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Some patterns of planktic foraminiferal assemblage turnover at the Cretaceous–Tertiary boundary

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ABSTRACT

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Three uppermost Cretaceous through basal Paleocene stratigraphic sequences are examined for planktic foraminiferal assemblage stability and temporal succession patterns. These sequences are at mid-latitude South Atlantic DSDP Site 528, then-equatorial Pacific DSDP Site 577 and the Tethyan shelf Ben Gurion section of the Negev, Israel. In order to better estimate biogeographic patterns and habitat preferences, the results of these analyses are compared to previous Cretaceous biogeographic studies and to previous analyses of Cretaceous–Tertiary (K/T) boundary shelf and epicontinental sections.

Results indicate that immediately following the K/T boundary, the examined epicontinental and open-ocean sites were exploited primarily by previously epicontinental planktic foraminiferal assemblages. This pattern of K/T boundary assemblage dominance suggests the geologically instantaneous break-down of Late Cretaceous epicontinental and open-ocean biogeographic provincialization. This shift in open-ocean foraminiferal assemblages is not consistent with models of non-selective K/T boundary extinctions, but is consistent with models of extinction resistence and offshore expansion of near-shore taxa.

The re-establishment of stable biogeographic differences between open-ocean and epicontinental planktic foraminiferal assemblages occurs by the basal *Parvularugoglobigerina eugubina* Zone. At open-ocean sites 528 and 577 and the outer-shelf Ben Gurion section, P0 and *P. eugubina* Zone faunal records are marked by a pronounced alternation between Paleocene biserial- and non-biserial-dominated assemblages. This alternation appears strongly damped at shelf and epicontinental sections previously examined. The first appearance and peak magnitude of abundant earliest Paleocene trochospiral forms (*Parvularugoglobigerina, Eoglobigerina, Morozovella, Globoconusa*) also vary from site to site and may depend closely on levels of primary carbonate productivity.

Introduction

This report will examine species-level changes in the relative abundance of > 63 μm planktic foraminifera from three Upper Cretaceous through Lower Paleocene sequences: South Atlantic Deep Sea Drilling Project (DSDP) Site 528, then-equatorial Pacific DSDP Site 577 and the Ben Gurion section of the Negev, Israel (a Tethyan outer-shelf sequence) (Fig. 1). The purpose of this study is to develop a better understanding of latest Cretaceous through earliest Paleocene planktic foraminiferal assemblage stability, biogeographic provincialization and temporal patterns of faunal succession. In order to better determine these paleobiological parameters, the results of this study will be compared to the results of previous K/T boundary assemblage studies (Smit, 1977, 1982; Gerstel et al., 1986, 1987; Keller, 1988, 1989a) and mid and Late Cretaceous epicontinental and open-ocean

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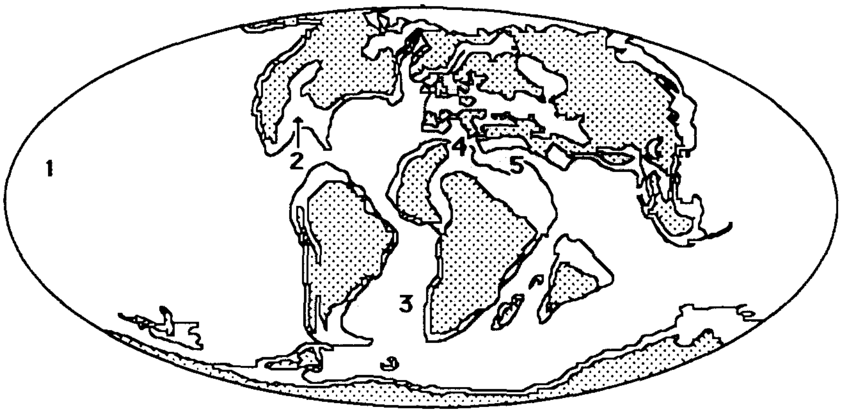


Fig. 1. Location map illustrating the approximate position of these sites at the K/T boundary. Oceans and shallow seas are unshaded; land areas are stippled. From left to right, the numbered localities are: (*1*) DSDP Site 577; (*2*) Brazos River, Texas; (*3*) DSDP Site 528; (*4*) El Kef, Tunisia; (*5*) Ben Gurion, Israel. Modified from a Maestrichtian stage paleogeographic reconstruction by Zeigler et al. (1983).

planktic foraminiferal studies (Pessagno, 1970; Douglas, 1971, 1972; Sliter, 1972a,b; Leckie, 1987).

