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Extinction and evolution of planktonic foraminifera after a major impact at the Cretaceous/Tertiary boundary

J. Smit
Geologisch Instituut
Nieuwe Prinsengracht 130
1018 VZ Amsterdam
Netherlands

ABSTRACT

The mass-extinction event at the Cretaceous/Tertiary boundary (C/T in text; K-T on figures) exterminated all but one species of the planktonic Foraminifera (*Guembelitria cretacea* Cushman). Although not all details have been clarified yet, all Paleocene planktonic Foraminifera may have evolved from this sole survivor. *Globigerina minutula* Luterbacher and Premoli Silva is the first true Paleocene species to appear; it develops into *Globigerina fringa* Subbotina, and later on probably into *Globigerina eugubina* Luterbacher and Premoli Silva. Essentially, the stratigraphy of several complete sections shows a similar pattern: abrupt extinction of plankton followed by deposition of a thin lamina with high concentrations of siderophile elements, considered as the direct fallout level of the impact event. This lamina is followed by a 1- to 30-cm-thick clay or marl layer (which represents the normal background supply of hemipelagic clay) and a gradual return to calcareous sedimentation associated with the appearance of the first new Paleocene species.

The biostratigraphy of the Gredero section in southeast Spain is analyzed in detail, complemented with data from the Kef section in Northern Tunisia. A new zone, the *Guembelitria cretacea* Zone, which contains only *G. cretacea,* and possibly *Globotruncanella monmouthensis* (Olsson) and *Globigerinelloides messinae* Brönnimann in situ, is established at the base of the Tertiary. It is essentially the same as the C/T boundary clay. New taxonomic descriptions are given of *G. cretacea, Globigerina minutula, G. fringa, G. eugubina,* and *Globotruncanella caravacaensis* n. sp. Preliminary results of a paleomagnetic survey are used to calculate sediment accumulation rates, from which the mass extinction is inferred to have occurred within 50 years and a new stable planktonic fauna re-established within 35,000 years. The earliest Paleocene faunas are highly unstable. Different species successively become dominant and show a rapid evolutionary development. The initial development thus is both explosive and unstable and seems to be consistent with the punctuated mode of evolution.

RODUCTION

The C/T boundary problem can be satisfactorily
d only after the biostratigraphic details have been clar-
Recent added tools in stratigraphy, such as magneto-
graphic zonation (Alvarez and others, 1977) and
rical time scales (Hinte 1976; Hardenbol and Berg-
1978), allow sedimentation rates to be estimated and, in turn, the rates of extinction and evolution. Recently, *Globigerina eugubina* Luterbacher and Premoli Silva was considered as the earliest representative of the Tertiary globigerinids. However, in the exceptionally thick boundary sequence of the Kef section, and possibly in Bavaria (Herm and others, 1981), *G. eugubina* is preceded by *G. minutula*

and *G. fringa.* By its small size and its highly characteristic ventral aspect, *G. eugubina* can be readily distinguished from other lower Paleocene globigerinids. However, the poor original figures and description of the species are the source of much confusion. Therefore, an amended description of *G. eugubina* is given, based on well preserved hypotype material from the Gredero section, its comparison with type material from the Ceselli section (Luterbacher and Premoli Silva, 1964) and excellently preserved material from DSDP site 390A, and from Biarritz (Perch Nielsen, 1979; Romein and Smit, 1981b).

The best sections for studying the C/T boundary are those with continuous sedimentation over some length of time, without a break in facies. Calcareous pelagic sequences satisfy this condition, but even the most complete (Caravaca: Smit, 1977; El Kef: Salaj, 1977) have some disadvantages (Fig. 1). Continuous pelagic sequences typically contain only microfossils, planktonic Foraminifera, and nannofossils, with subordinate amounts of benthic Foraminifera and ostracods. The macrofossil record can be satisfactorily studied only in Denmark where several apparently continuous sections exist (Bang, 1979c; Birkelund and Bromley, 1979). The best preserved faunas of the *G. eugubina* Zone come from DSDP sites (47.2; 199; 390A; 356; 465A; Pl. 2, figs. 3–5), but the complete evolutionary sequence of planktonic species is thus far known only from land-based outcrops (Fig. 2). Most DSDP cores are, moreover, mechanically highly disturbed by drilling, which has produced controversial biostratigraphic results. At site 465A, for example (Kyte and others, 1980, Michel and others, 1982); the C/T boundary layer consists of small chips, spread out over several decimeters of core. The estimated (Michel and others, 1981) concentration of 520 ng/cm^2 Ir at this site is probably too high, owing to the near impossibility of reconstructing the true stratigraphic thickness of the C/T boundary sequence. Relatively few complete sequences are known in outcrop, and most show some disturbance by tectonic movement (Biarritz, Caravaca, Gubbio); Pleistocene glaciation (Nye Klϕv, Kjϕlby Gaard); or authigenic gypsum growth (El Kef). Surface outcrop weathering also may produce some ambiguous oxygen isotope results (Perch Nielsen, 1979; Romein and Smit, in prep.). Nevertheless, the Caravaca and El Kef sections in particular show a complete succession of the events across the C/T boundary, allowing resolution of questions that arose from previous discussions of the earliest Paleocene faunas.

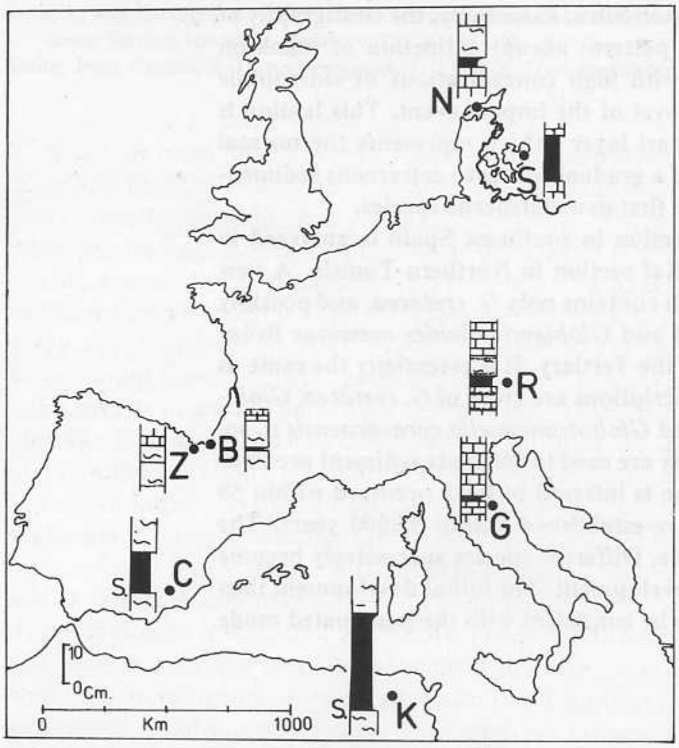

Figure 1. Map of western Europe showing localities mentioned in the text. Relative thickness of the C/T boundary clay (*G. cretacea* Zone) and lithology of boundary sequences indicated. C = Caravaca, B = Biarritz, Z = Zumaya, G = Gubbio, K = El Kef, S = Stevns Klint, N = Nye Klϕv, R = Reichenhall (Lattengebirge; after Herm and others, 1981), and S = sanidine spherules in the fallout lamina.

STRATIGRAPHY

All sections studied show well-defined common traits that allow reconstruction of the catastrophe at the C/T boundary (Smit and ten Kate, 1982) (Fig. 3).

A common characteristic is the distinct dark clay or marl layer at the C/T boundary (the *Guembelitria cretacea* Zone). If complete, this marl layer shows razor-sharp lower and a gradual upper boundary. The lower boundary represents the mass extinction level. Only a slight bioturbation or postdepositional dissolution may diffuse this level. Immediately after the extinction level are a few millimeters of clayey sediment, reddish in color if oxydized (Caravaca, El Kef, Nye Klϕv, Stevns Klint) or black (site 465A) and rich in siderophile elements, such as Ir, Os, Re, Rh, Pd, Pt, Ni, Co, and Cr (see Table 1) (Smit and Hertogen, 1980; Alvarez and others, 1980; Kyte and others, 1980; Ganapathy, 1980). Recently, microtektite-like spherules have been found in both the Gredero and Kef sections (Smit and Klaver, 1981). This lamina, which probably represents the direct fall out layer of the impact event, is overlain by a dark marl layer, grading into calcareous marls concurrent with the rise of the first new planktonic species. The components of this part of the C/T boundary clay are the normal background detrital clay and an impoverished benthic foraminiferal fauna. Only iridium still shows values above background levels, but this may be ascribed to delayed input, probably via transient deposits on the continent. Figure 4 shows the distribution of the most important geochemical variables across the C/T boundary, in relation to

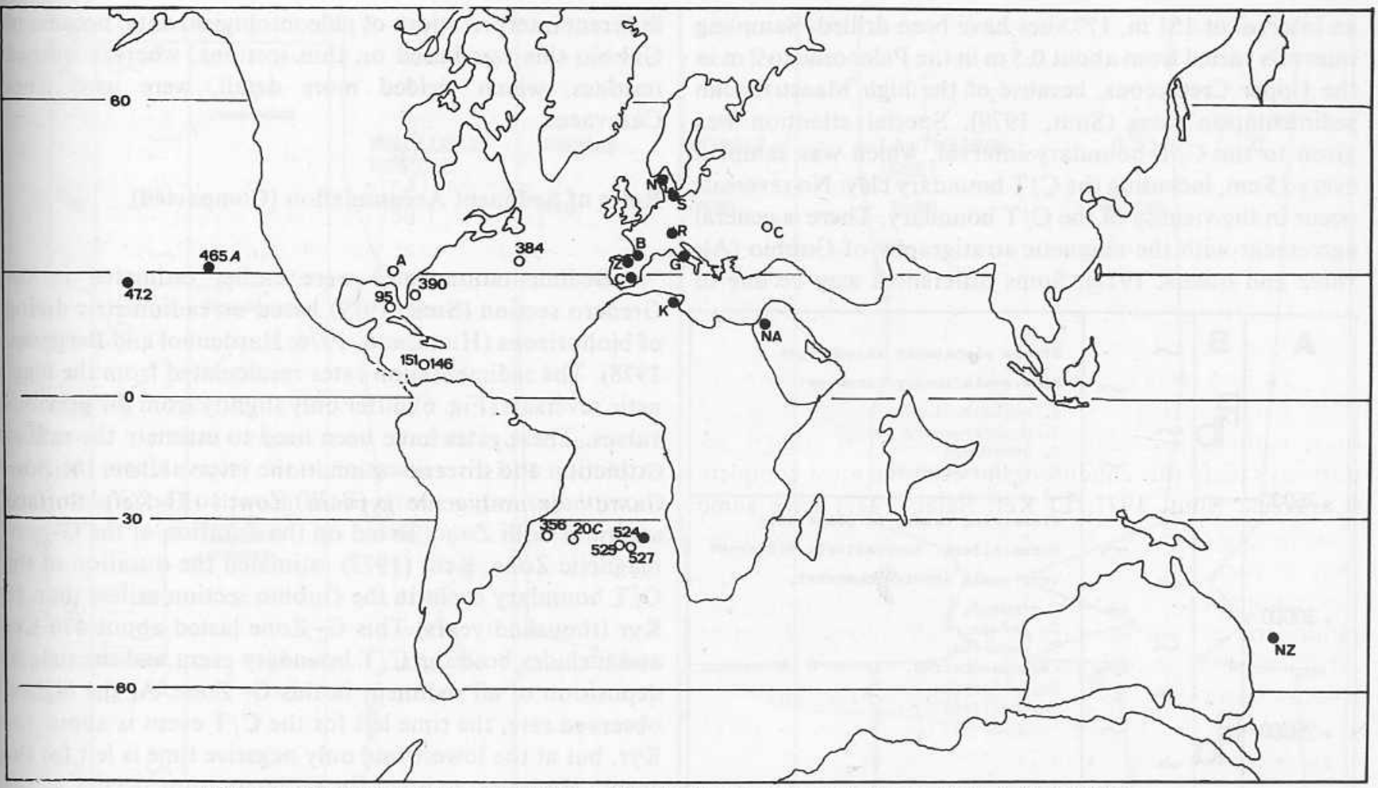

Figure 2. Paleogeographic map (60 m.y. (Mry); after Barron and others, 1981). (●) DSDP sites and surface outcrops with Ir enrichment and C/T boundary clay; (○) sites containing the *G. eugubina* Zone; A = Millers Ferry, Alabama; C = Crimea; NA = Nahal Avdat, Negev Desert, Israel; and NZ = New Zealand.

the faunal events. The detrital material of *all* boundary clays known to us is very fine grained. Pacific boundary clays occur in an environment where normally only fine-grained material is supplied (Fig. 2). In contrast, the C/T boundary clay in Europe and the Atlantic Ocean (Zumaya, Biarritz, Caravaca, Gubbio, Lattengebirge; Herm, 1963; Perch Nielsen, 1979; Smit, 1977; Alvarez and others, 1980; Herm and others, 1981) commonly occurs in a sequence with frequent intercalations of turbidites. These turbidites occur just below or above the C/T boundary, but never exactly at the extinction level, arguing against impact of an asteroid or comet in the vicinity of Europe or the Atlantic, as the resulting earthquakes and tsunamis almost certainly would have triggered a turbidite in one of the basins. Only impact in the Pacific would not trigger turbidites in Europe, hence evidence of turbidites at the C/T boundary should be sought in the Pacific region.

