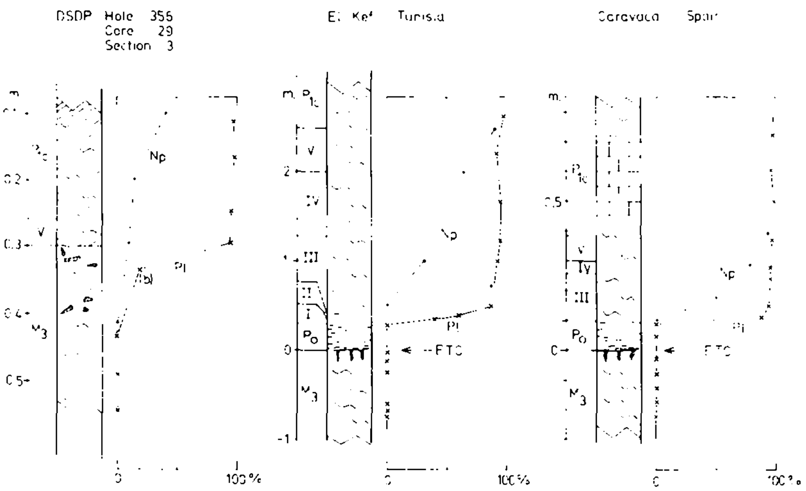

Fig. 3. Abundance ratios of Tertiary (in %) to Cretaceous species from nannoplankton (*Np*) and planktonic foraminiferal species (*Pl*). Nannoplankton abundances of DSDP site 365 after Thierstein [3], El Kef after Perch Nielsen et al. [11] and Caravaca after Romein [17]. Depth in meters of core section in DSDP 356, and in meters from the K/T boundary in the Kef and Caravaca sections. Arrow indicates ETC-rich layer. Zonation in Fig. 4. (*b*) = burrows.

ent globigerinid forms and are probably largely overlapping. For the majority of sections this is the maximum resolution which can be obtained. It was demonstrated later that a very thin [7] "intermediate" zone existed without the majority of typical Cretaceous forms, thus younger than the mass extinctions, and yet without the small earliest Paleocene forms. In the few sections where this zone is documented (El Kef, Caravaca) [8] it is characterized by an abundance of *Guembelitria cretacea*, a cosmopolitan "generalist" survivor of the Cretaceous, and hence it is named the *Guembelitria cretacea* Zone [8]. The *Abathomphalus mayaroensis* Zone has since its creation [4] not further been subdivided which points to its uniform and stable foraminiferal assemblages. The high resolution of the El Kef section allows to combine all these zonations into one zonal scheme (Fig. 4) and is here proposed as the planktonic foraminiferal zonation of the K/T boundary interval. The subdivision of the "*G.*" *eugubina* zone into subunits I to V has probably mainly a local (Tethys?) significance, as the earliest development of Paleocene globigerinids, on which these subunits are based, appears to differ between different ocean basins. The "*Globigerina*" *fringa* zone, a zone recently proposed by von Hillebrandt [10] below the "*G.*" *eugubina* Zone, is equivalent to

	This Paper			Boersma and Premoli Silva [12]	Herm et al (1981) [13]
$P1_c$	Globigerina pseudobulloides Zone			Globigerina pseudobulloides Zone	Globorotalia Compressa Zone Globigerina edita Zone
$P1_b$	'Globigerina' eugubina Zone	Eog. taurica Zone	V	Planorotalites eugubinus Zone (late)	Globigerina eugubina Zone
			IV		
$P1_a$			III	P eugubinus Zone (early)	
			II		'G' fringa Zone
			I		
P_0	Guembelitria cretacea Zone				
M_3	Abathomphalus mayaroensis Zone			A mayaroensis Zone	A. mayaroensis Zone

Fig. 4. Planktonic foraminiferal biozonation used in this paper, and compared with recently published zonations. *I*: subzone between the first occurrences of "*G.*" *minutula* and "*G*" *fringa*; *II*: subzone between the first occurrences of *G. fringa* and "*G.*" *eugubina*; *III*: subzone between the first occurrences of "*G.*" *eugubina* and *Eoglobigerina taurica*; *IV*: subzone between the first occurrence levels of *E. taurica* and large (0.125–0.25 mm) flat "*G.*" *eugubina*; *V*: subzone between the first occurrence levels of large "*G.*" *eugubina* and *G. pseudobulloides*. M_3 to $P1_b$ after Smit [8].

subunit II (Fig. 4) between the first occurrences of "*Globigerina*" *fringa* and "*G.*" *eugubina*. However, this subunit has so far only been found in the El Kef and the Wasserfall graben [10] sections. "*Globigerina*" *eugubina*, is retained here in the genus *Globigerina* (pending revision of its systematics; Smit, in preparation), but is probably a different genus, hence its name is put between quotation marks.

2. Standard K/T boundary event sequence

Due to unusually high sedimentation rates the El Kef section in Tunisia [8,11] and the Caravaca section in Spain [7] show the most detailed lithological succession known across the K/T boundary. These sections, allowed us to put the K/T boundary events into a time frame, and establish their proper sequence and interrelation (Fig. 5). From bottom to top the standard K/T event sequence shows a succession of 5 lithologic units (1 to 5), which reflect the sequence of events across the K/T boundary. The sequence thus established, or parts of it, can be found back in almost every K/T boundary event sequence worldwide, and seems to indicate a globally similar sequence of events, although locally details may differ. This sequence is here termed the K/T boundary standard event sequence. A major impact, or shower of impacts, can best explain these data. The El Kef and Caravaca sections are in hemipelagic facies and show a sedimentation rate much higher than any true pelagic deep-sea section (Fig. 6). Sedimentological investigation of these outcrops shows that this is not due to turbidite influx [12]; turbidites form only a minor contribution to the total thickness. The unusual thickness instead is rather due to a combination of high plankton productivity and high influx of detrital hemipelagic clays, probably reflecting the position of both sections close to the continental margin (upwelling). Bioturbation did not disturb the sequence completely and mix significant time intervals. One of the effects of the mass extinction—further reducing bioturbation—is the temporary disappearance of the burrowing organisms in some sections (Caravaca, Stevns Klint, DSDP site 465A) preserving thin laminae at the K/T boundary.