Studies of K/T boundary foraminiferal turnover at open-ocean DSDP Site 577 (Gerstel et al., 1986, 1987), the Tethyan shelf El Kef sequence (Brinkhuis and Zachariasse, 1988; Keller, 1988) and the epicontinental Brazos River sections (Keller, 1989a,b) delineate local assemblage stability and faunal succession patterns. A comparison of similar studies from both open-ocean and epicontinental sites would greatly elucidate our understanding of habitat preferences and geographic variation in assemblage stability and succession across the Cretaceous–Tertiary boundary. Unfortunately, such a comparison cannot be done solely on the basis of previously published studies. Cretaceous foraminiferal dissolution at Site 577, the use of a coarser size fine fraction by Gerstel et al. (1986, 1987) than by Keller (1988, 1989a) and analysis at different taxonomic levels preclude direct comparison of the genera-level and assemblage-level open-ocean studies of Gerstel et al. (1986, 1987) with the species-level epicontinental and shelf studies of Keller (1988, 1989a,b) and Brinkhuis and Zachariasse (1988).

In addition to these differences, the taxonomic nomenclature applied to earliest Paleocene planktonic foraminifera varies considerably from one worker to another. Several workers (Luterbacher and Premoli Silva, 1964; Premoli Silva and Bolli, 1973; Premoli Silva, 1977; Smit, 1977, 1982; Gerstel et al., 1986, 1987; Brinkhuis and Zachariasse, 1988; Keller, 1988, 1989a) have applied different names to the same earliest Paleocene taxa and the same name to different taxa. These species include those discussed in this study as *Guembelitria trifolia* (*Guembelitria* (?) *trifolia* (Morozova) of Blow, 1979; *Guembelitria trifolia* of Keller, 1988, 1989a), *Parvularugoglobigerina morphotype* 1 (*Woodringina hornerstownensis* group of Premoli Silva and Bolli, 1973), *Parvularugoglobigerina morphotype* 2 (some *Parvularugoglobigerina fringa* of Brinkhuis and Zachariasse, 1988), *Parvularugoglobigerina morphotype* 3 (*Globorotalia* (*Turborotalia*)? cf. *pentagona* (Morozova) and *Globorotalia* (*Turborotalia*) cf. *tetragona* (Morozova) of Blow, 1979; *Parvularugoglobigerina edita* (Subbotina) of Brinkhuis and Zachariasse, 1988), *Parvularugoglobigerina longiapertura* (*Planorotalites longiapertura* of Blow, 1979; *Parvularugoglobigerina eugubina* (var.) of Smit, 1982 and Keller, 1988), *Globoconusa tripartita* [*Globoconusa tripartita* of Morozova, 1961; *Globastica* sp. type 1 of Blow (1979); *Globastica daubjergensis* (var.) of Keller, 1988], *Woodringina claytonensis* Loeblich and Tappan (*Woodringina hornerstownensis* Olsson of Smit, 1977, 1982 and of Keller, 1988, 1989a,b; *Chiloguembelina midwayensis* (Cushman) of Olsson, 1970) and *Woodringina hornerstownensis* Olsson (*Chiloguembelina taurica* Morozova of Hofker, 1978, Gerstel et al., 1987 and Keller, 1988, 1989a). The present study follows Brinkhuis and Zachariasse (1988) in extending the generic name *Parvularugoglobigerina* (Hofker, 1978) to all forms closely related to *Parvularugoglobigerina eugubina*. Morphotypes were included within *Parvularugoglobigerina* on the basis of apparent intergradation of species endmembers, faunal association and shared surface texture, apertural characteristics and chamber shape (Brinkhuis and Zachariasse, 1988). However, this study also differs from Brinkhuis and Zachariasse (1988) and Keller (1988, 1989a) in limiting the generic designation *Globoconusa* strictly to *daubjergensis* and *tripartita*.