TABLE 1. RESULTS OF INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS OF THE CARAVACA SECTION

	Upper Cretaceous	'Fall-out' Lamina	Lower Paleocene	Range of Error (%)
Na	787	1490	503	4 - 11
Al	33178	119000	27767	2 - 5
K	6207	13900	4106	5 - 11
Ca	309964	20900	329324	2 - 5
Sc	5.6	9.46	4.9	2 - 4
Ti	2029	20900	1809	10 - 25
V	54.5	241	53.1	3 - 16
Cr	56	801	66	3 - 5
Mn	472	121	750	2 - 8
Fe	13796	52200	11811	1 - 3
Co	9	537	5.2	1 - 8
Ni	22	1990	31.6	1 - 12
Cu	-	253	-	- 33
Zn	28.8	760	26.3	2 - 35
As	1.6	456	1.35	10 - 25
Br	1.02	4.3	1.62	11 - 16
Zr	-	327	-	- 23
Sb	0.3	13.7	0.21	4 - 14
La	16.9	3.78	20.2	1 - 7
Ce	33.8	9.19	31.1	1 - 7
Sm	2.9	0.662	3.6	3 - 12
Eu	0.6	0.204	0.65	3 - 13
Yb	1	0.557	1.3	3 - 26
Hf	1.26	4.54	1.05	2 - 12
W	1.6	5.93	1.6	11 - 24
Au	-	0.0223	-	- 23
Th	3.7	8.59	3.05	2 - 6
U	0.95	11.7	1.04	8 - 25
^{x}Ir	0.000057	0.0266	0.00034	2 - 10
^{x}Os	0.00008	0.0205	0.00041	2 - 10
^{x}Se	0.00073	5	0.00138	3 - 10

Note: Values in ppm.
Analyses made at the Interuniversitary Reactor Institute, Delft, Netherlands.
x = Radiochemical analyses, communicated by J. Hertogen

The thinner boundary clays (Gubbio, Biarritz) do not show this division into fallout lamina and detrital interval, and it is assumed that here the two parts are mixed. The transition to normal calcareous sedimentation with new Foraminfera is relatively rapid, but gradual. Apparently carbonate production was only slowly restored to the same level as in the Cretaceous, and in many sections this level was not regained (Zumaya, Biarritz, Gubbio, Caravaca).

A paleomagnetic survey was made in the Gredero section in order to check the magnetostratigraphic zonation and determine sediment accumulation rates (Fig. 5). Over an interval of 151 m, 177 sites have been drilled. Sampling intervals varied from about 0,5 m in the Paleocene to 2 m in the Upper Cretaceous, because of the high Maastrichtian sedimentation rates (Smit, 1979). Special attention was given to the C/T boundary interval, which was sampled every 15 cm, including the C/T boundary clay. No reversals occur in the vicinity of the C/T boundary. There is general agreement with the magnetic stratigraphy of Gubbio (Alvarez and others, 1977). Some differences may be due to different interpretations of paleontological data, because in Gubbio this was based on thin sections, whereas washed residues, which yielded more detail, were used from Caravaca.

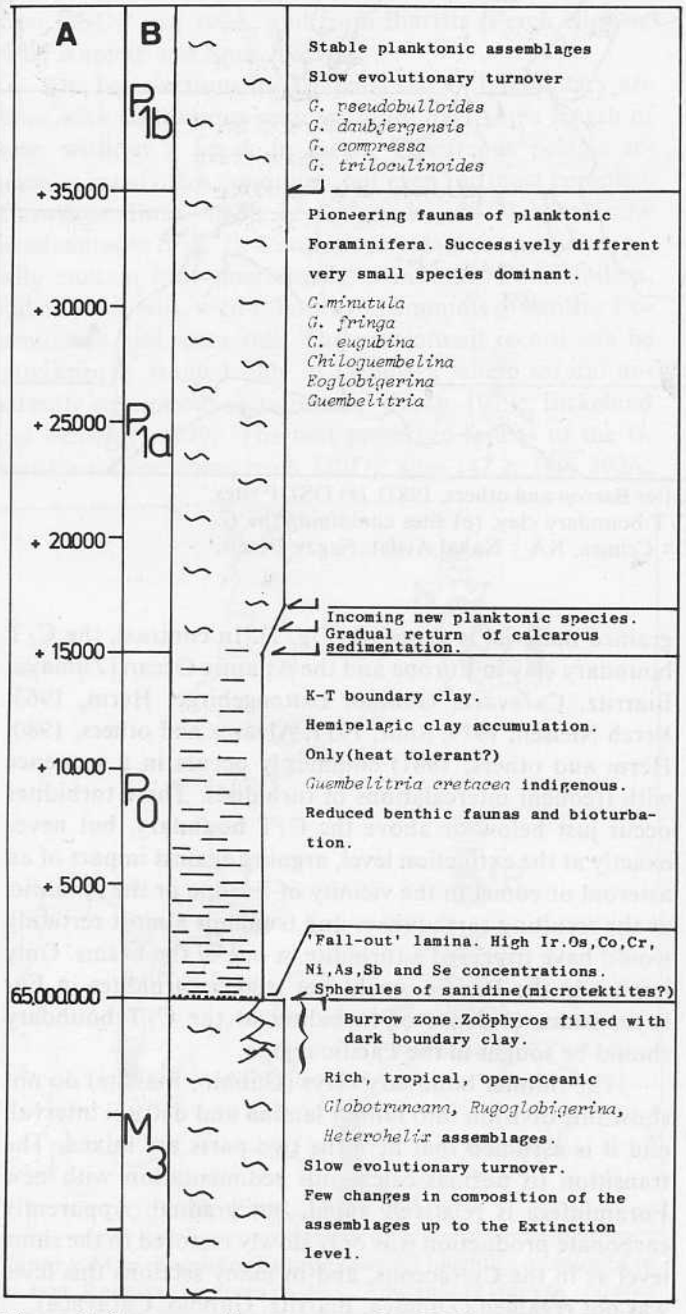

Figure 3. Sequence of events near the C/T boundary (K-T) in pelagic sediments. A = Time scale in years past C/T boundary; ← entries and ← exists of important planktonic species; B = biozonation.

Rates of Sediment Accumulation (Compacted)

Sedimentation rates were earlier estimated in the Gredero section (Smit, 1979) based on radiometric dating of biohorizons (Hinte, van, 1976; Hardenbol and Berggren, 1978). The sedimentation rates recalculated from the magnetic reversals (Fig. 6) differ only slightly from the previous values. These rates have been used to estimate the rate of extinction and diversification in the interval from the *Abathomphalus mayaroensis* (Bolli) Zone to the *Globorotalia uncinata* Bolli Zone. Based on the duration of the G- geomagnetic Zone, Kent (1977) estimated the duration of the C/T boundary event in the Gubbio section as less than 10 Kyr (thousand years) This G- Zone lasted about 470 Kyr and includes both the C/T boundary event and the time of deposition of all sediment in this G- Zone. At the highest observed rate, the time left for the C/T event is about 180 Kyr, but at the lowest rate only negative time is left for the event. However, a break in sedimentation occurs at the C/T boundary in both the Gubbio and Gredero sections, and the Paleocene part of the G- Zone probably was deposited at the low Paleocene rate. Then the time left for the C/T boundary event is about zero. A better resolution than about 30 Kyr may not be expected by this method. Still another approach is to use the hemipelagic clay supply as a constant factor. Using the lowest sedimentation rates, deposition of the C/T boundary clay required about 17 Kyr and the 40-cm-thick *G. eugubina* Zone about 15.9 Kyr. Probably the maximum time available for the extinction and renewed development of the planktonic Foraminifera is 32.9 Kyr.

In the 6.5 m.y. of the interval *A. mayaroensis* to *Gl. uncinata* Zone, about 17 new species appeared; 13 of these originated in the 32.9 Kyr of the *G. cretacea* and *G. eugubina* Zones. In other words, about 80% of the speciation takes place within 0.5% of the time.

BIOSTRATIGRAPHY OF THE GREDERO SECTION

The Gredero and El Kef sections allow a detailed biozonation of the lowermost Paleocene. Figure 7 shows the zonation proposed in this report in comparison with some well-known zonations. The P-lettered zonation of Blow and Berggren (Blow, 1979) is slightly modified in order to incorporate the basal part of the Paleocene. Range data are shown on Figure 8.

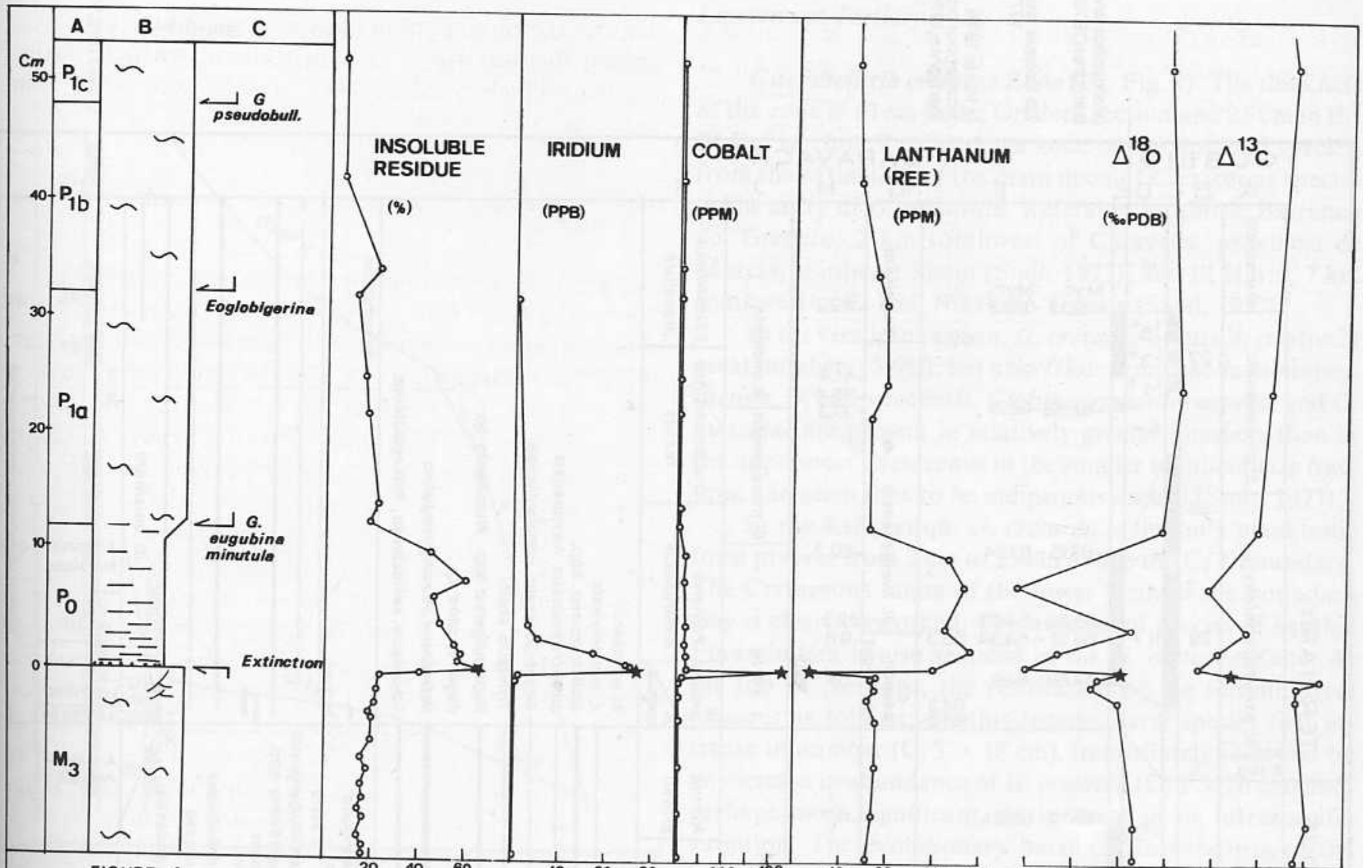

FIGURE 4

Figure 4. Distribution of insoluble residue, trace elements, and stable carbon and oxygen isotopes, in relation to lithology and planktonic foraminiferal events in the Gredero section, Caravaca, Spain. A = biozonation; B = lithology: – – clay or clayey marl, ~ ~ marls; C = planktonic foraminiferal events. Oxygen and carbon isotope data after Romein and Smit (1981a). Insoluble residue and Ir data after Smit and Hertogen (1980). Co and REE data after Smit and ten Kate (1982). Cr, Ni, Sb, As, and Se show a distribution similar to Co. Ce, Sm, Eu, Tb, and Yb show a curve similar to La. Fe, Sc, V, Zr, Al, Hf, and Th show a distribution similar to that of the insoluble residue.