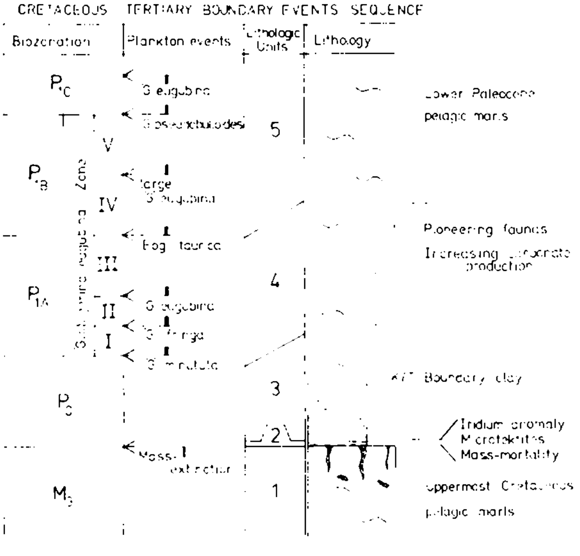

Fig. 5. Standard Cretaceous-Tertiary boundary events sequence as discussed in the text. Vertical scale is not measured, but the relative thickness is averaged from the most typical sections. *1–5* lithological units. See also Fig. 8.

2.1. Unit 1: Uppermost Cretaceous

This unit usually consists of a thick series of pelagic calcareous oozes, limestones or marls, at El

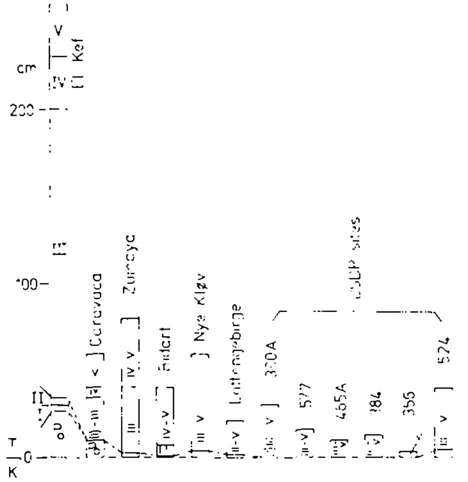

Fig. 6. Comparison of thickness of the *G. cretacea* and "*G.*" *eugubina* Zones of the sections analysed.

Kef and Caravaca more than 100 m. The unit is homogeneous, except for striking marl-limestone bedding alternations in limestone sequences. The top 10–20 cm are always pierced by conspicuous burrows, bringing down Paleocene contaminants. The significance of these burrows is rarely appreciated, and usually they are overlooked. In our opinion it is the cause of reports of Paleocene forms already in the uppermost Cretaceous in a number of occasions [12,14–16]. The record in this interval is critical for the test of graded vs. catastrophic extinction mechanisms, as an increase in extinction rate towards the K/T boundary, would cast doubt on catastrophic, i.e. major impact-related extinction as the primary cause of the terminal Cretaceous extinctions. Thus far there is few evidence that documents this alternative, and the few raised points seem to have a simple sedimentological explanation.

Quantitative analyses of nannoplankton [3,17] and planktonic foraminiferal assemblages [7] or brachiopods [18] show no increase or decrease in number of species or species ratios towards the K/T boundary.

However, several reports [15,19,20] claim there is evidence of changing biota below the boundary. An important factor in this question is the position of the K/T boundary (Erathem boundary) in a given section. Criteria differ for drawing the K/T boundary. Ideally it should be a synchronous time line, but there are numerous practical problems. One could draw the K/T boundary at: (1) the mass-extinction; (2) at the extinction of the last Cretaceous species; or (3) at the first appearance of true Paleocene taxa. Reworking, especially in the case of nannoplankton, may diffuse extinction or first appearance levels. Consider the El Kef section. Criteria (1) would place the boundary at the iridium level, (2) about 3 cm higher up section, and (3) at 34 cm above the Ir anomaly. It is the authors opinion that it is most useful to define the K/T boundary at the mass-extinction level, because it is worldwide, coincides exactly with the iridium anomaly respectively ETC-rich layer both in marine rocks and on land (with pollen extinctions [13,21], and it is probably synchronous. Doubts about the synchronism of the K/T boundary, expressed by some [14,15,22] are based on the alleged occurrence of the K/T boundary in different polarity intervals. However, the data from the San Juan Basin in New Mexico and the Raton Basin which appeared to support this, have been revised [22,23]. All known K/T boundary sequences now fall within a reversed geomagnetic polarity interval (see remarks on DSDP site 384).

In the case of ammonites [24] and possibly dinosaurs [25] there is perhaps little doubt that these groups show a progressive decline in diversity, but the ammonites more or less slowly and continuously over more than 40 million years. Moreover, Ward and Signor [26] show that the long living taxa—presumably generalists—which survived several other crises (the *Phylloceratidae* for over 180 million years), remained constant in numbers and diversity until their final extinction at the very end of the Cretaceous [24,26]. It seems, however, not likely that this decline leads to their final extinction. In the case of the dinosaurs and the terrestrial mammal extinction record Smit and van der Kaars [13] argued recently that the assumed turnover in mammal diversity below the K/T boundary may have been based on miscorrelation of floodplain and fluvial channel sediments in combination with a K/T boundary level which was drawn too high.

2.2. Unit 2: ETC-rich layer

This unit probably has had an initial thickness of less than 0.5 cm [1,27] when an (estimated) correction is made for mixing by drilling or bioturbation, tectonic interference or other sedimentological processes like turbidity currents, winnowing or slumping. Only a few sections (DSDP hole 465A, Caravaca) allow a direct estimate of its thickness, because of reduced bioturbation. In other sections, only inferences can be made of its thickness. It is important to stress that this layer is not equivalent to the often mentioned "boundary clay". That clay has usually a much greater thickness and is part of the next unit. Unit 2 shows the peak in Ir concentration [1,13,27,28] and now appears to contain microtektite-like spherules [2] in almost every section where the iridium anomaly has been found (Fig. 2), and corresponds thus to the direct fallout and ejecta level of the K/T impact(s). The presence of macroscopically visible microtektite-like spherules, makes this level recognizable in DSDP cores although, unfortunately, it is usually dispersed by bioturbation and drilling.