Methods

Bulk sediment samples were soaked in a solution of 40 g sodium hexametaphosphate and 20 l distilled deionized water, lightly buffered with 58% ammonium hydroxide to equilibrate the pH to 7. Disaggregated samples were washed with tap water in 38 and 63 μm sieves and oven-dried overnight at temperatures less than 50°C. This process was repeated two to three times in order to fully disaggregate and clean the foraminiferal samples.

Population counts were based on representative splits of 300 or more specimens of the >63 μm foraminiferal population in each sample. The >63 μm size fraction was chosen as more representative of the sampled population than coarser fractions: most planktic foraminifera of the Cretaceous/Tertiary boundary interval are relatively small and many abundant species, including *Guembelitria* species, are commonly represented only by individual specimens <100 μm in diameter (Leckie, 1987; Keller, 1988). All specimens were identified and mounted on microslides for a permanent record.

Carbonate content was determined for all DSDP Site 528 and Ben Gurion samples using a CO_2 Coulometer titration system. Samples were finely crushed and dried at 50° Celsius prior to carbonate analysis. Approximately 20 mg of bulk sediment were used per analysis. At critical intervals, such as the boundary clay, duplicate analyses were run. Duplicate analyses indicate total analytic variability of approximately 1.0%. The DSDP Site 577 carbonate and coarse fraction records are from Zachos et al. (1985).

Sites of deposition, lithology and preservation

DSDP Site 528 is presently located on the Walvis Ridge at 28°31.49′S in the eastern South Atlantic. Using a fixed hotspot reference frame (Morgan, 1971), the paleolatitude of this open-ocean site was approximately 38°S in the latest Cretaceous and earliest Paleocene. According to the age–depth relationship of Parsons and Sclater (1977) modified by Sclater et al. (1985), water depth at this site was approximately 1850 ± 100 m at that time. The Upper Cretaceous Site 528 lithologic sequence is composed of cyclically alternating white foraminiferal nannofossil chalks and tan to red marls and chalks. At the Cretaceous–Tertiary boundary, white uppermost Cretaceous chalks are immediately overlain by a thin red clay layer, about 0.5 cm thick. In turn, this clay layer is overlain by Lower Paleocene red marls and reddish-tan foraminiferal nannofossil chalks (Moore et al., 1984). Foraminiferal preservation is variable at this site. Cretaceous foraminifera exhibit poor-to-moderate preservation and some Upper Cretaceous samples are noticeably enriched in solution-resistant foraminifera relative to solution-susceptible species.

Lower Paleocene samples are moderate-to-well preserved. Some test breakage and minor calcite overgrowth is observed, but the Lower Paleocene faunas do not appear to be seriously affected by dissolutional effects.

The Ben Gurion section is located immediately downslope of the Ben Gurion research station in the southern Negev, Israel. At the time of the K/T boundary event, this site was located in a Tethyan outer-shelf environment. The Ben Gurion Cretaceous–Tertiary boundary lies within the lower part of the Taqiye Formation approximately 1 meter above the Ghareb/Taqiye formational contact in the southern Negev. The sampled sequence is composed of white well-lithified Upper Cretaceous foraminiferal nannofossil chalks and tan poorly-lithified Upper Cretaceous and Lower Paleocene marls and chalks. Although a decrease in sedimentary carbonate percent occurs at the K/T boundary, there is no pronounced lithologic marker at that horizon. The lowermost Paleocene marly chalk sequence is marked by step-like decreases in carbonate content, culminating a dark horizon approximately 2 m above the K/T boundary and then stabilizing at a higher carbonate content above that clay level. Foraminiferal preservation is moderate at this site: some test recrystallization is observed, but the faunas do not appear to be affected by dissolutional effects.