Description of Zones

Uppermost Cretaceous

***Abathomphalus mayaroensis* Zone.** Range zone of the zonal marker. The upper boundary at the main extinction level of Cretaceous planktonic Foraminifera. Thickness in the Gredero section about 100 m. Important species ranging throughout the zone include: *Trinitella scotti* (Brönnimann, *Globotruncana contusa* (Cushman), *Racemiguembelina fructicosa* (Egger), *Guembelitria cretacea* (Cushman), *Globotruncanella monmouthensis* (Olsson), and *Globotruncanella havanensis* (Voorwijk).

A detailed description of the fauna has been given by Abtahi (1975) and Smit (1977). Nearly all species that are found in the Gredero section are known from deep water, tropical regions. Probable shallow-water species such as *Globotruncana falsocalcarata* Said and Kerdany have not been found. The variation in assemblages of different sampled levels is rather small; nearly all species persist up to the last millimeter of the Cretaceous (Smit, 1979). *Rugotruncana subpennyi* (Gandolfi) disappears about 60 m and *R. gansseri* (Bolli) 23 m below the C/T boundary. In all complete pelagic sequences (Smit and ten Kate, 1982) the *A. mayaroensis* Zone is the last planktonic foraminiferal zone of the Cretaceous. The suggested placement of the *G. eugubina* Zone in the top of the Cretaceous (Blow, 1979; Hofker, 1978) cannot be accepted; both authors based their observations on core 11 of DSDP site 47.2, which is highly disturbed according to my re-examination of Hofker's samples.

Recently, Perch Nielsen (1979) established the nannofossil *Micula prinsii* Perch Nielsen Zone, which is correlative to the top of the *A. mayaroensis* Zone (Romein and

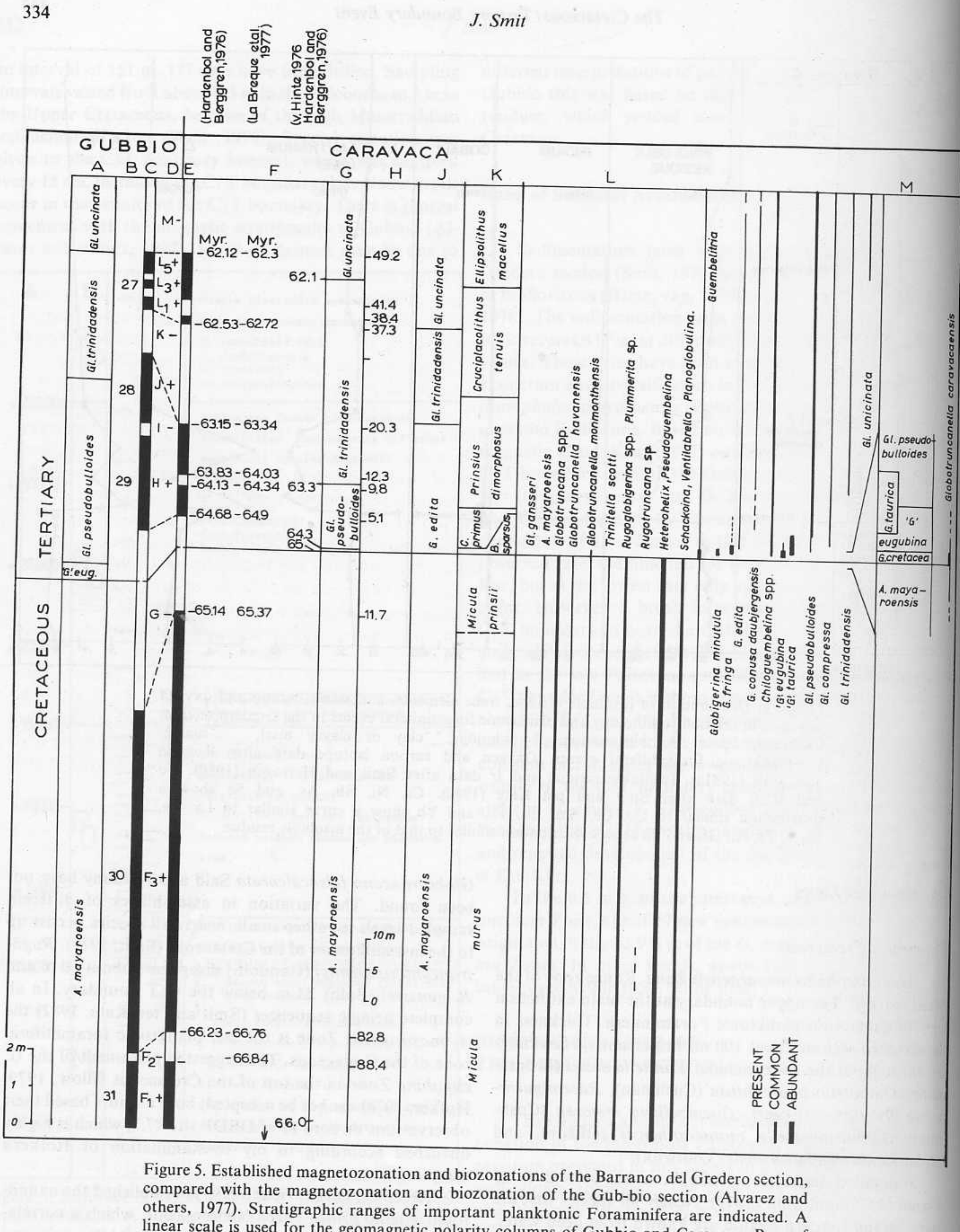

Figure 5. Established magnetozonation and biozonations of the Barranco del Gredero section, compared with the magnetozonation and biozonation of the Gub-bio section (Alvarez and others, 1977). Stratigraphic ranges of important planktonic Foraminifera are indicated. A linear scale is used for the geomagnetic polarity columns of Gubbio and Caravaca. Base of anomaly F^1 + and top of anomaly L^5 + are placed at the same level.

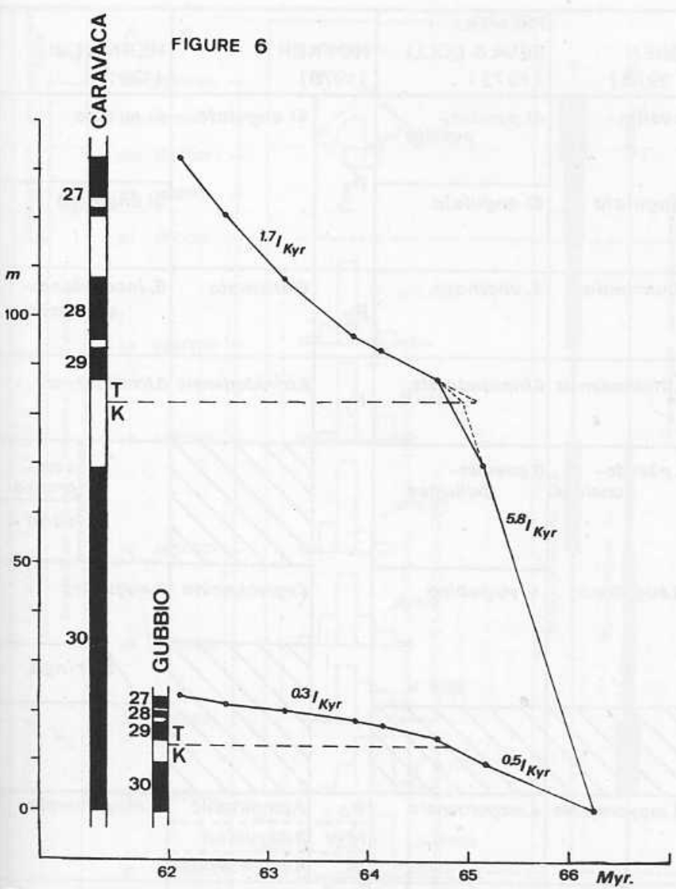

Figure 6. Sedimentation rates of the lower Paleocene and Upper Cretaceous of the Gubbio and Gredero sections in cm/Kyr, based on the numerical ages assigned to the seafloor geomagnetic reversals (LaBreque and others, 1977). Extrapolation of the lowermost Paleocene and uppermost Maastrichtian rates leaves a negative time for the C/T boundary event. Using the overall Paleocene rate (1.7 cm/Kyr) gives the best fit (dashes). Average clay content in the Upper Cretaceous in Caravaca is about 18.5%; in the *G. cretacea* Zone, 54%; and in the *G. eugubina* Zone, about 12.8%. The maximum duration of the 10-cm-thick *G. cretacea* Zone (assuming constant hemipelagic clay supply rate) is thus $54/18.5 \times 10/1.7 = 17.2$ Kyr, and of the *G. eugubina* Zone is $12.8/18.5 \times 40/1.7 = 15.9$ Kyr. Note the decrease in sedimentation rate from the Cretaceous to the Paleocene in both sections.

Smit 1981a, 1981b). Very large (1 to 1.3 mm) planktonic Foraminifera such as *Globotruncana contusa, G. stuarti* (De Lapparent), and *Racemiguembelina fructicosa* occur in the topmost 40 m of the *A. mayaroensis* Zone. Evidently the final Cretaceous planktonic fauna became extinct while in full development. Among the species present in the size fraction smaller than 0.125 mm, no species other than *G. cretacea* were identified which appear to be ancestral to the *G. minutula–G. fringa–G. eugubina,* or the *Globoconusa* lineage. As only *G. cretacea* survived the C/T boundary crisis, this species is suggested here to have been ancestral to all Tertiary globigerinids.

Lowermost Tertiary

***Guembelitria cretacea* Zone** (P_0, Fig. 7). The thickness of the zone is 10 cm in the Gredero section and 25 cm in the El Kef section. Partial range zone of the nominal species, from the extinction of the main mass of Cretaceous species to the entry of *G. minutula.* Reference localities: Barranco del Gredero, 2 km southwest of Caravaca, provincia de Murcia, southeast Spain (Smit, 1977), and El Haria, 7 km southwest of El Kef, Northern Tunisia (Salaj, 1977).

In the Gredero section, *G. cretacea* occurs in relatively great numbers (5.6%), but also *Globotruncanella monmouthensis, G. caravacaensis, Globigerinelloides aspera,* and *G. messinae* are present in relatively greater numbers than in the uppermost Cretaceous in the smaller sediment-size fraction, and seem thus to be indigenous as well (Smit, 1977).

In the Kef section, *G. cretacea* is the only planktonic form present from 3 cm to 25 cm above the C/T boundary. The Cretaceous fauna of the lower 3 cm of the boundary clay is clearly reworked. The number of species of benthic Foraminifera is also reduced in the *G. cretacea* Zone. At the top of the zone, the restoration of the foraminiferal fauna is as follows: Benthic foraminiferal species first increase in number (C/T + 18 cm), immediately followed by an increase in abundance of *G. cretacea* (C/T + 20 cm) and, perhaps more significant, an increase in its intraspecific variation. The evolutionary burst of *Guembelitria* at the top of the *G. cretacea* Zone is soon followed by (C/T + 25 cm) the first appearance of a true Paleocene species, *Globigerina minutula,* which then grades into *G. fringa.* The number of specimens remains relatively low at first, but with the entry of *G. eugubina* (C/T + 39 cm), the number of specimens per-gram-sediment and the planktonic/benthic ratio increase.

Whether the C/T boundary should be placed above or below the *G. cretacea* Zone was discussed by Smit and ten Kate (1982) who concluded that the boundary should be placed at the major extinction event at the base of the C/T boundary clay and not at the entry of the first true Tertiary species at the top of the C/T boundary clay. It is already common practice where no fauna is found in the clay to place the C/T boundary at the base of the clay (Alvarez and others, 1980).

***Globigerina eugubina* Zone** (P_{1a}, Fig. 7). Partial range zone, extending from the entry of *Globigerina minutula* Luterbacher and Premoli Silva to the entry of *G. pseudobulloides* Plummer. Thickness in the Gredero section 40 cm, in the Kef section 265 cm.