If preserved, this unit appears to be essentially carbonate free, and may indicate locally dysaerobic oceanic bottom waters for a very short time. Evidence for a dysaerobic environment are the near absence of benthic foraminifera (El Kef, Caravaca, Stevns Klint, DSDP hole 465A), the widespread occurrence of pyrite in this layer [29,30], the anomalies of chalcophile elements (As, Se, Sb and Zn) in some of the sections and the sometimes very conspicuous slowing down of bioturbation. Also, during the following 5 15 kyr sediments (the boundary clay of unit 3) were carbonate free to carbonate poor [1].

Unit 2 invariably indicates the level of the main mass-mortality and mass-extinction.

Two interesting lithologies belong probably also to this unit 2, if we accept the evidence from terrestrial sections [33] and from the Brazos river outcrop in Texas [31,34]. Each may correspond to an immediate effect of the impact itself, and may provide significant clues to the magnitude and location of the impact. Both in Montana [13,32] and in the Raton basin in New Mexico [33] the maximum Ir concentration occurs on top of a ±1 cm thick "tonstein", which may represent altered remains of ejecta [32]: This "tonstein" looks like a bentonite of altered volcanic glass, but does not contain phenocrysts in contrast to altered volcanic ashes in the same outcrops. In thin section the tonsteins appear to contain spherules [33] and, in Montana, to show a graded texture. The implication is that larger ejecta settled faster than the (finer-grained) Ir carrier phase.

A second lithology is a turbidite-like layer in the Brazos river section. Ganapathy et al. [31] did not recognize this unit as such, but our examination of the outcrop shows that the only turbidite in the Upper Cretaceous and Lower Tertiary in the Brazos river occurs exactly at the K/T boundary, and the Ir anomaly occurs on the top of it [34]. This may be the first evidence of impact (?tsunami) -triggered sediment. A major obstacle in modelling a major impact in the ocean, has been the lack of an impact-triggered turbidite in those pelagic sections where turbidites abound [8], where the ETC-rich level has been determined, but where no turbidite occurs exactly at the K/T boundary (Caravaca, Wasserfallgraben [8,10], DSDP site 524, Zumaya, Bidart, many sites in the Italian Apennines). It is assumed that also the deposition of this turbidite took place earlier than the settling of the Ir carrier.

2.3. *Unit 3: Boundary clay*

This unit corresponds to the deposition of the boundary clay. Material in this level consists mainly of the same background detrital clay minerals [35] as in units 1 and 5 and is consequently only preserved in sections with an anomalousy high background clay supply rate. The layer usually (except El Kef; [11] contains some 20–40% carbonate, either from reworked species or the few survivors [8]. Paleocene planktonic foraminifera do not occur and the *Guembelitria cretacea* Zone to which it is assigned, is biostratigraphically an intermediate zone between the Cretaceous and the Tertiary [7,8]. The unit is always graded from dark at the base to lighter at the top, and the color gradation continues on in unit 4, the "*G.*" *eugubina* Zone. This grading corresponds to increasing carbonate production. Enhanced Ir levels in this unit and also in the next, are probably either due to bioturbation/reworking or to erosion and redeposition from other eroded fall-out deposits, e.g. on land [1,8].

2.4. *Unit 4*

The boundary between units 3 and 4 is lithologically often difficult to observe, but is defined by the first occurrence of new Paleocene planktonic foraminifera [8]. Usually (El Kef, Caravaca, Stevns Klint, Nye Klov) it is associated with an increase in the carbonate supply rate, resulting from the first explosive development of the planktonic biota. Unit 4 also shows the first adaptive radiation of planktonic foraminifera and nannoplankton, characterized by rapid evolution of new species, abundance of very short living species (opportunists like "*G.*" *eugubina* or "*G.*" *longapertura*) and rapid alternation of the dominance of different species [7,8]. In the El Kef section several first appearance levels of the new planktonic species can be demonstrated; each defines a subzone [8] (Figs. 4 and 5, I-V).

2.5. Unit 5

This unit is in almost all respects comparable to unit 1—the uppermost Cretaceous—except for the completely new planktonic biota. In most sections both carbonate production and detrital clay supply are significantly lower than in the Cretaceous. Lithologically it is more or less homogeneous, and shows no color grading.

3. Material

The lithology of fifteen DSDP cores and seven landbased outcrops was examined and sampled as close as possible around the K/T boundary (Fig. 1). The planktonic faunas were analysed and assigned an age in comparison with the highly detailed zonation of the El Kef section in Tunisia [8] (Fig. 5). The DSDP cores were selected on the basis of reported continuous deposition across the K/T boundary, presence of K/T the boundary within one core section, and order to obtain a worldwide coverage.

Most DSDP cores in soft sediment appear disturbed by the rotary drilling which resulted in smearing out the ETC-rich layer over up to several decimeters (hole 465A), and diffuse first appearance levels of new Paleocene planktonic species. This problem was partly remedied in a triplet of hydraulic piston cores (HPC) 577, 577A and 577b across the K/T boundary on the Shatsky Rise, West Pacific. However, these cores show disturbance by bioturbation, which resulted in upward reworking of the microtektite-like spheroid bearing ETC-rich layer over 10 cm, comparable to the thickness of bioturbation in the El Kef section.

In the Initial Reports of the DSDP almost invariably the K/T boundary is defined at the first occurrence of Paleocene species, especially nannoplankton species. Lithological criteria were rarely taken into account. As noted before this gives a local K/T boundary in a different position as the ETC-rich level. The result is that the K/T boundary invariably is drawn higher in the section, and in some cases (390a, 305) it was even entirely missed. Claims of the "most complete K/T boundary" [9,15,36], made in many of the Initial Reports of the DSDP, have to be rejected, because parts of the basal-most Paleocene planktonic foraminiferal zonation appear missing (e.g. in the much discussed DSDP holes 356 and 384).

3.1. Pacific

Samples from the DSDP were obtained from the Hess Rise (site 465), Shatsky Rise (sites 47.2, 305 and 577), north of New Zealand (site 208), and from the Caroline abyssal plain (site 199).