DSDP Site 577 is presently located on the Shatsky Rise at 32°26.51′N in the western pacific ocean. Utilizing a fixed hotspot reference frame (Henderson and Gordon, 1981), the paleolatitude of this open-ocean site in the latest Cretaceous and earliest Paleocene was between 8 and 10°N in the central pacific. The lithologic sequence is composed of white Upper Cretaceous nannofossil chalks overlain by tan Lower Paleocene foraminiferal nannofossil chalks (Heath et al., 1985). Foraminiferal preservation is variable at this site. Cretaceous foraminifera exhibit extremely poor preservation: only the most solution-resistant foraminiferal species (Malmgren, 1987) are present. Poor Cretaceous foraminiferal preservation is consistent with the preferential dissolution of planktic foraminifera relative to nannofossils (Berger, 1970) and the lack of foraminifera-sized material ($\leq 1\%$ sediment ≥ 63 mm) in the DSDP Site 577 Upper Cretaceous sequence (Zachos et al., 1985). No improvement in the preservation of Cretaceous foraminifera is seen prior to the K/T boundary. Despite the poor preservation of Cretaceous taxa, well-preserved Lower Paleocene foraminifera are present within the uppermost Cretaceous and Lower Paleocene sequence of this site. Good Lower Paleocene foraminiferal preservation is consistent with the abundance of foraminifera-sized material (15% to 30% sediment ≥ 63 mm) in this Paleocene sequence (Zachos et al., 1985).

Bio-, magneto-, and chronostratigraphy

The Foraminiferal Zonal Scheme

Several planktic foraminiferal zonal schemes have been applied to uppermost Cretaceous and lowermost Paleocene sequences (Bolli, 1966; Berggren, 1969; Premoli Silva and Bolli, 1973; Smit, 1977, 1982; Toumarkine and Luterbacher, 1985; Berggren and Miller, 1988; Brinkhuis and Zachariasse, 1988; Keller, 1988) (Fig. 2). The zonation applied in this study incorporates elements of many of these previous schemes, but is identical to none of them in its entirety. This foraminiferal zonation incorporates the latest Cretaceous *Abathomphalus mayaroensis* total-range Zone (Bolli, 1966; Caron, 1985), the earliest Paleocene P0 (*Guembelitria cretacea* partial-range) Zone [of Smit (1977, 1982) as modified by Keller (1988)], the *Parvularugoglobigerina eugubina* interval Zone (Luterbacher and Premoli Silva, 1964) and the *Morozovella pseudobulloides* interval Zone (Bolli, 1966; Berggren, 1969) (Fig. 2).

For this study, the *A. mayaroensis* Zone is defined as the total range of the nominate

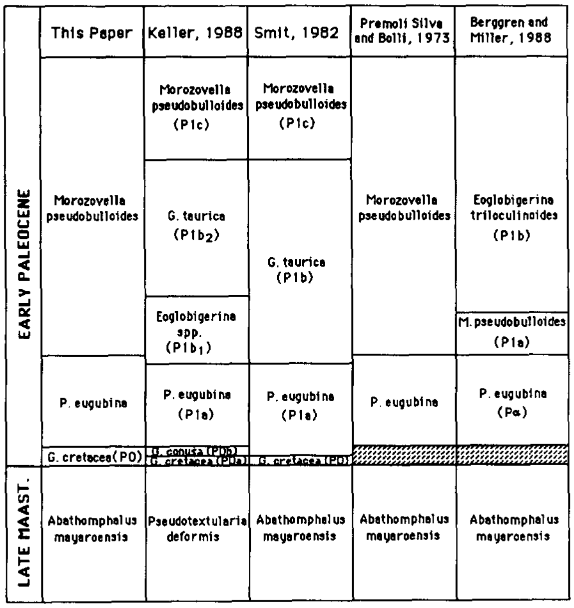


Fig. 2. Comparison of previous latest Cretaceous and earliest Paleocene planktic foraminiferal biozonations with that utilized in this study.