Important species: *G. eugubina, G. fringa, Guembelitria cretacea, Chiloguembelina* spp., and *Chiloguembelitria danica* Hofker. The type locality of the zone is in the Bottaccione gorge, near Gubbio, Italy (Luterbacher and Premoli Silva, 1964). The zone has been recognized worldwide, mainly from warm-water regions but also from higher lati-

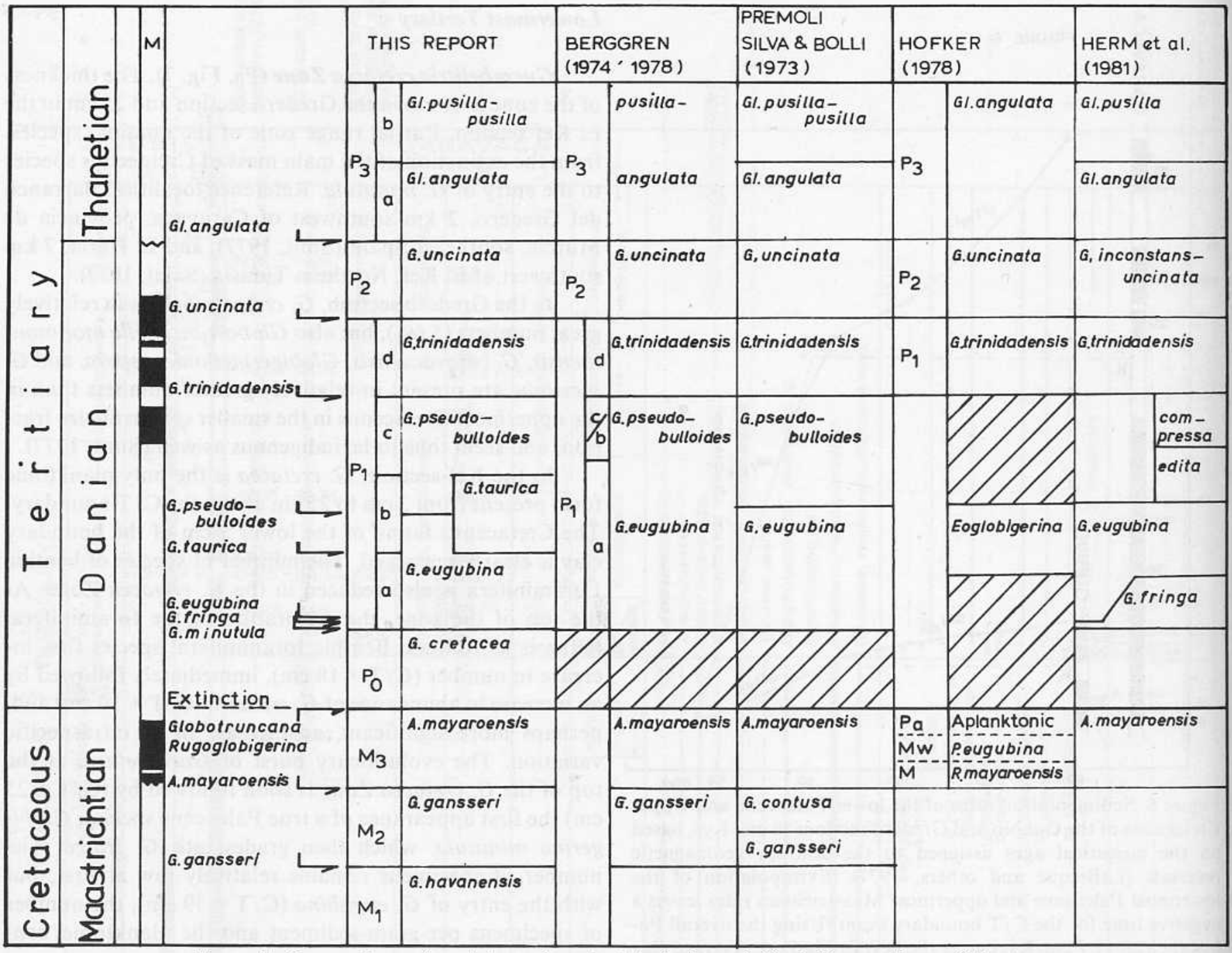

Figure 7. Comparison of certain earlier planktonic foraminiferal biozonations of the top Maastrichtian and lower Paleocene with that of this report. M = magnetic polarity patterns of the Gredero section (no vertical scale).

tudes (Denmark, Walvis ridge, DSDP site 524). The zone varies in thickness from a few centimeters in most sections (10 cm at the type locality at Gubbio) to 265 cm at Kef.

The zone was originally based on the occurrence of very small specimens in thin sections in the Gubbio section (Luterbacher and Premoli Silva, 1964). Many Cretaceous species are equally small and may be reworked into younger levels. Hence, Berggren (1965) suggested that the *G. eugubina* fauna might be reworked from Cretaceous strata. As the holotype of *G. eugubina* is badly preserved, Bang (1979a) and Hofker (1978) misidentified another species as *G. eugubina.* (Hofker described it as a new genus, *Parvularugoglobigerina).* Merely based on size, many other small Tertiary species are considered to belong to the *G. eugubina* group (Krasheninnikov and Hoskins, 1972; Premoli Silva and Bolli, 1973; Boersma, 1979). But actually these are somewhat younger though related forms (eoglobigerinids).

Eoglobigerina taurica Subzone (P_{1b}, Fig. 7). Partial range zone. Includes part of the range of the nominal species, from the entry of the *Eoglobigerina* spp. to the extinction of *G. eugubina.* Thickness: 125 cm in the Gredero section and 425 cm in the Kef section. This subzone comprises the main occurrence of the *Eoglobigerina taurica* fauna as defined by Morozova (1961), and is the same as the *E. taurica* Zone of Salaj (1977). The subzone overlaps the upper part of the *G. eugubina* Zone and the base of the *G. pseudobulloides* Zone. Characteristic species: Large *G. eugubina* (up to 0,23 mm), *Eoglobigerina hemisphaerica* (Morozova), *E. trifolia* (Morozova), *E. tetragona* (Morozova), *E. pentagona* (Morozova) (syn. *G. edita* Subbotina), *E. taurica* (syn. *Eoglobigerina danica* (Bang), and *E. eobul-*

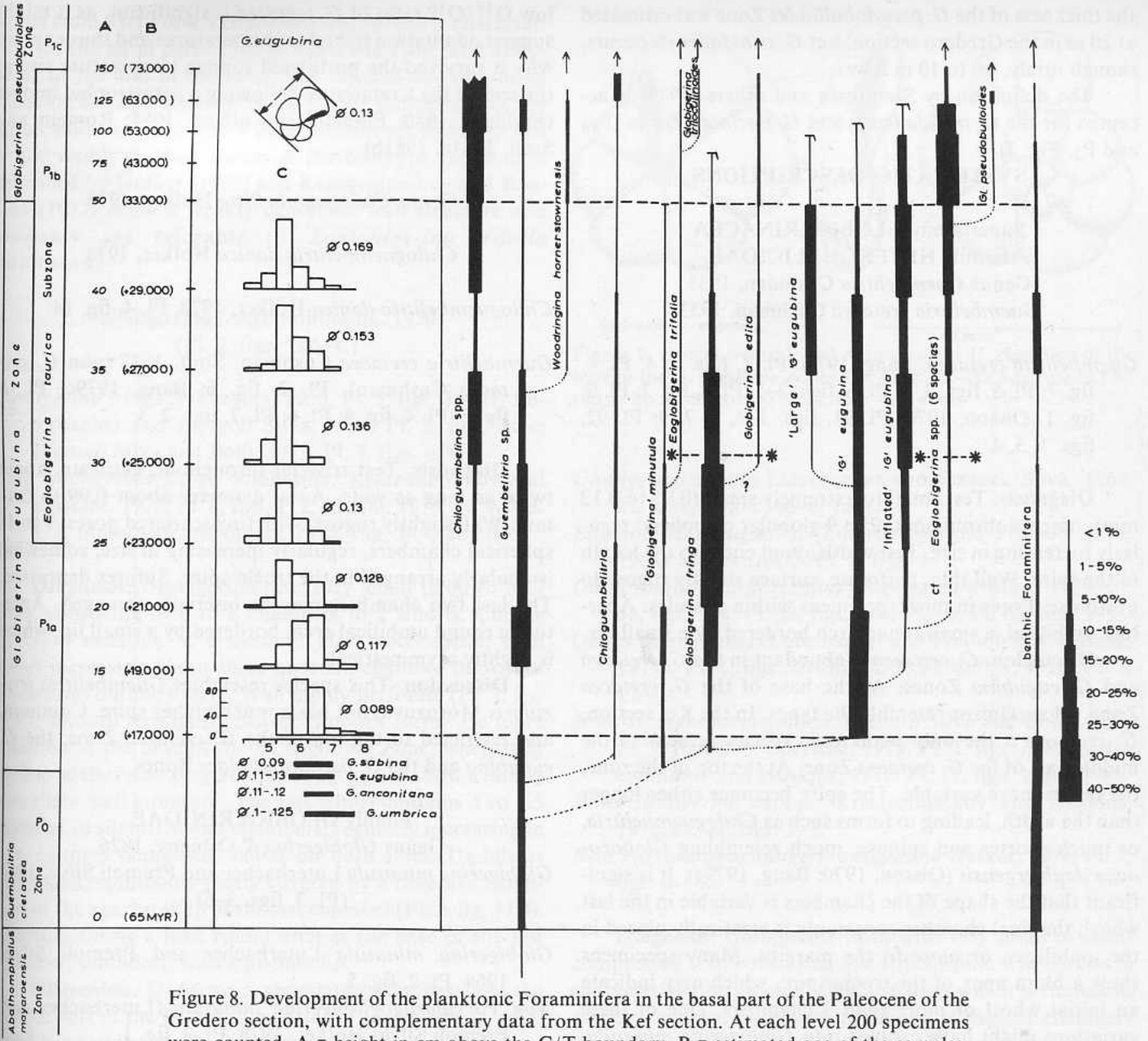

Figure 8. Development of the planktonic Foraminifera in the basal part of the Paleocene of the Gredero section, with complementary data from the Kef section. At each level 200 specimens were counted. A = height in cm above the C/T boundary. B = estimated age of the samples, the C/T boundary regarded as 0. C = size (ϕ) in mm and number of chambers in the last whorl of *G. eugubina. G. sabina, G. anconitana, G. umbrica,* and *G. eugubina* at the base of the column refer to the original types of these species, described by Luterbacher and Premoli Silva (1964) from the *G. eugubina* Zone. Bars give range in number of chambers in the last whorl of these types. Stainforth and others (1975) and Premoli Silva and Bolli (1973) merged these forms into the single species *G. eugubina.* Suggested lineages indicated by dotted lines. Vertical column has no scale.

loides (Morozova). All these species have a *Globigerina*-like appearance, but the cancellate wall structure is only weakly developed.

Globigerina pseudobulloides Zone (P_{1c}, Fig. 7). Partial range zone of the zonal marker, from the entry of *G. pseudobulloides* to the first appearance of *G. trinidadensis.* Thickness: 10.5 m in the Gredero section and about 50 m in the Kef section. *Chiloguembelina* spp. is dominant throughout the zone. *Globoconusa daubjergensis* (Brönnimann) appears about halfway through the zone, although rugose, small *Globoconusa*-like *Guembelitria* sp already occur in the upper part of the *G. cretacea* Zone. The upper boundary is difficult to locate accurately because *Globigerina pseudobulloides* grades almost imperceptibly into *G. trinidadensis* by an increase in size and number of chambers in the last whorl. Originally, (Hillebrandt, 1975; Smit, 1977) the thickness of the *G. pseudobulloides* Zone was estimated at 20 m in the Gredero section, but *G. trinidadensis* occurs, though rarely, up to 10 m lower.

The definition by Stainforth and others (1975) is accepted for the *G. trinidadensis* and *G. uncinata* Zones (P_{1d} and P_2, Fig. 7).

SYSTEMATIC DESCRIPTIONS

Superfamily GLOBIGERINACEA
Family HETEROHELICIDAE
Genus *Guembelitria* Cushman, 1933
Guembelitria cretacea Cushman, 1933

Guembelitria cretacea. Bang, 1979c Pl. 1, figs. 3, 4; Pl. 4, fig. 7; Pl. 5, figs. 3, 4; Pl. 6, figs. 2–5; Pl. 8, fig. 3; Pl. 9, fig. 1. Olsson, 1970, Pl. 91, figs. 1–4, 6, 7, 9; Pl. 92, figs. 1, 3, 4.