Sites 577, 47.2 and 305 (Figs. 7 and 8). A set of 40 samples from the Shatsky Rise DSDP leg 86, site 577A, core 12, section 4, spaced at 1-2 cm in the vicinity of the K/T boundary, were analyzed and compared with some 20 samples from DSDP site 47.2, (earlier analysed by Hofker, [37]) and 3 samples from site 305. The latter sites are close to 577 on the Shatsky Rise, and are at the same ocean depth. The lithology of 47.2 and 305 is comparable if not identical, to that at site 577, and shows a continuous calcareous deposition of dominantly nannoplankton oozes across the K/T boundary. However, because of the very severe drilling disturbance no reliable sequence of events could be deduced from neither 47.2 or 305, but nevertheless a U-shaped dark marl containing "microtektites" is present in both 47.2 and 305. In all three sites the foraminifera in the uppermost Cretaceous are almost dissolved (Figs. 7, 8), which led Hofker [37] to the conclusion that an "Aplanktonic Zone" existed at the top of the Cretaceous.

Most of the "standard" K/T event sequence can be recognized in 577 (Fig. 8).

Contrary to a preliminary conclusion [8] from earlier inspection of samples from sites 47.2 and 465A and from review of published reports [6,37,38] of other core sections across the K/T boundary (199, 305), typical representatives of the "*G.*" *eugubina* assemblage do exist in Pacific, but

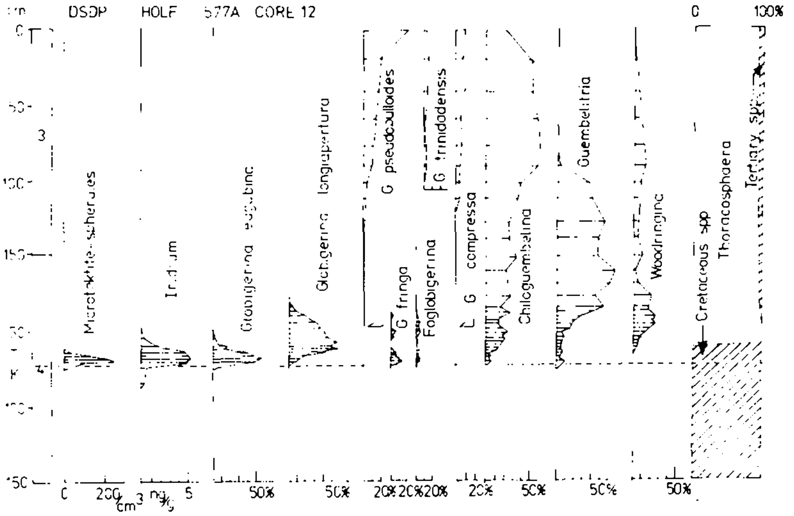

Fig. 7. Abundance profiles of microtektite-like spherules, iridium (from DSDP hole 577B after Asaro et al. [39]), and relative abundances of planktonic foraminifera and nannoplankton of DSDP hole 577A-12 sections 3/4. Depth in centimeters in core section. - - - - - = K/T boundary level.

show interesting differences with Tethyan/ Atlantic faunas.

Since site 577 is the only HPC core-site available across the K/T boundary in the Pacific, we might expect a non-disturbed sequence of the *G. cretacea* and "*G.*" *eugubina* Zones in a well preserved carbonate sequence. The lithology is very well comparable to the K/T standard event sequence, and the remains of the ETC-rich layer are clearly marked by numerous microtektite-like spherules of glauconite and some of magnetite [2] composition, showing relict quench textures. A peak concentration of 5.4 ng/g Ir was found at the maximum concentration of microtektite-like spherules in 577 [39] (Fig. 8). Supposedly due to the lower sedimentation rate and to the much lower detrital background clay supply rate compared to El Kef and Caravaca (40–80 × less), no boundary clay layer (unit 3; *G. cretacea* Zone) was preserved in any of the analysed core sections; the first Paleocene forms occur directly above and within the ETC-rich layer. Bioturbation and winnowing mixed unit 2–3 with other lithologies.

Although the "*G.*" *eugubina* Zone is thinner than at El Kef (23 vs. 250 cm) almost all members of the fauna of the El Kef "*G.*" *eugubina* assemblage are found. However "*Globigerina*" *minutula*, the first Paleocene form to appear at El Kef, has not been found in 577 or any of the other Pacific DSDP cores. Further, evolved forms of the "*G.*" *eugubina* group, having a larger (0.1–0.25 mm) and inflated test, with a more rugose surface sculpturing, but without wall-pores, occur in the upper part of the "*G.*" *eugubina* Zone (577A-12-4, from 25 to 70 cm; Fig. 7). Up to 50% of the specimens show the development of a dorsal secondary aperture in up to the fourth last chamber. On this aperture, usually 1–4 chambers are formed, arranged in a spire, with a different axis as the main trochospire, leading to bizarre individuals. The form is probably referable to "*Globigerina*" *longiapertura* 574574 [38] but is observed in none of the Atlantic/Tethys "*G.*" *eugubina* faunas.

Some acmes of planktonic foraminifera occur at different stratigraphic levels, as those observed in Caravaca, El Kef, and other Atlantic-Tethys sites. An acme of *Guembelitria cretacea* occurs within the *G. pseudobulloides* zone, instead of at the base of the "*G.*" *eugubina* Zone. The top 100 cm of the Cretaceous is very rich in nannoplankton, but very poor in planktonic foraminifera. In most samples only some heavily corroded large *Globotruncana stuarti* are preserved. Immediately above the K/T boundary, the faunas are rich and diversified. Even the most fragile and easily dissolved early Paleocene forms are preserved in every detail. This can also be seen on the Hess Rise (465A), and in a number of other cores from the Atlantic (356, 390A, 384). The change in preservation appears closely related in time to the K/T boundary, and