taxon. The P0 Zone is defined as the partial-range of *Guembelitria cretacea* following the extinction of *Globotruncana, Pseudotextularia* and *Racemiguembelina* and preceding the first appearance datum (FAD) of *P. eugubina*. The *P. eugubina* Zone is defined as the partial range of the nominate taxon, extending from the FAD of *P. eugubina* to the FAD of *Morozovella pseudobulloides*. The *M. pseudobulloides* Zone is defined as the partial range of the nominate taxa between the FAD of *M. pseudobulloides* and the FAD of *Morozovella trinidadensis*. These zonal definitions follow those of Premoli Silva and Bolli (1973) and Toumarkine and Luterbacher (1985) with one important exception: their zonal schemes do not include the P0 Zone originally defined by Smit (1977) (Fig. 2). The P0 Zone is included in the present study because it can be shown to be of global extent, having been found in Cretaceous–Tertiary boundary sections of Spain (Smit, 1977), Tunisia (Smit, 1982; Brinkhuis and Zachariasse, 1988; Keller, 1988), New Zealand (Strong et al., 1987) and Texas (Keller, 1989a). At all of these sections, the P0 Zone occurs immediately above the extinction horizon of heavily ornamented Upper Cretaceous forms and immediately underlying typical *P. eugubina* strata.

More precise earliest Paleocene foraminiferal zonations have been erected for some shelf and epicontinental sites (Smit, 1982; Keller, 1988) (Fig. 2). In a study of the Tunisian El Kef section, Smit (1982) defined the basal *P. eugubina* (P1a) Zone by the first appearance of *G. minutula* Luterbacher and Premoli Silva [*G. conusa* Khalikov of Keller (1988, 1989a)]. Additionally, he assigned the lowermost *M. pseudobulloides* Zone to a *Globigerina taurica* range (P1b) Subzone. In analyzing the El Kef section, Keller (1988) modified Smit's zonation (Fig. 2). Keller erected a *G. conusa* partial range (P0b) Subzone above the *G. cretacea* (P0a) Zone, defined at the base by the FAD of *G. conusa* and at the top by the FAD of *G. eugubina* Luterbacher and Premoli Silva [Keller's (1988, 1989a) concept of *G. eugubina* is *P. longiapertura* Blow in the present study]. Keller (1988) defined the base of the *G. eugubina* (P1a) Subzone as marked by the FAD of the nominate species and erected a *Eoglobigerina* species ($P1b_1$) Subzone at the base of Smit's *G. taurica* Subzone. Keller's $P1b_1$ Subzone is defined at the base by the main proliferation of *Eoglobigerina* species and at the top by the extinction of *G. eugubina*. The present study does not utilize these locally precise zonations of Smit (1982) and Keller (1988) because the nominate taxon *G. taurica* is not commonly present in the examined sections (DSDP Sites 528 and 577 and the Ben Gurion section) and the first proliferation of *Eoglobigerina* species is diachronous between these sections. Additionally, like the zonation of Smit (1982) and the Brazos River studies of Keller (1989a,b), the present study does not subdivide the P0 Zone. At the localities examined for this study, the P0 Zone is represented by only a few samples (0 samples at Site 577, 1 at Site 528 and 2 at the Ben Gurion section).

The Cretaceous nannofossil zonation utilized in this report is that of Perch-Nielsen (1979, 1983). The Paleocene nannofossil zonation is that of Martini (1971).

DSDP Site 528

Planktic foraminiferal species ranges of the Site 528 K/T boundary sequence are illustrated in Fig. 3. This section contains a complete foraminiferal zonal sequence across the K/T boundary, including the *A. mayaroensis* through *M. pseudobulloides* foraminiferal zones (Boersma, 1984) (Fig. 3). The P0 zonal interval is condensed at this site, consisting solely of the ~0.5 cm "boundary clay". The P0 Zone is followed by about 50 cm of *P. eugubina* Zone sediments overlain by almost 16 m of *M. pseudobulloides* Zone sediments (Fig. 3).