Diagnosis. Test small to extremely small (0.05 to 0.12 mm), triserial throughout; 7 to 9 globular chambers, regularly increasing in size. Test width about equal to the length of the spire. Wall thin, perforate, surface slightly rugose to pustolose. Pores in most specimens within pustules. Aperture umbilical, a small round arch bordered by a small lip.

Discussion. *G. cretacea* is abundant in the *G. cretacea* and *G. eugubina* Zones. At the base of the *G. cretacea* Zone, all specimens resemble the types. In the Kef section, *G. cretacea* is the only planktonic species present in the middle part of the *G. cretacea* Zone. At the top of the zone, the test is more variable. The spire becomes either longer than the width, leading to forms such as *Chiloguembelitria,* or much shorter and spinose, much resembling *Globoconusa daubjergensis* (Olsson, 1970; Bang, 1979c). It is significant that the shape of the chambers is variable in the last whorl; the final chamber commonly is erratically placed in the umbilicus, or more to the margins. Many specimens show a blunt apex of the trochospire, which may indicate an initial whorl of more than 3 chambers. One of these variations might have evolved into *Globigerina minutula,* the first true Tertiary planktonic species.

The "grainstone" of *G. cretacea* mentioned by Olsson (1970), lying upon the C/T boundary, may well represent this acme of *G. cretacea* at the base of the Paleocene. Bang (1979b) indicated that recent *G. cretacea*–like species (*Guembelitria vivans* Cushman) thrive in the Gulf of Persia in a habitat not favorable for "normal" stenothermal and stenohaline planktonic Foraminifera. Olsson (1970) concluded from the abnormal distribution of *G. cretacea* in planktonic assemblages that the species may even be in part benthic. According to stable isotope analyses (Boersma and others, 1979), oxygen and carbon isotope values of *G. cretacea* deviate from those of other planktonic species.

In view of these observations, seemingly *G. cretacea* is not characteristic of normal planktonic assemblages. The low O^{18}/O^{16} ratio of *G. cretacea* is significant, as it might suggest adaptation to higher temperatures and thus explain why it survived the postulated sudden temperature rise at the end of the Cretaceous, following a catastrophic impact (Emiliani, 1980; Emiliani and others, 1981; Romein and Smit, 1981a, 1981b)

Genus *Chiloguembelitria* Hofker, 1978

Chiloguembelitria danica Hofker, 1978

Chiloguembelitria danica Hofker, 1978, Pl. 4, fig. 14.

Guembelitria cretacea Cushman. Smit, 1977 (non *G. cretacea* Cushman), Pl. 2, fig. 6; Bang, 1979c; Pl. 1, fig. 5; Pl. 4, fig. 4; Pl. 6; Pl. 7, figs. 2, 3.

Diagnosis. Test triserial throughout, elongate, about twice as long as wide. Axial diameter about 0.09 to 0.14 mm. Wall slightly rugose, with tiny scattered pores; 9 to 10 spherical chambers, regularly increasing in size, somewhat irregularly arranged in the trochospire. Sutures depressed. The last two chambers may be biserially arranged. Aperture a round umbilical arch, bordered by a small lip, which is slightly asymmetrical.

Discussion. This species resembles *Guembelitria irregularis* Morozova, but has a much higher spire. Common, and restricted to the top of the *G. cretacea* Zone, the *G. eugubina* and the *G. pseudobulloides* Zones.

Family GLOBIGERINIDAE
Genus *Globigerina* d' Orbigny, 1826
Globigerina minutula Luterbacher and Premoli Silva, 1964
(Pl. 3, figs. 3–6)

Globigerina minutula Luterbacher and Premoli Silva, 1964, Pl. 2, fig. 5.

Non Parvularugoglobigerina minutula (Luterbacher and Premoli Silva) Hofker, 1978, Pl. 3, fig. 1.

Non Globigerina minutula. Krasheninnikov and Hoskins, 1972, Pl. 5, figs. 1–3.

Diagnosis. Trochospiral test, extremely small (0.06 to 0.08 mm); 6 to 11 globular chambers forming 2 to 3 whorls; those of the last whorl elongated. The initial whorl consists of 4.5 to 5 chambers, with later whorl(s) triserial. Wall very thin, surface smooth, probably minutely perforate (the Caravaca and Kef specimens do not show pores, due to recrystallization). Sutures slightly depressed and radial on both sides. Aperture umbilical, small and round, bordered by a thin lip.

Discussion. *G. minutula* is the first true Paleocene species to appear in the Kef section. It evolves into *G. fringa* simply by increasing the number of chambers in the last whorl from 3 to 4 or 4.5 chambers. The species is characteristic for the basal part of the *G. eugubina* Zone, and disappears at the end of the zone. The original description by Luterbacher and Premoli Silva (1964) indicates that the initial whorl contains more than 3 chambers, although this is not visible in their figure of the holotype. Specimens described by Hofker (1978) and Krasheninnikov and Hoskins (1972) show a weakly cancellate wall structure and probably are referable to *Eoglobigerina trifolia* (Morozova).

Globigerina fringa Subbotina, 1950
(Pl. 2, figs. 11A–C)

- *Globigerina fringa* Subbotina, 1950, Pl. 5, figs. 19–21; Luterbacher and Premoli Silva, 1964, Pl. 2, figs. 4a–c; Premoli Silva and Bolli, 1973, Pl. 7, figs. 6, 9.
- *Non Globigerina fringa* Subbotina. Krasheninnikov and Hoskins, 1972, Pl. 8, figs. 1, 2; Abtahi, 1975, Pl. 9, figs. 1, 2; Stainforth and others, 1975, Fig. 50, 3 and 6.

Diagnosis. Globigerine test, very small (0.08 to 0.12 mm), consisting of 6 to 8 chambers in 2 whorls. Coiling direction random, in a medium high trochospiral, each whorl increasing about three-quarters chamber thickness. Equatorial outline lobate. Wall highly perforate (Pl. 2, fig. 11A), smooth to slightly hispid. Smooth forms are more common at the base of the *G. eugubina* Zone, whereas at the top of the zone, they are more rugose and show a faintly cancellate wall structure. The last whorl contains 4 to 4.5 globular to slightly ovoid chambers, regularly increasing in size. Sutures depressed, radial on both sides. Umbilicus very small, commonly partly covered by a tube-like extension of the apertural lip of the last chamber (Pl. 2, fig. 11B). Aperture forms a low, round arch at the base of the last chamber, umbilical, with a distinct lip.

Discussion. *G. fringa* is abundant in the base and the middle part of the *G. eugubina* Zone. The younger *G. edita* Subbotina probably developed from *G. fringa,* as it is similar in shape but is about twice as large and shows a distinct cancellate wall.

Globigerina eugubina Luterbacher and Premoli Silva, 1964
Fig. 9–11; (Pl. 1, figs. 1–20; Pl. 2, figs. 1–8; Pl. 3, figs. 1, 2; Pt. 4, fig. 5)

- *Globigerina eugubina* Luterbacher and Premoli Silva, 1964, Pl. 1, figs. 8a–c. Cita and Premoli Silva, 1977, Pl. 6, figs. 5, 6. Smit, 1977, Pl. 1, figs. 1–7. Stainforth and others, 1975, Fig. 47, 1–6.
- *Globigerina umbrica* Luterbacher and Premoli Silva, 1964, Pl. 2, figs. 2a–c.
- *Globigerina anconitana* Luterbacher and Premoli Silva, 1964, Pl. 2, figs. 3a–c.

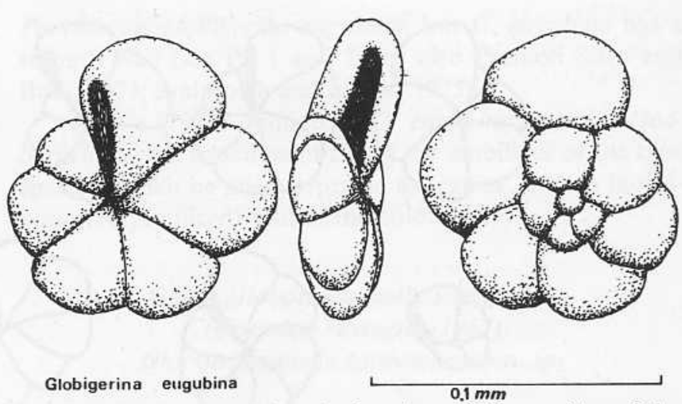

Figure 9. Dorsal, ventral, and edge views of *G. eugubina* of the base of the *G. eugubina* Zone. The long, slit-like aperture has no rim or lip. Coll. no. Sm75521. Bar = 0.1 mm.

- *Globigerina sabina* Luterbacher and Premoli Silva, 1964, Pl. 2, figs. 1a–c, 6a–c, 7a–c.
- *Eoglobigerina eugubina* (Luterbacher and Premoli Silva, 1964). Abtahi, 1975, Pl. 9, figs. 4–7.
- *Globorotalia (Turborotalia) longiapertura* Blow, 1979, Pl. 56, figs. 3, 4; Pl. 58, figs. 3–6; Pl. 63; Pl. 68, figs. 1–3.
- Genus *'L' eugubina* (Luterbacher and Premoli Silva). Bang, 1979c, Pl. 1, figs. 20–30; Pl. 2; Pl. 6, figs. 9, 10; Pl. 7, 17–19.
- *Non Globigerina eugubina.* Premoli Silva and Bolli, 1973, Pl. 7, figs. 2–5. Boersma, 1979, Pl. 1, figs. 6–8. Krasheninnikov and Hoskins, 1972, Pl. 11, figs. 1–3.
- *Non Globigerina sabina.* Krasheninnikov and Hoskins, 1972, Pl. 11, figs. 5–7.
- *Non Parvularugoglobigerina eugubina* Hofker, 1978, Pl. 1, figs. 6–10.

Diagnosis: Globigerine form with very small to small compressed test, coiled in a low trochospire. The species is characterized by an elongated aperture, which is rimless in early specimens, the closed umbilicus, triangular chamberform, leading to a "peeled tangerine" appearance on the umbilical side, and the smooth, thin chamber wall. The shape of the test is highly variable (Figs. 9, 10).

The last 1 to 4 chambers commonly extend toward the umbilicus, increasing the trochospirality (Pl. 1, figs. 5, 6). Chambers equatorially compressed, regularly increasing in size. The number of chambers ranges from 8 to 15 (mean 10), forming 2 to 2.5 whorls (Pl. 1, fig. 5). The last whorl consists of 4 to 9 chambers, usually 5 to 6 (Pl. 1 and Fig. 8 and 9 show the variation in chamber number in the last whorl, in the *G. eugubina* Zone of the Gredero section). Note the slight decrease in number of chambers in the last whorl with the increase in size at higher stratigraphic levels.

At the base of the *G. eugubina* Zone, the chamber form is typically triangular, but from the mid–*G. eugubina* Zone some specimens develop more globular chambers (Pl.