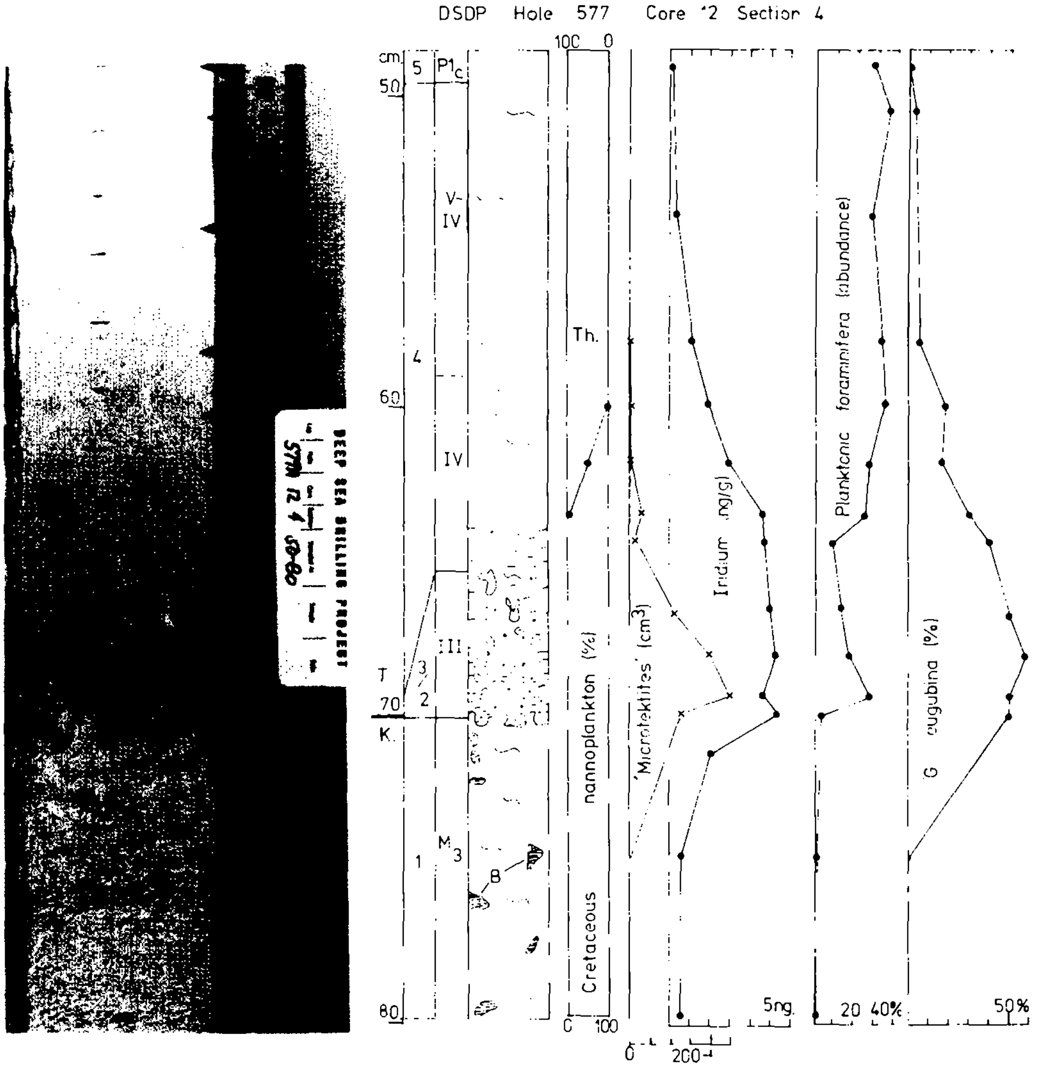

Fig. 8. Photograph and detail of the K/T boundary interval of DSDP site 577A-12-4, showing distribution of iridium and microtektite-like spherules in the grading boundary marl (units 2–4 of the standard K/T boundary event sequence) in relation to the abundance of planktonic foraminifera (measured on dry weight of the sieve fraction larger than 40 $\mu m/cm^3$), abundance of "*G.*" *eugubina* and the turn from 100% Cretaceous nannoplankton species to 99% *Thoracospaera* (*Th*). The first Paleocene nannoplankton species occur at 46 cm. Surface toothpick samples (the marks are visible on the photograph) from the initial nannofossil analysis are probably contaminated. The cutting wire, used to split the core halves, is moved from the top to the bottom of the section and brings down younger nannofossils to lower levels at the surface. *B* = burrows with Paleocene and boundary marl material; *M* = microtektite-like spherules.

might be a response to a worldwide change in ocean chemistry, presumably a drop of the lysocline and CCD. It might be speculated if this is due to the mass-mortality, following the impact, more specifically to the disappearance of carbonate-shelled biota. The "*G.*" *eugubina* Zone is within a marl grading from dark to light, which probably indicates a gradual increase in surface productivity back to normal values. A complete restoration is reached apparently at 20 cm above the K/T boundary estimated on carbonate content [39] and number of planktonic forms larger than 40 $\mu m/cm^3$ (Fig. 8).

Site 465A. This core was drilled on the Hess Rise. The Initial Reports of the DSDP give no details on foraminiferal biostratigraphy of the K/T boundary interval, but many samples have been analysed on trace elements [27,40] demonstrating a peak iridium anomaly associated with the darkest fragments in the core [40]. These dark fragments correspond to unit 2, the ETC-rich layer. In spite of the extreme drilling disturbance, which spread fragments of the dark layer over 40 cm –from 465A-3-4-115 to 4-4-5 cm—it can be inferred that it was originally not bioturbated, because due to a light lithification entire chunks survived in the stirred oozes, with white uppermost Cretaceous and grey lowermost Paleocene still attached to the 2 mm thick black layer [41]. Boersma [42] indicates the probably correct way to sample this core, by sampling on color—assuming that the dark marl layer grades from dark to light, as at site 577–rather than just on the position within the section. White (Upper Cretaceous) and dark (lowermost Paleocene) stringers can be traced over at least 450 cm, which means mixing of faunas, and enhanced iridium levels over a comparable distance. The top of the Cretaceous consists of nannoplankton ooze, as in 577 with dissolved *Globotruncana* faunal remainders. Only sample 3-4-143 contains a fairly well preserved *Abathomphalus mayaroensis* fauna, close to the dark ETC-rich layer. The black ETC-rich layer does not contain carbonate [41] but it does contain many pyrite and sanidine-rich spherules [2]. The dark levels immediately above the ETC-rich layer also contain shiny green glauconite spheroid fragments, identical to those in 577. Their numbers decrease rapidly upward, earlier than the change from dark to light sediment. The lowermost Paleocene faunas are excellently preserved as in 577, and sow identical assemblages. A sample taken directly above the ETC-rich layer, in darkest oozes, contains extremely small planktonic foraminifera, comparable to basal "*G.*" *eugubina* III faunas and may be even II, if the few "*G.*" *eugubina* are contaminants.