Site 528 also contains a complete nannofossil zonal sequence across the K/T boundary (Manivit, 1984; Bralower, personal communication), with uppermost Cretaceous *Micula prinsii* Zone sediments underlying NP1 Zone strata containing nannofloral assemblages dominated by *Thoracosphaera* species. The FAD of *Cruciplacolithus primus* appears 60 to 80 cm above the K/T boundary and the base

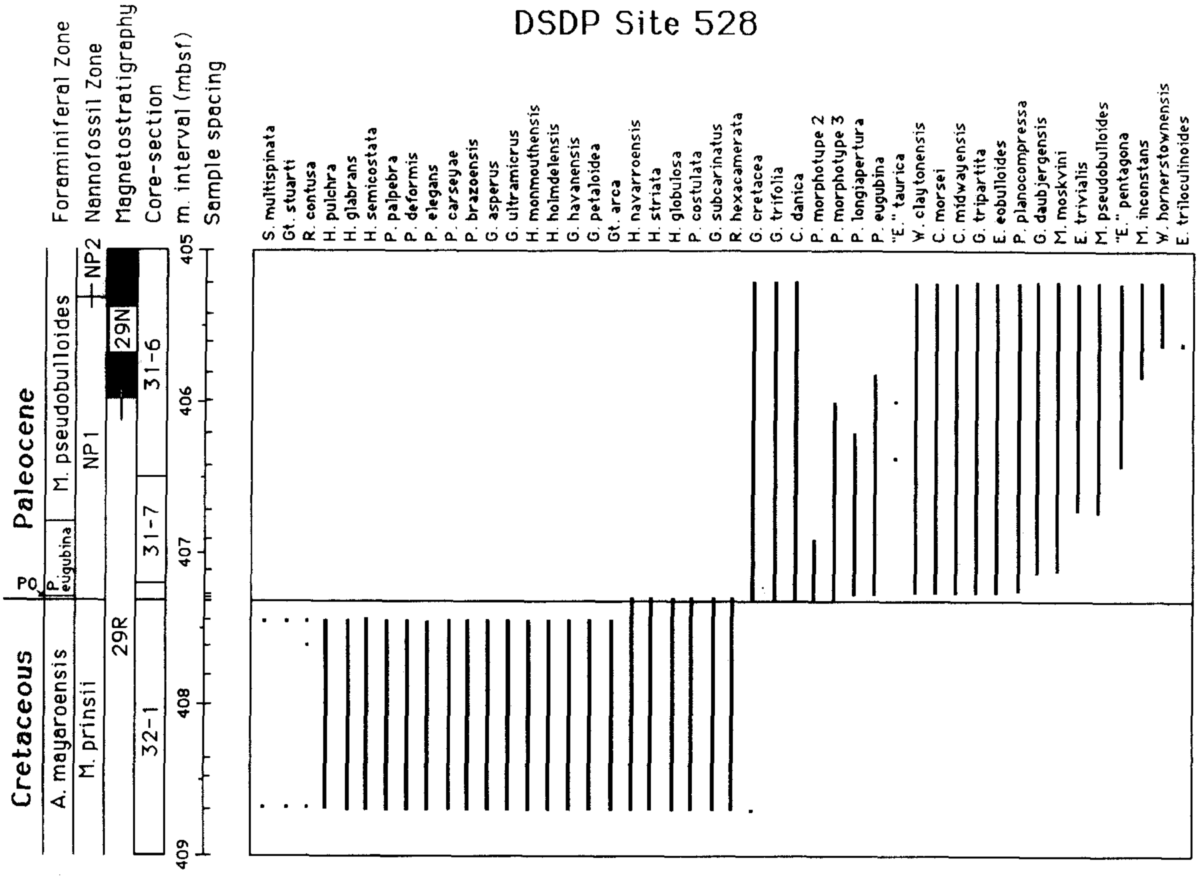


Fig. 3. Earliest Paleocene planktic foraminiferal stratigraphic ranges at DSDP Site 528. The Site 528 nannofossil and the paleomagnetic zonations are from Manivit (1984), Bralower (unpubl.) and Chave (1984). The planktic foraminiferal zonation is from this study. Core depth is in meters below seafloor (mbsf).