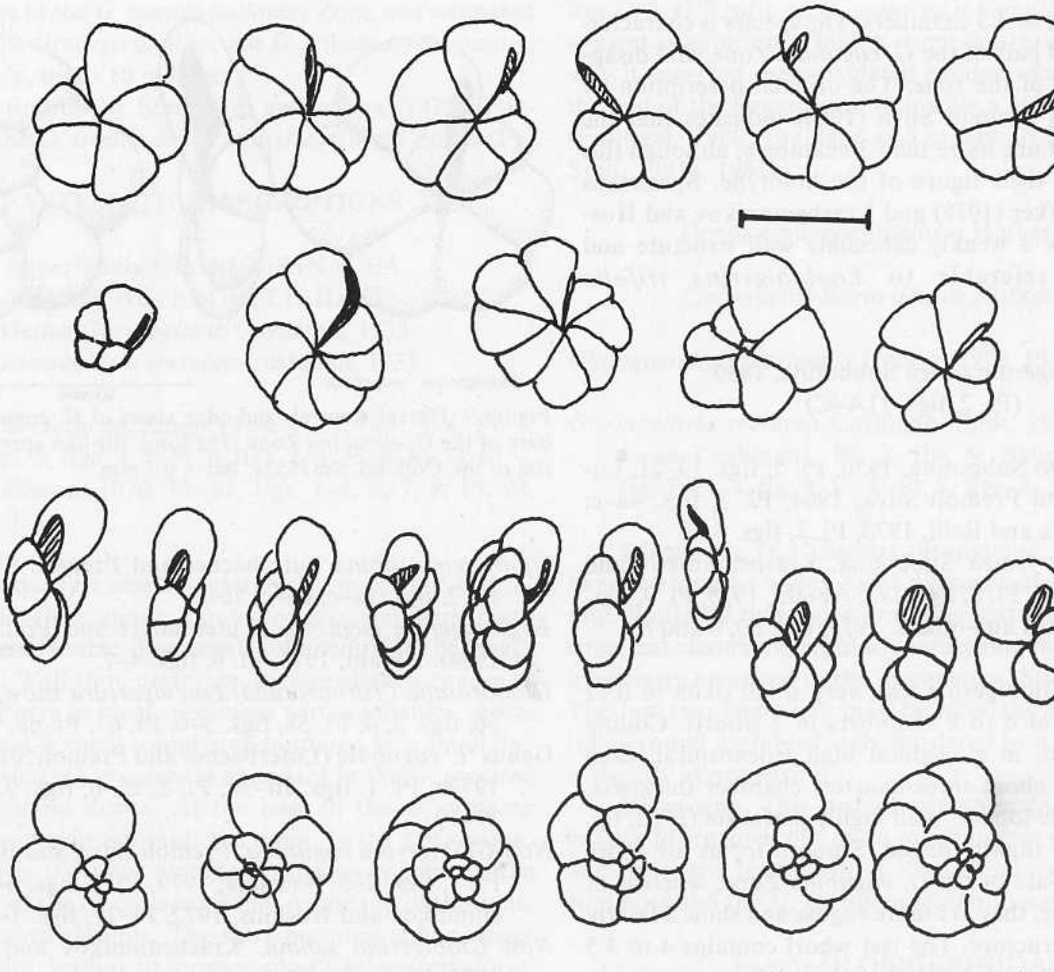

Figure 10. Specimens of *G. eugubina,* showing variation in suture form and aperture, and in form and number of chambers. Bar = 0.1 mm. A = ventral aspect, showing tight umbilicus and general aspect of common *G. eugubina,* with "peeled tangerine" look. B = ventral aspect, showing variation in number of chambers in the last whorl, and the form of the sutures. Less common forms, showing the extremes in variation. C = lateral view, showing the form of the aperture and last chamber, commonly protruding into the umbilicus. From left to right: increase in inflation of the chambers at progressively higher stratigraphic levels. D = spiral (dorsal) aspect, showing variability in curvature of the sutures and in the form of the chambers.

2, figs. 1–5, and Fig. 9) grading into forms like those of the *Eoglobigerina* group (Morozova, 1961), whereas others become more compressed (Pl. 2, figs. 7, 8), simultaneously increasing in size (0.23 mm). Wall very thin and smooth. Only some of the well-preserved specimens from DSDP site 390A, Blake plateau, and Biarritz have extremely small, scattered perforations (Pl. 3, figs. 1, 2), but it remains questionable if the wall is perforated at all. The rugose appearance of the type specimens is solely due to recrystallization.

In dorsal aspect, the first 6 chambers are equidimensional, the next 2 to 9 either are equidimensional (Pl. 1, figs. 1, 5) or become progressively elongated (Fig. 9 and Pl. 1, figs. 2–4). Consequently, the equatorial profile ranges from strongly lobate to rather smooth. Dorsal sutures slightly depressed, radial between equidimensional chambers, and strongly curved between elongated chambers. The ventral aspect is highly characteristic. It is reminiscent of a "peeled tangerine; regardless of the number of chambers in the last whorl, the umbilicus is closed, although the last chambers of younger specimens tend to have a more open umbilicus (Pl. 2, fig. 3). Sutures slightly depressed, radial in most specimens, to strongly curved (Fig 9 and Pl. 1).

The aperture is highly variable but, as pointed out by Abtahi (1975), Smit (1977), Bang (1979a, c), and Blow (1979), is a narrow, elongated interiomarginal-umbilical slit in most specimens (Figs. 9, 10, and Pl. 2, figs. 1–3, 5–8) that extends over the apertural face from the umbilicus nearly to the periphery. Specimens at the base of the *G. eugubina* Zone lack a lip or rim around the aperture (Pl. 1, figs. 6–12), whereas those from higher levels, with either com-

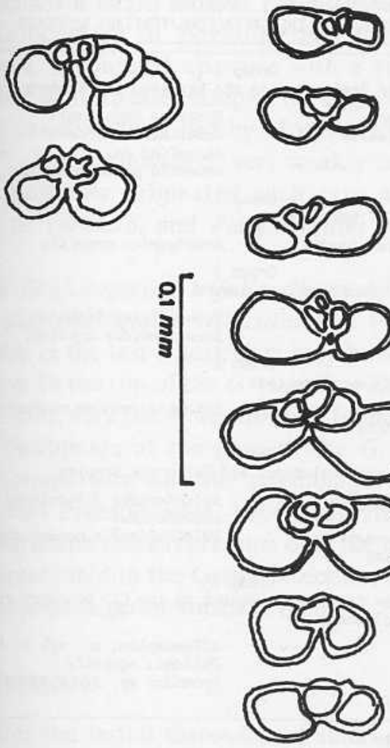

Figure 11. Line drawings of thin sections from the *G. eugubina* Zone of Gubbio (left) and Caravaca (right). Upper left: figure of Luterbacher and Premoli Silva (1964) showing the somewhat thicker wall and open umbilicus of a typical eoglobigerine form, indicating that the type *G. eugubina* Zone is equivalent to the *G. taurica* Zone (P_{1b}).

pressed or globular chambers, have a slender lip (Pl. 2, figs. 1, 3–5). The more globular chambered forms generally have a more rounded aperture (Fig. 9 and Pl. 2, fig. 4). The (mean) tests increase in size at higher stratigraphic levels (fig. 8) from 0.089 to 0.169 mm.

Discussion. Premoli Silva and Bolli (1973, Pl. 3, figs. 7, 8), Boersma (1979, Pl. 1, figs. 6–8), and Krashenninnikov and Hoskins (1972, Pl. 11, figs. 1–3) erroneously figured typical eoglobigerinids with weakly cancellate, well-perforated wall and rounded aperture with a distinct lip as belonging to the *G. eugubina* group. Hofker (1978) referred small rugose globigerinids from DSDP site 47.2, core 11, to *Parvularugoglobigerina eugubina,* but *G. eugubina* has a smooth wall (see Pl. 1 and 2; see also Premoli Silva and Bolli, 1973; Stainforth and others, 1975).

Blow's (1979) opinion of *G. eugubina* as small *Hedbergella* is due to sediment filling the umbilicus of the type species, which he misinterpreted as tegillae, and to the rugose (recrystallized) wall of the holotype.

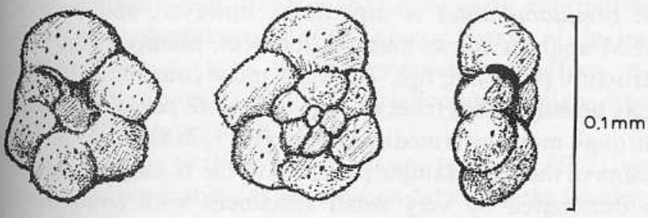

Figure 12. Holotype drawing of *Globotruncanella caravacaensis* nov. spec. Coll. no. M5803.

Genus *Globotruncanella Reiss, 1957*
(emended Pessagno, 1967)
Globotruncanella caravacaensis n. sp.

(Pl. 3, figs. 7, 9 and Fig. 12)

Derivation of name. From the town of Caravaca, southeast Spain.

Holotype:A sinistrally coiled specimen (Museum No. M5803) from sample Sm 509, from the base of the *G. eugubina* Zone, from the Barranco del Gredero, near Caravaca, southeast Spain (Fig. 12).

Paratypes. (Pl. 3, figs. 7A–C) from the Blake plateau, DSDP site 390A, core 11-5-145/146 cm, and sample Sm 509 (Museum No's. M5804-M5807). Types deposited at the Geological Institute, University of Amsterdam.

Diagnosis.A small species, tentatively placed in the genus *Globotruncanella,* on its imperforate peripheral bands and umbilical/extraumbilical primary aperture, although it possesses umbilical portici rather than tegilla. Test small (0.1 to 0.15 mm) with semiglobular chambers and imperforate pustulose peripheral band. Chambers compressed on dorsal side and spherical on ventral side.

Regular low trochospire, coiled in a random direction. Periphery lobate, 11 to 12 chambers in 2 whorls, regularly increasing in size; 5.5 to 6 chambers in the last whorl. Chamber form subspherical, angular at the periphery in lateral view. Wall perforate with imperforate marginal band on each chamber. Surface smooth, but with scattered pustules, especially on the imperforate margin. Wide umbilicus, portici visible in the umbilicus of well-preserved specimens (see Pl. 3, fig. 7C). Aperture a low round arch, umbilical/extraumbilical, with a distinct lip. Dorsal sutures depressed, curved; ventral sutures radial, straight. Stratigraphic distribution: very rare in the *A mayaroensis* Zone, rare in the G. cretacea Zone, reworked (though best preserved) in the *G. eugubina* Zone.

Discussion. The species differs from *Globotruncanella monmouthensis* (Olsson) which has spherical chambers, in the imperforate and angular *Globigerina uncinata*–like margin of the chambers. It differs from *Globotruncanella havanensis* (Voorwijk) which has chambers compressed on both dorsal and ventral sides.

The shape varies little, and the species is easy to recognize by its angular, asymmetrical margins.

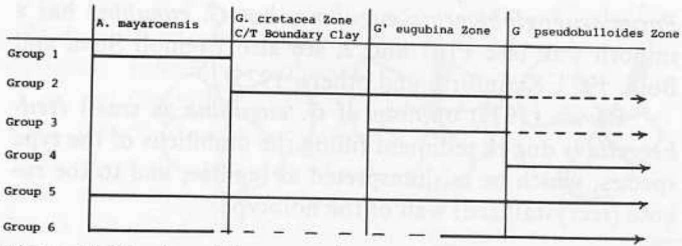

Figure 13. Stratigraphic range of groups of benthic Foraminifera in the C/T boundary interval of the Gredero section. Important species of these groups listed in Table 2.

SMALLER BENTHIC FORAMINIFERA

The benthic Foraminifera in the Gredero and Kef sections usually comprise a minor fraction (0.5% to 2.0%) of Upper Cretaceous and lower Paleocene assemblages. In the *G. cretacea* and *G. eugubina* Zones, benthic Foraminifera are relatively more abundant. (3% to 15%, see Fig. 8). B. J. Romein of the Geological Survey of the Netherlands has analyzed benthic foraminiferal assemblages from samples ranging from 1 m below to 17 m above the C/T boundary. He identified 228 species, of which 138 were found only once. The others are divided into six groups (Fig. 13 and Table 2). Although 34% of the benthic species do not become extinct at the C/T boundary, about 20% disappear temporarily in the Gredero section (group 6). In addition, all ornamented ostracods disappear, at least temporarily, at the C/T boundary.

TABLE 2. STRATIGRAPHICALLY IMPORTANT SPECIES OF BENTHIC FORAMINIFERA AROUND THE CRETACEOUS/TERTIARY BOUNDARY

Group 1	
Restricted to the Upper Cretaceous in the Barranco del Gredero	
Bolivinoides draco draco *Bolivinoides draco miliaris* *Bouvigerina cretacea* *Stensioina esnehensis*	*Eponides megastoma* *Gavelinella brotzeni* *Anomalina sp.* *Reusella pseudospinulosa*
Group 2	
Occurrence above the C/T boundary	
Angulogavelinella bettenstaedti	*Bouvigerina gracilis*
Group 3	
Occurrence from the *G. eugubina* Zone upward	
Ammobaculites texanus *Nodosarella subnodosa*	*Verneuillina limbata* *Loxostomoides applinae*
Group 4	
Occurrence above the *G. eugubina* Zone	
Krausella ouedermelensis *Spiroplectammina excolata*	*Spiroplectammina mexicaensis*
Group 5	
Occurrence throughout the Cretaceous and Paleocene samples	
Bolivina incrassata gigantea *Bolivina plaita* *Bolivinoides draco dorreeni* *Bolivinoides paleocenica*	*Bolivinoides delicatulus delicatulus* *Pulvinulinella navarroana*
Group 6	
Occurrence in the Upper Cretaceous, absent in the C/T boundary clay, and reappearance in the Paleocene	
Fissurina orbignyana *Marssonella oxycona* *Neoflabellina jarvisi* *Spiroplectammina rosula*	*Allomorphina sp. cf. A. bullata* *Pullenia coryelli* *Eponides sp. cf. E.bronnimanni*

Note: Determinations by B. J. Romein.

EVOLUTION OF THE EARLIEST TERTIARY GLOBIGERINDS

Figure 8 shows the possible development of the globigerinids as recorded in a closely sampled (every 5 cm) sequence through the *G. cretacea* and *G. eugubina* Zones in the Gredero section. As the lowermost sample of the *G. eugubina* Zone there already contains a diversified fauna, data are added from the Kef section, which seems to preserve an earlier phase in development. Within this sedimentary sequence of 90 cm (representing 20,000 yr.) appear successively *G. minutula* (C/T boundary + 25 cm), *G. fringa* (C/T boundary + 27 cm), *G. eugubina* (C/T boundary + 39 cm), and *G. taurica* (C/T boundary + 110 cm).