Sites 208 and 199. From these sites a few samples were obtained, which show the presence of a true "*G.*" *eugubina* assemblage in 199 (core 11-1, at 64 cm), and the ETC-rich level with microtektite-like spherules in 208. In hole 199 most of the recovered core is fragmented, but approximately at the K/T boundary, a distinct graded dark marl interval occurs, with microtektite-like spherules in the darkest part.

In conclusion, most Pacific DSDP cores show an ETC-rich layer indicated by microtektite-like spherules. Where Ir was analysed its maximum concentration is in the same layer. All cores were comparable with the standard K/T event sequence. The presence of the "*G.*" *eugubina* Zone, comparable to the subzones II–V of the zone at El Kef, indicates a good exchange of planktonic biota some 5 15 kyr after the impact event, although the differences in morphotypes and abundances between the Tethys/Atlantic Ocean and the Pacific may point to biogeographic differences, which seem to disappear with the uniform *G. pseudobulloides* assemblages.

3.2. Indian Ocean

Site 217 (at the Bengal abyssal plain) core 17-1 shows a lithological succession of calcareous oozes and marls compatible with the standard K/T event sequence; a dark layer with sharp lower and diffuse upper boundary is present between 110 and 136 cm. In the archive half (no material remains in the working half) with the handlens numerous 0.5 mm sized greenish spherules could be observed at 134 cm, an indication for the presence of microtektite-like spherules also in the Indian Ocean. Unfortunately the core was already over-sampled and it proved impossible to obtain another representative set of samples. At 137 cm a well-preserved, complete *A. mayaroensis* fauna was found, and at 10 cm a typical "*G.*" *eugubina* IV fauna, the first from the Indian Ocean.

3.3 South Atlantic

Many reasonably complete K/T boundary cores were recovered from this area, most of which (356, 516F, 524, 525A, 527) show little drilling disturbance because of the lithification of the sediments.

Sites 516F, 524, 525A and 527. These cores show the standard K/T event sequence with a well-developed boundary marl, although bioturbation is severe and covers the finer details. The ETC-rich level is clearly indicated by concentrations of green and black (magnetic) microtektite-like spherules at the base of the clay in cores 516F, 524, 525A, and 527. At site 524, Hsü et al. [43] found an Ir maximum (3 ng/g) at the level corresponding to the maximum concentration of the spherules. The boundary clay is in these cores preserved, because of the high detrital clay supply rate. Analysis of the planktonic faunas shows the presence of a well developed *A. mayaroensis* fauna at the top of the Cretaceous, and a typical "*G.*" *eugubina* III–IV fauna at the base of the Paleocene. All faunas show signs of dissolution, probably due to deposition close to the lysocline. Lithologically the K/T boundary sequences in 516F, 525A and 527 are remarkably similar. A thin boundary clay is present but the "horsetail" lamination in 516 F indicates pressure solution showing that part of the clay may originate due to dissolution of carbonate.

Site 356. This site was considered when it was drilled as one of the most complete K/T boundary sequences. Thierstein [3] published nannoplankton and stable isotope data, and Boersma [36] and Boersma and Premoli Silva [9] indicated that the basal Paleocene contained one of the most primitive Paleocene planktonic Foraminiferal faunas. Our analyses of the faunas and cores, however, show it is not so complete (Fig. 3). Lithologically this core, which is excellently preserved, does not compare with the standard K/T event sequence. It lacks the ETC-rich layer with microtektite-like spherules, or an iridium anomaly and a grading boundary clay. The planktonic foraminifera from a closely spaced sample set across the K/T boundary show the absence of a primitive basal Paleocene fauna, but a fauna comparable to the upper "*G.*" *eugubina* V/*G. pseudobulloides* Zone at the base of the Paleocene. The planktonic foraminifera have a well-developed cancellate wall structure in all forms, which is a more advanced characteristic of planktonic foraminifera in the El Kef and Caravaca sections. It is likely that a significant hiatus is present, which explains why only a minor Ir enhancement was found.

3.4. North Atlantic

Sites 384 and 390A. Both sites are drilled in a thick carbonate sequence, deposited well above the carbonate line. Site 384 was considered to be the most complete across the K/T boundary [44], but our analysis of the planktonic faunas show a significant part missing. Lithological analysis of core 13-3, shows that the boundary clay and ETC-rich layer are not present, confirming the planktonic analysis. Recently this section was cited as evidence against a catastrophic impact at the K/T boundary [15].

Fig. 9 shows the nannoplankton distribution of Thierstein and Okada [44], combined with our analysis of planktonic foraminiferal faunas. As this comparison is made on different suites of samples we have tried to correct for possible misfits by looking at the color of the sediments sampled. As at site 356 the lower part of the "*G.*" *eugubina* Zone (I–III) is missing, indicating a hiatus. The presence of the nannoplankton *Cruciplacolithus tenuis* just at the K/T boundary confirms this hiatus, as in other sections of the Atlantic/Tethys Ocean [11,17] this form develops higher in the Danian from *C. primus*, also a strictly Paleocene species. There is controversy about possible drilling disturbance of this core [15], but the well-preserved burrow structures at all levels, and the good lithification of the pelagic marls speak against a significant mixing. There is a very well visible color change from Cretaceous to Paleocene, but the bioturbation has all but destroyed its sharp boundary level. Dark burrows filled with Paleocene planktonic foraminifera and nannoplankton extend down to level 168.20 m.