of the NP2 Zone (FAD *Cruciplacolithus tenuis*) occurs approximately 2 m above the K/T boundary (Bralower, personal communication). Foraminiferal and nannofossil assemblages show no occurrence of Paleocene fauna and flora prior to the P0 Zone and only floral survivors and rare Cretaceous fauna above the basal 2 cm of the *P. eugubina* interval (Bralower, personal communication) (Fig. 3).

A previous magnetostratigraphic study of this site indicates that the K/T boundary occurs within the 29R magnetochron (Chave, 1984). The FAD's of *M. pseudobulloides* and *C. primus* also occur within the 29R magnetostratigraphic intervals (Fig. 3). Chemostratigraphically, the P0 Zone sediments of this site are marked by a small iridium anomaly (Lindinger, 1988). Additionally, radical decreases in carbonate accumulation rate and the oceanic surface-to-deep $\delta^{13}C$ gradient occur between the last Cretaceous sample and the P0 Zone sample of this sequence (D'Hondt and Lindinger, 1988).

Ben Gurion Section

Planktic foraminiferal species ranges at the Ben Gurion K/T boundary section are illustrated in Fig. 4. On the basis of foraminiferal stratigraphy, the Ben Gurion boundary section also appears stratigraphically complete, containing the *A. mayaroensis* through *M. pseudobulloides* foraminiferal zones. The P0 zonal interval at this site is ~6 cm thick, followed by 25 to 30 cm of *P. eugubina* Zone sediments overlain by at least 2.5 m of *M. pseudobulloides* Zone sediments. Due to bioturbation and reworking of K/T boundary sediments at this and other Negev K/T boundary sections, individual specimens of some Paleocene taxa (*Parvularugoglobigerina morphotype 1, Parvularugoglobigerina morphotype 2, Woodringina claytonensis*) occur prior to the base of the P0 Zone (Fig. 4; Keller et al., in press). No heavily ornamented Cretaceous taxa appear above the basal P0 Zone of this section. Currently, there is no nannofossil stratigraphy or magnetostratigraphy available for the Ben Gurion sequence.

DSDP Site 577

Planktic foraminiferal species ranges of the Site 577 K/T boundary sequence are illustrated in Fig. 5. As previously discussed by Heath et al. (1985) and by Gerstel et al. (1986), *Parvularugoglobigerina eugubina* appears at this site more than a meter below the K/T boundary (LAD *Globotruncana*). *Woodringina* and *Chiloguembelina* spp., *Chiloguembelitria danica, Parvularugoglobigerina morphotype 1*, and *Parvularugoglobigerina morphotype 2* all appear prior to the K/T boundary as well (Heath et al., 1985) (Fig. 5, Plate I). The presence of a relatively diverse assemblage of well-preserved earliest Paleocene taxa in these heavily dissolved uppermost Cretaceous samples appears to result from core contamination or bioturbation. In part for this reason, no P0 Zone sediments are known at this site and the base of the *P. eugubina* Zone is defined by the last appearance of globotruncanid species, not by the first appearance of *P. eugubina.* Examination of K/T boundary sections from nearby DSDP Sites 47.2 and 577A reveal foraminiferal FAD patterns similar to those of DSDP Site 577 (D'Hondt, unpubl.).

At Site 577, as at Site 528, uppermost Cretaceous *Micula prinsii* Zone sediments are overlain by lowermost Paleocene strata containing nannofloral assemblages dominated by *Thoracosphaera* species (Monechi, 1985). The FAD of *Cruciplacolithus primus* occurs approximately 30 cm above the K/T boundary. The base of the NP2 Zone (FAD *Cruciplacolithus tenuis*) occurs between 95 and 125 cm above the K/T boundary (Monechi, 1985).