With the increase in abundance of *G. cretacea* at the top of the *G cretacea* Zone, this species also increases in variability. It is suggested here that a single ancestral species, *G. cretacea,* may have given rise to all Tertiary planktonic Foraminifera. Two main series may lead from *G. cretacea,* one to the *G. minutula–G. fringa/G. eugubina–Eoglobigerina* lineage, and a second from hispid variations of *G. cretacea* leads to other hispid mostly triserial taxa such as *Globoconusa* (see also Bang, 1979c; Olsson, 1970), *Woodringina, Chiloguembelitria,* and *Chiloguembelina.* The extremely small size of *G. cretacea* and related preservational problems make it difficult to recognize intermediate forms between *G. cretacea* and *G. minutula,* the "blunt" spired specimens in the top of the *G. cretacea* Zone being perhaps an exception. The apparent scarcity or even absence of pores in the wall of *G. eugubina* could provide another objection to the proposed lineage from *G. fringa* to *G. eugubina; G. fringa* is distinctly perforated (Pl. 2, fig. 11A). Part of the *Eoglobigerina* fauna (*E. trifolia, E. edita, E. quadrata,)* may be derived directly from *G. fringa,* and the *G. eugubina* group could represent a dead end in the lineage. As alternative to this lineage, Hofker (1978) suggested that the *G. eugubina* fauna (his *Eoglobigerina* fauna) arose from a (pelagic?) larval stage of a benthic species. Despite the presence of an indigenous fauna in the *G. cretacea* Zone in the Gredero section, no other small species from the top of the Cretaceous nor from the *G. cretacea* Zone could be identified as possibly ancestral to the globigerinids. *Globotruncanella monmouthensis* (Olsson) has been suggested (Berggren, 1962; Olsson, 1970) as the ancestral form of the Tertiary globigerinids. The resemblance to *G. pseudobulloides* is superficial, however, and detailed SEM analysis shows many differences, mainly in the wall structure (see Pl. 3, figs. 7A, 8). A more convincing lineage may be established from *G. eugubina* to *G. pseudobulloides* through many intermediate stages (Pl. 1, 2; and Fig. 8). The fauna in the basal sample (Sm 509) of the *G. eugubina* Zone is dominated by very small specimens with compressed chambers and elongated, rimless aperture. Specimens from the succeeding 10 cm are slightly larger and have more globular chambers. The next 10 cm show the development from *G.eugubina* to *Eoglobigerina,* with more globular chambers, a rounded aperture with a rim, and a faintly cancellate wall. In later samples the eoglobigerinids develop into all varieties described by Morozova (1961). From this "stock" of smooth-walled, very weakly cancellate globigerinids, probably originated such taxa as *G. pseudobulloides, G. varianta,* and *Planorotalites compressa* (Plummer).

As *Eoglobigerina trifolia, E. microcellulosa* (Morozova), and *Globigerina triloculinoides* Plummer have few chambers in the last whorl, they may have originated from *G. fringa.* In the top of the *G. eugubina* Zone, a "giant" (up to 0.23 mm), very flat *G. eugubina* is found (Pl. 2, figs. 7, 8), which disappears at the base of the *G. pseudobulloides* Zone. Comparison with the assemblages at Ceselli (Luterbacher and Premoli Silva, 1964) suggests that the type *G. eugubina* fauna there represents only the middle part of the zone represented in the Gredero section, and consequently contains eoglobigerine forms (Fig. 8).

DISCUSSION

After the initial discovery of siderophile elements in the C/T boundary clay (Alvarez and others, 1980; Smit and Hertogen, 1980; Kyte and others, 1980), the impact of a large cosmic body at the C/T boundary has at least been accepted as a very testable working hypothesis. The total amount of iridium, the Os^{184}/Os^{190} and Ir^{190}/Ir^{192} isotope ratios, and also the relatively nonfractionated mutual ratios of the noble metals in the C/T boundary clays (Ganapathy, 1980; Kyte and others, 1980) indicate that an increased influx of cosmic, solar-system material is much more likely than an increased terrestrial source. Simply assuming an impact does not solve the problem of how, in fact, the extinctions took place. Three major variants of impact-induced environmental stress have been proposed: Alvarez and others (1980) suggested suppression of sunlight by upthrown dust as the causal mechanism. A drop in temperature, however, would be one of the effects (Romein and Smit, 1981a). Hsü (1980) suggested poisoning as the main agent, but it is not clear how the groups that escaped evaded similar poisoning.

DeLaubenfels (1956), Urey (1973), and Emiliani (1980) suggested a temperature rise as the main killing agent. Emiliani and others (1981) gave some alternatives for transfer or generation of the kinetic energy of the impacting body into heat. Secondary greenhouse effects, especially after impact of a CO_2-rich comet, might also increase the temperature.

The timing of the events (Smit and ten Kate, 1982) (see Fig. 4) and our stable oxygen-isotope data from the Gredero and Biarritz sections (Romein and Smit, 1981a, 1981b) gave support to a catastrophic temperature rise after the impact. The negative δO^{18} excursion at Caravaca is recorded on top of the fallout lamina; some calcareous plankton must have been able to record the temperature rise after the impact. Extrapolating our (lower) sedimentation rates, the extinction of marine calcareous plankton took place within 1 mm of sediment, or in less than 50 years. The δO^{18} spike occurs within 1 cm of boundary clay, or in less than 500 years after the impact. The record in the Gredero and Kef sections shows that whatever was the causative agent, it did not have a very long-lasting effect. The classical development of a pioneering fauna occurred only a few thousand years after the extinctions, and no evidence suggests a long-lasting destruction of the environment. As suggested above, most speciation is believed to have taken place during the 34 Kyr of the *G. cretacea* and *G. eugubina* Zones. However, speciation did not immediately follow the extinction, as in a substantial part of the C/T boundary clay (representing 5,000 to 15,000 years) no new species appeared. According to Smit and ten Kat (1982), this strong speciation pulse may reflect the competitive repopulation of empty habitats left by the elimination of those animals and plants formerly occupying these niches. Lineages are thus able to speciate substantially and quickly after a catastrophic elimination event.

It seems that a similar pattern of extinction and renewal as at the C/T boundary may be also valid for other geologic periods; for instance, at the Cenomanian/Turonian boundary (Pessagno, 1967) and early Miocene for planktonic Foraminifera, and several times in the upper Cambrian for trilobites (Palmer, 1979). Whether also in these crises a catastrophic impact is involved is questionable, but possibly a general scenario arises which might shed light on the causes of macro-evolution: slow adaptation and evolution is usually the rule for planktonic Foraminifera and other taxa, but apparently the elimination of dominating species in certain habitats is essential for accelerated speciation of taxa, which under normal conditions would have been suppressed. With this in mind, it may be suggested that the "punctuations" in the evclution of life may all be tied to catastrophic changes in the environment, to external changes rather than to survival in a free competition for ecologic space.

ACKNOWLEDGMENTS

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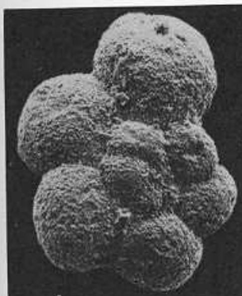
PLATE 1

Globigerina eugubina Luterbacher and Premoli Silva. Figures 1–5, 7–12, 15, and 17 from base of *G. eugubina* Zone, Gredero section. Figure 6 from middle part of the *G. eugubina* zone in the Gredero section. Figures 13, 14, 16, 18, and 19 from the top of the *G. eugubina* Zone (*G. taurica* subzone), Gredero section. Figure 20 from DSDP leg 44, site 390A, core 11. Figures 1–5, spiral views. Figures 6–20, ventral views, showing variation in number of chambers in the last whorl and generally rimless aperture. Note decrease in lobateness from left to right. Figures 4 and 5, stereo pair, showing increase in trochospirality in the latest chambers. Figures 13, 16, larger flat type, apertural rim present in figure 16. Figures 14, 15, 17 and 18, transitional forms from *G. eugubina* to *Eoglobigerina.* Figure 20, well-preserved specimen, showing tendency of umbilicus to open. All figures × 275.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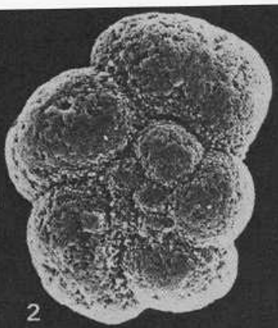
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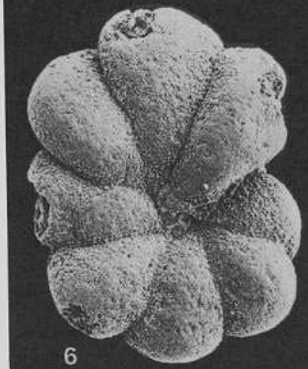
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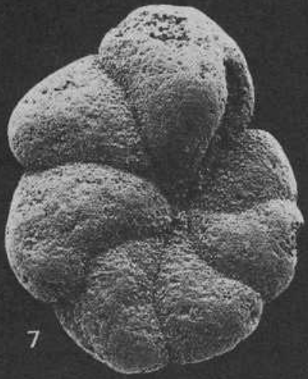
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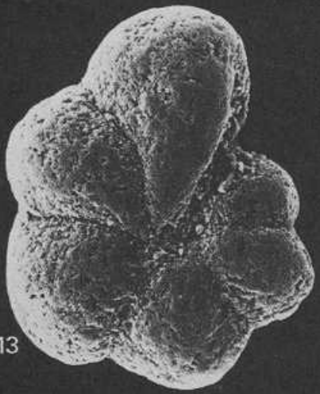
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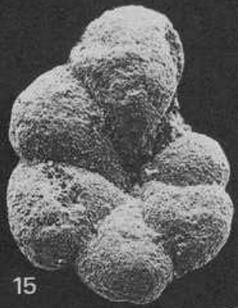
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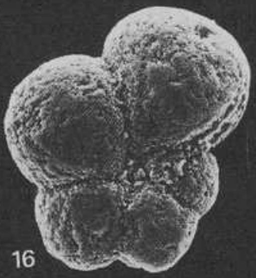
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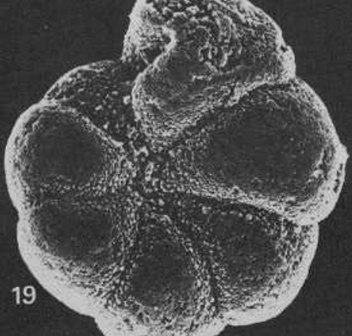
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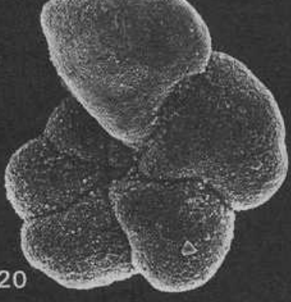
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PLATE 2

Figures 1–8, *Globigerina eugubina* Luterbacher and Premoli Silva edge views; 1–5, 7 and 8 X 285; figure 6 X 405. Figures 1, 3, 5, Blake plateau, DSDP leg 44, site 390A, core 11. Note long, rimmed aperture, smooth surface, and last chambers protruding into the umbilicus. Figure 2, Gredero section, middle part *G. eugubina* Zone. Figure 4, Gredero section, top *G. eugubina.* Figures 7 and 8, Gredero section, large, flat types from the top of the *G. eugubina* Zone. Figure 9, *Woodringina hornerstownensis* Olsson. DSDP leg 44, site 390A, core 11. X 200. Figure 10, *Chiloguembelitria danica* Hofker, lateral view. DSDP leg 44, site 390A, core 11, X 325. Figure 11, *Globigerina fringa* Subbotina. X 405. A = dorsal view, specimen in castor oil, in transmitted light, showing highly perforate wall. From base of *G. eugubina* Zone, Gredero section.