In the Initial Reports of DSDP site 384 [44] the K/T boundary is drawn at 167.90 m which coincides with a color change, and the beginning of the nannoplankton turnover. One of the key arguments of Officer and Drake [15] against synchronous extinction, and thus against impact, is the supposed occurrence of the K/T boundary within normal polarity interval 29N in the San Juan basin [23] and in hole 384, at 167.60 m. This would be at odds with the vast majority of K/T sequences where the K/T boundary is in the reversed interval 29R. The correct K/T boundary is difficult to

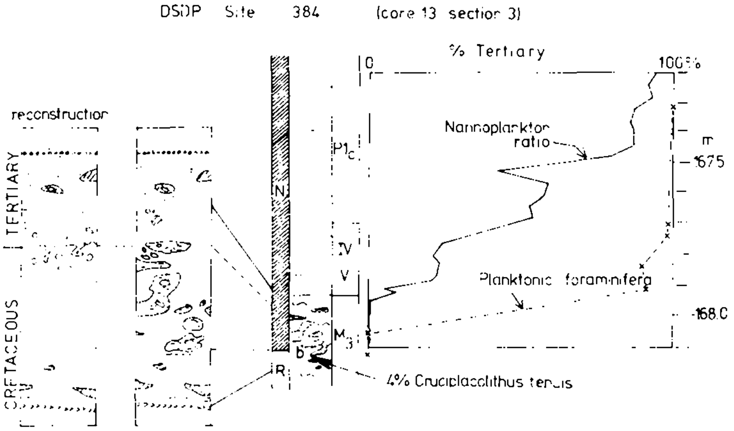

Fig. 9. Magnetozonation, lithology, zonation and ratio of abundance of nannoplankton [44] and planktonic foraminifera of site 384, core 13, section 3 (North Atlantic) across the Cretaceous-Tertiary boundary. N = normal and R = reversed magnetic polarity interval. *b* = darker burrows with Paleocene material, extending below the K/T boundary. Zonation in Fig. 4. At left the reconstruction of the Initial Reports of the DSDP [44]. Note burrows extending beyond the R-N magnetic reversal. Depth in meters subbottom.

define in core 384, but is certainly located closer to the color change at 167.90 m, than at 167.60 [44]. This is within 20 cm of the change to polarity interval 29R. Burrows extend down from the Paleocene above 167.90 to below this reversal, and it is well known that these can bring down the magnetisation from higher levels: The Paleocene *C. tenuis* Zone occurs within normal interval 28N. Thus even if the Paleomagnetic data are correct, which is challenged by Alvarez et al. [45], the K/T boundary could very well be located in interval 29R, consistent with all other analysed K/T sequences.

Site 390A contains a good continuous sequence of calcareous pelagic oozes across the K/T boundary, although it is disturbed by drilling. The pres-

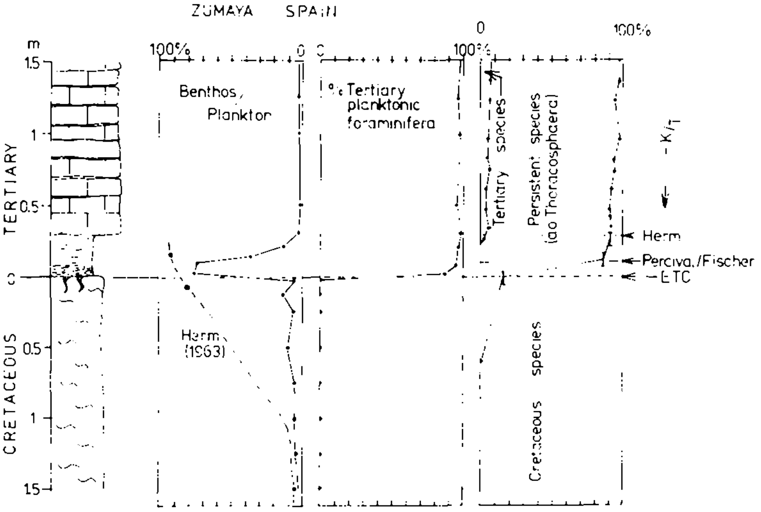

Fig. 10. Zumaya section, showing from left to right; the ratio of benthic to planktonic foraminifera after Herm [20] and as analysed in this paper; the ratio of Cretaceous to Paleocene planktonic foraminifera (this paper); and the ratio of Cretaceous to Paleocene to "disaster species" [30] like *Thoracosphaera* and *Braarudosphaera* (see also Figs. 8, 9). *K/T* = earlier determined K/T boundary levels [20, 30] and the extraterrestrial component (ETC) -rich layer (= K/T boundary in this paper).

ervation of planktonic foraminifera is good to excellent. Lithologically the site compares very well with the standard sequence, and both an ETC-rich layer, indicated by numerous green microtektite-like spherules, and a grading boundary clay are present. The K/T boundary was originally placed in the wrong core section (11-5). So contrary to other K/T boundary levels in DSDP cores it is barely sampled. Our samples place the boundary in core 11, section 6, approximately 18 cm. The planktonic foraminiferal fauna of the basal Paleocene is in all respects comparable to the El Kef and Caravaca sections, but is too disturbed to establish a good biostratigraphic sequence. Sampling according to the color change from light to dark reveals a turnover from 100% Cretaceous taxa in the light ooze in core 11, section 6, at 24 cm to 80% Tertiary forms in the darker ooze in core 11, section 6, at 16 cm, which is more rapid than the nannoplankton change consistent with the other analysed DSDP sites.

3.5. Landbased sections

Terrestrial outcrops have the advantage of much more rock volume, generally higher sedimentation rates which gives higher resolution, and better control on the stratigraphy and sedimentology. On the other hand most outcrops are weathered and leached, tectonic and diagenetic effects destroy many features, and the planktonic faunas are usually not well preserved. There are but a few known good sections; El Kef, Tunisia [8], Caravaca and Zumaya, Spain [1,30] and Nye Klov, Denmark [46]. These sections are described in detail elsewhere [46], and only some points will be mentioned here. The El Kef section [8] shows the most complete evolutionary development of planktonic foraminifera at the base of the Paleocene. As in the DSDP cores, nannoplankton and planktonic foraminifera show different replacement patterns. Figs. 3 and 10 show that the complete replacement of Cretaceous assemblages of nannoplankton by Paleocene forms always takes place later than the replacement of planktonic foraminifera.