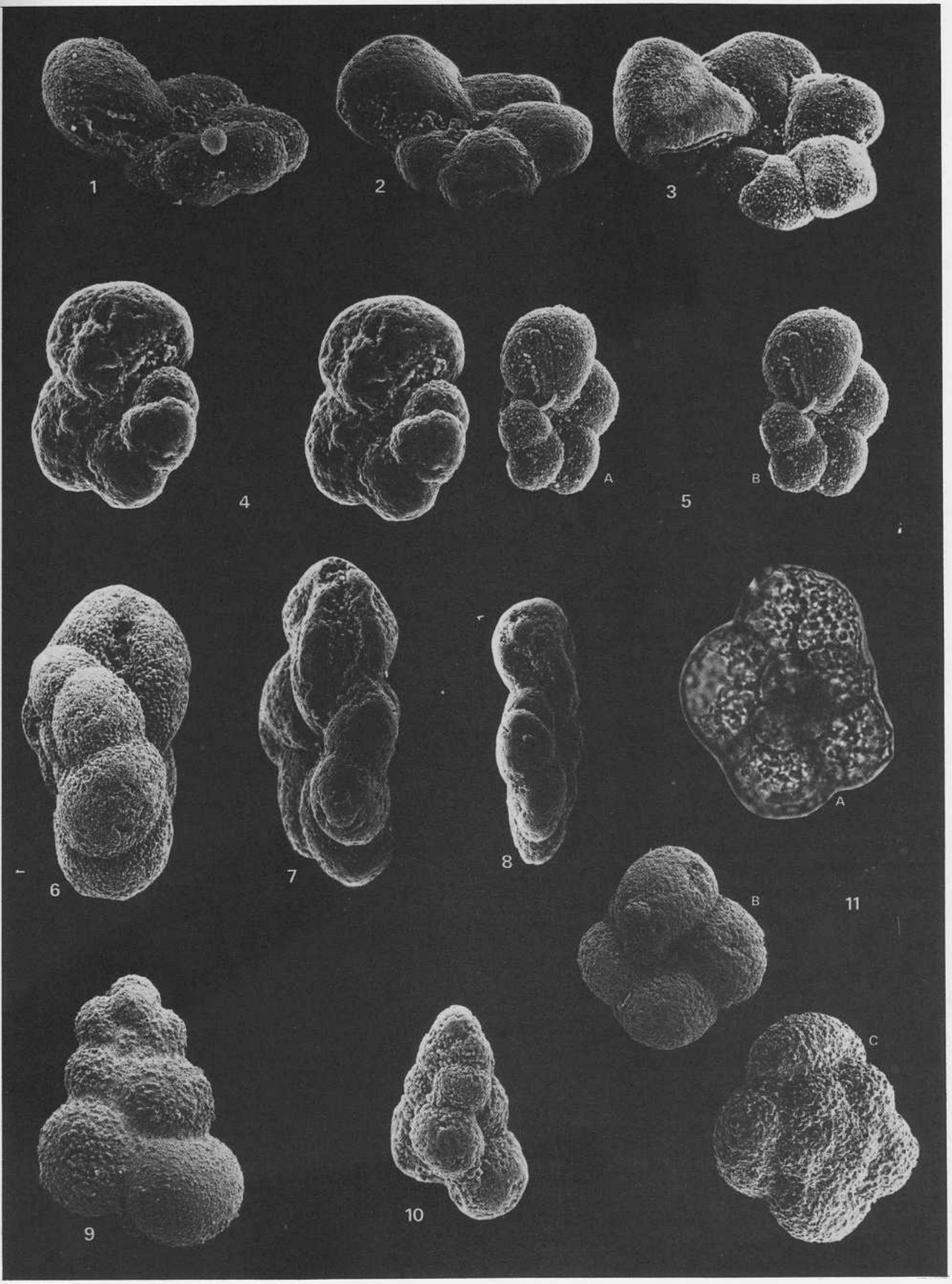
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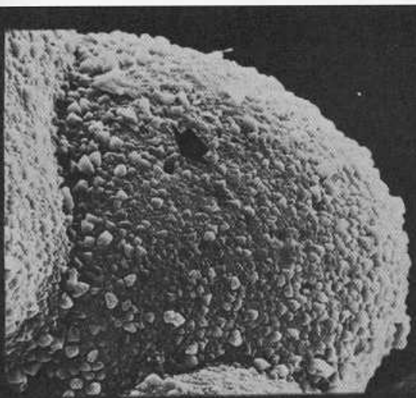
PLATE 3

Figures 1 and 2, *Globigerina eugubina* Luterbacher and Premoli Silva. Figure 2, broken chamber in transmitted light, showing scattered perforations. X 650; base *G. eugubina* Zone Biarritz. Figures 3–6, *Globigerina minutula* Luterbacher and Premoli Silva. X 700; Gredero section, base *G. eugubina* Zone. Figure 3, dorsal view, showing 5-chambered initial whorl. Figure 4, edge view. Figure 5, ventral view, showing small, umbilical aperture. Figure 6, oblique view, showing triserial final 2 whorls. Figures 7 and 9, *Globotruncanella caravacaensis* n. sp. Figure 7, paratype (Coll. no. Sm M 5804), DSDP leg 44, site 390A, core 11. Figures 7A and 7B, ventral and edge views, X 285. Figure 7C, detail of umbilicus, showing portici, X 650. Figure 9, paratype (Coll. no. M 5805), Gredero section, X 285. Figure 8, *Globirina trinidadensis,* X 150. Ventral view, Gredero section, base of *G. trinidadensis* Zone, showing the superficial resemblance of *Globotruncanella* with early globigerinids.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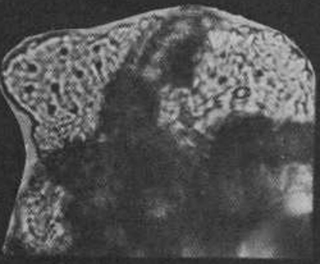
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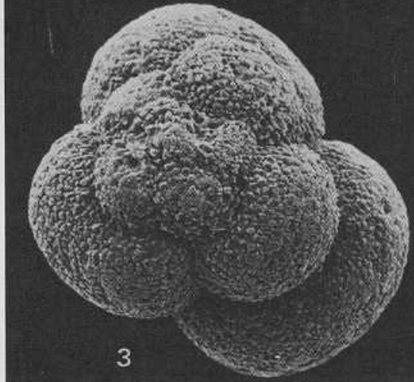
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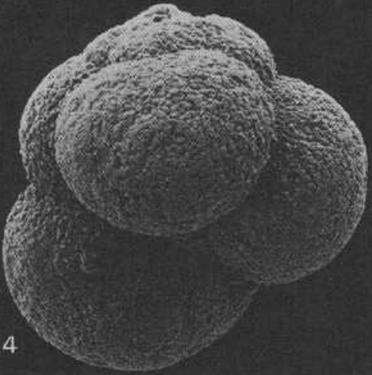
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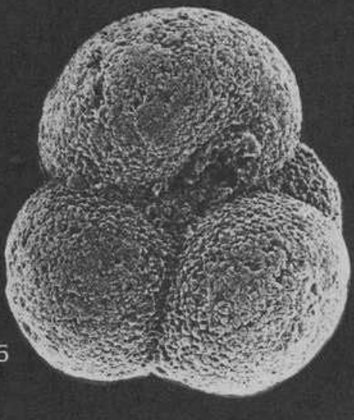
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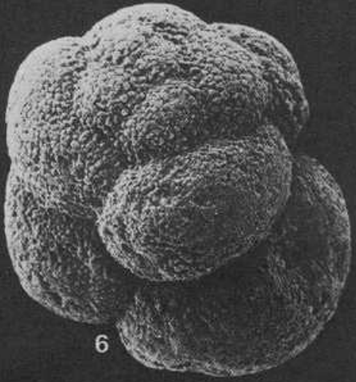
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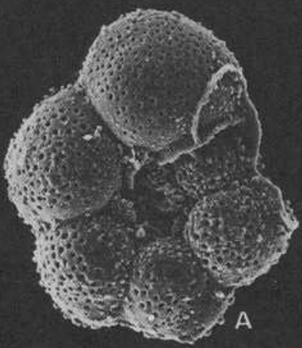
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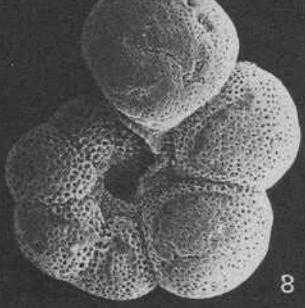
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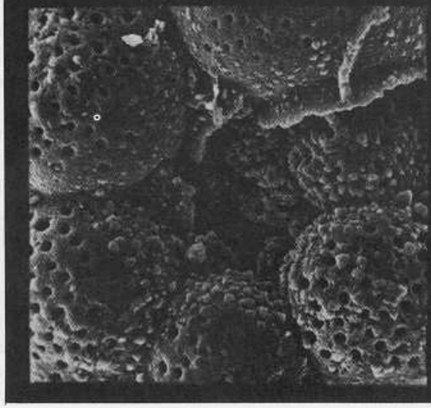
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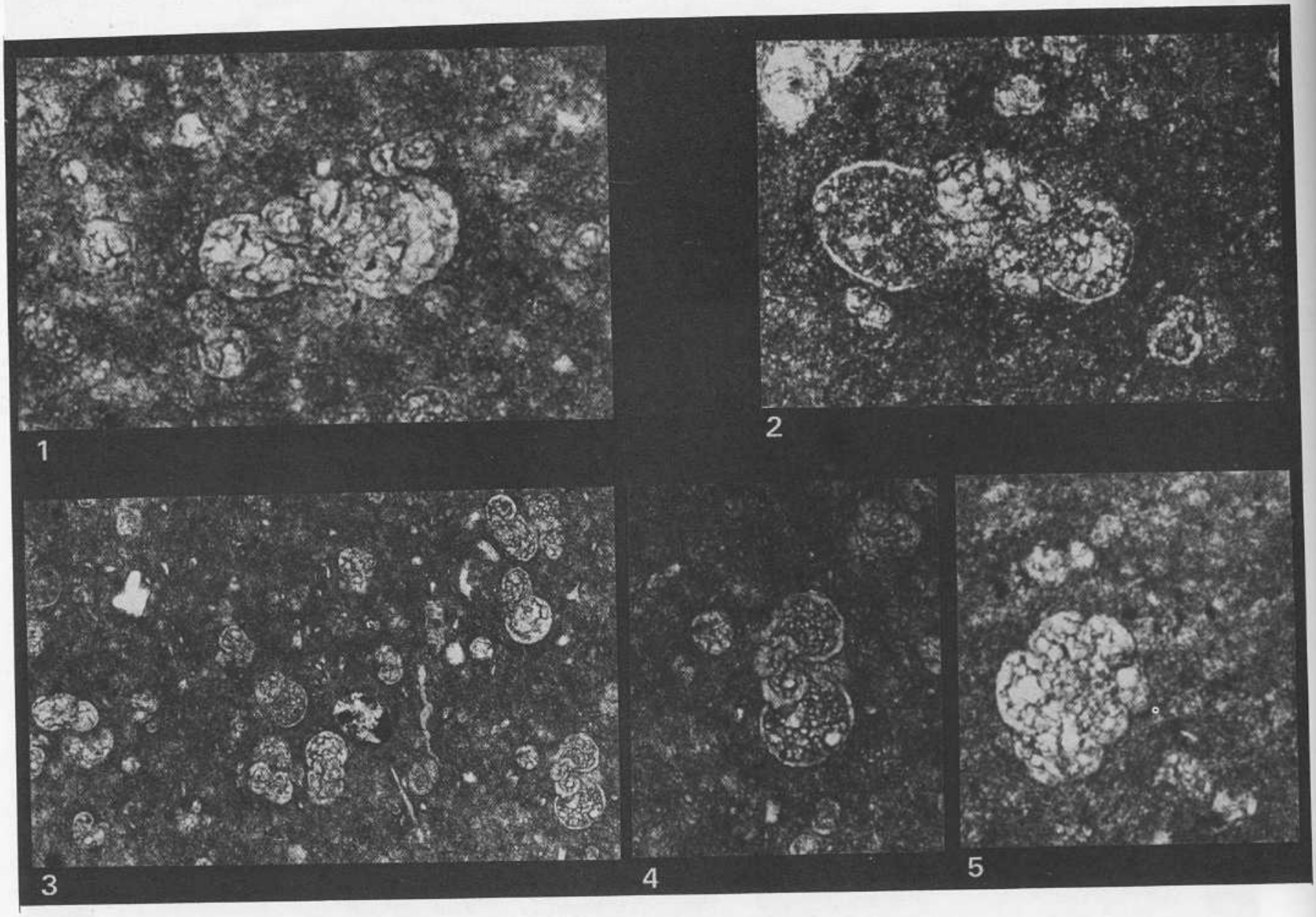

PLATE 4

Thin sections of the *G. eugubina* Zone. Figures 1, 2, 4, and 5 X 200; figure 3 X 100. Figures 1 and 2, Gubbio section, base *G. eugubina* Zone. Figures 3 and 4, Gredero section, upper part of the *G. eugubina* Zone. Figure 4 is a detail of figure 3, showing eoglobigerine type, with inflated chambers and narrow, open umbilicus. Figure 5, equatorial view of *G. eugubina,* Ceselli section, Italy (Luterbacher and Premoli Silva, 1964).

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