The Zumaya section is a good example of how it can give a confusing picture, when specialists in different fields place the K/T boundary at different levels (Fig. 10). Herm [20] and von Hillebrandt [47], placed the K/T boundary at the top of the "boundary shale" [30], on the basis of first occurrence of Paleocene planktonic foraminifera. But Herm's curve of the ratio of planktonic to benthic forms suggest changing conditions below the K/T boundary. Percival and Fischer [30] found Paleocene planktonic foraminifera down to the middle of the "boundary shale", due to more detailed sampling, and placed the K/T boundary accordingly, but they noted an important change in nannoplankton biota 10 cm lower (equivalent to 10,000 years), again suggesting changing biota below the K/T boundary. However, our analysis and sampling was even more detailed, and showed Paleocene planktonic foraminifera down to the base of the "boundary shale" just at the iridium anomaly (W. Alvarez, personal communication) and the level with microtektite-like spherules. The confusion starts when these locally defined K/T boundaries are equated with the erathem boundary (indicated by the ETC-rich level), because the impression has arisen [15] that extinctions are well underway before the impact. However. Fig. 10 shows that the changes occur all above the ETC-rich layer. There remains the question of the disappearance of ammonites and inoceramids in this section, about 10 m below the K/T boundary. It appears to coincide with a lithology change, which suggests a local change rather than a global one, and is probably asynchronous with the extinction in Denmark [26,46].

Nye Klov. The Nye klov section in northern Jutland, is generally considered as the best preserved pelagic calcareous section in high latitudes. The lithology and both the planktonic foraminiferal and the macrofossil record agree very well with the standard sequence. The first Paleocene planktonic foraminifera are found sparsely about 10 cm above the ETC-rich layer, and comprise well-preserved forms of the *"G." eugubina* III Zone [49]. *"Globigerina" minutula* and *"G." fringa* have not been found suggesting these species could be lower latitude species. The uppermost Cretaceous contains almost no planktonic forms, except for a marl interval some 8 m below the K/T boundary, which lacks the most important marker species for the uppermost Maastrichtian, regarded as a high latitude effect.

4. Discussion

As shown in Figs. 3 and 7–10, when the relative abundances of Paleocene and Cretaceous species of nannoplankton and planktonic foraminifera are plotted, the shift from dominant Cretaceous to dominant Paleocene forms is consistently later for the nannoplankton. The planktonic foraminifera disappear within centimeters of the K/T boundary, the nannoplankton 10–50 cm higher in the section. Besides that this difference gives problems in defining the K/T boundary (as mentioned above), it might indicate a marked difference in the response of the phytoplankton opposite the zooplankton to (impact induced) environmental stress, which first lead to mass-mortality [43], and subsequently to mass-extinction.

A problem is that we do not know if the Cretaceous populations above the K/T boundary are indigenous. Thierstein and Okada [44] argued for a burrow-mixing of an initially sharp layer. If burrow-mixing alone were responsible for these different abundance profiles, one would expect that the planktonic foraminifera would duplicate the nannoplankton distribution, which they do not. The other explanation given by Thierstein [3], would be that large-scale erosion of upper Cretaceous rocks would rework nannoplankton preferentially above foraminifera, because of their smaller size. Although reworking of nannoplankton is frequently observed we doubt that this process would operate on a global scale, because of the absence of sedimentological support for this reworking, such as a possible lag deposit of washed out planktonic foraminifera. Moreover the basal layers of unit 3 in Stevns klint, Caravaca, Biarritz, and especially El Kef contain less Cretaceous species and numbers of nannoplankton than slightly higher levels [12,48].

Another argument against reworking may be the definitely different carbon and oxygen isotopic signal (up to −2‰) of the nannoplankton carbonate, in layers immediately above the ETC-rich layer—usually consisting of Cretaceous nannoplankton species [3,50]—as compared to the uppermost Cretaceous. Thierstein [50] argued that this could be due to dissolution or diagenetic alteration of the nannoplankton rather than to a primary signal. However, considering the fact that marls in the Caravaca and El Kef sections immediately above the −2‰ signal are lithologically identical, but show different isotopic values signals we consider diagenetic alteration an unlikely explanation.

Although we cannot rule out reworking processes, we think that the different plankton abundance patterns are better explained as primary signals, and might thus give important information about the extinction. The scenario which is favored here, follows the scenarios given by Smit and ten Kate [1] and Hsu et al., [43]. The lithological evidence shows a mass mortality immediately following the impact. Unfortunately resolution even in the most complete record is by far too poor to resolve any of the modelled catastrophic effects (blocking of sunlight, temperature rise) as direct consequences of an impact. But following the mass-mortality we observe some different patterns. Planktonic foraminifera, supposedly dependent on phytoplankton did not survive the great reduction of these. But the phytoplankton, represented by the calcareous nannoplankton, survived, be it in greatly reduced numbers, and apparently succumbed in competition with the new planktonic biota that underwent an explosive development.

5. Conclusions

This research shows that the same lithological succession across the K/T boundary can be traced over all major ocean basins, and that this succession is best explained by a major impact, followed by a series of longer lasting biotic stress. We designate this sequence the standard K/T sequence event since it can serve as a standard reference for all K/T boundary sections. Its worldwide distribution shows that the sequence of K/T boundary events must be similar over all ocean basins. However, until now only the El Kef section in Tunisia appears to contain almost all subdivisions of this sequence, all other sections

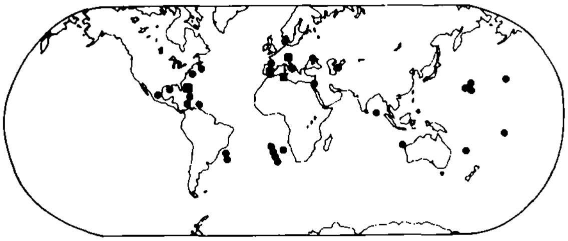

Fig. 11. Map showing the worldwide distribution of assemblages of the "*G.*" *eugubina* Zone. Squares indicate sites where assemblages of subzones I and/or II were found.

show either a low sedimentation rate which obliterates details, or are subject to burrow-mixing, or are severely disturbed by drilling.

We show here the presence of a major, worldwide strewnfield of microtektite-like spherules. These "microtektites" prove to be a consistent indicator of the ETC-rich layer, and always occur in a consistent place in the K/T boundary event sequence, at the iridium anomaly. We have established the presence of the basal Paleocene "*G.*" *eugubina* Zone in all major ocean basins (Fig. 11).

Contrary to the conclusions of Officer and Drake [15], the K/T boundary appears synchronous worldwide. Only a major impact with all its environmental consequences seems capable of explaining all lithological, trace element, and biological evidence.

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