The magnetostratigraphy of this site indicates that the K/T boundary occurs within the 29R magnetochron (Bleil, 1985). As at Site 528, the FAD's of *M. pseudobulloides* and *C. primus* occur within the 29R magnetostra-

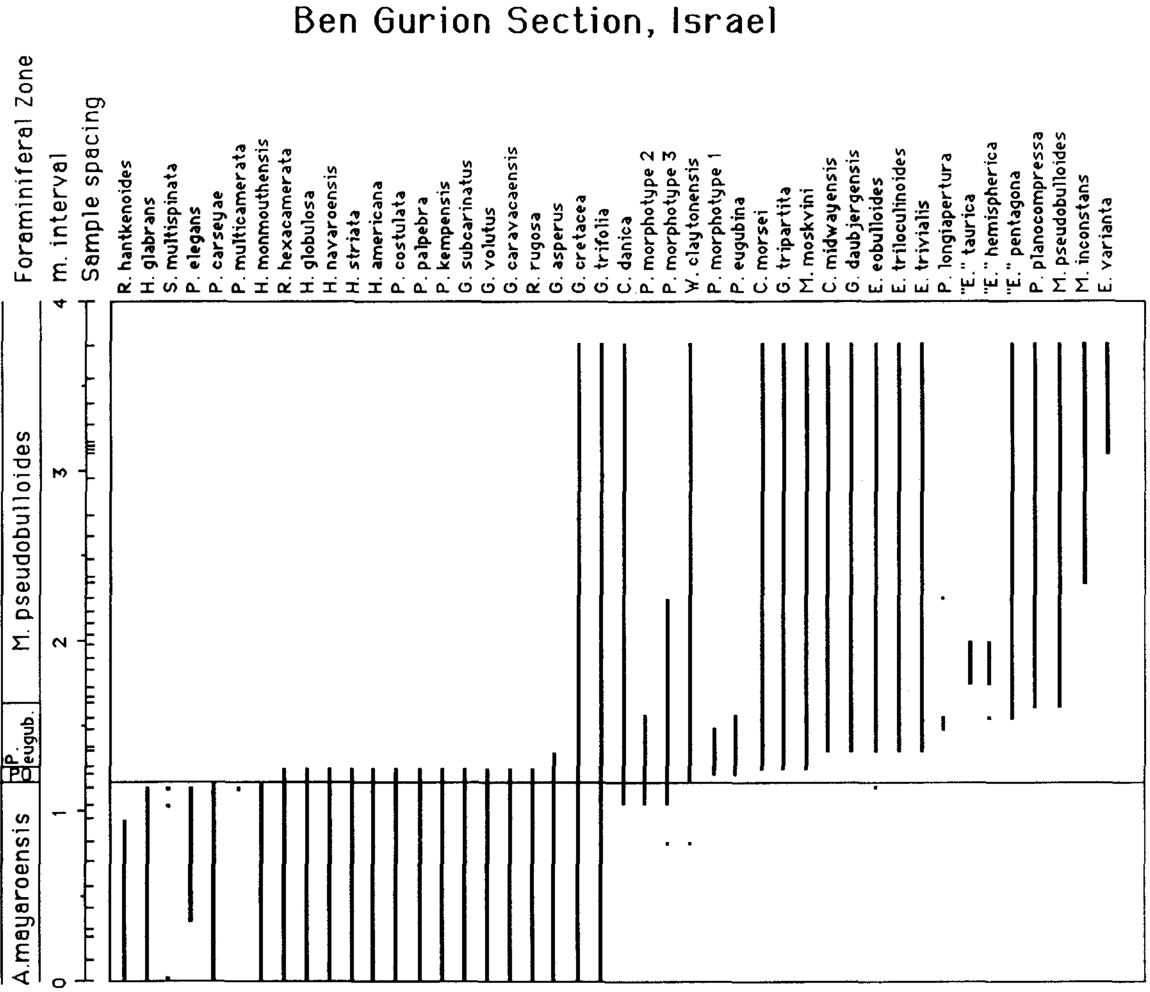


Fig. 4. Earliest Paleocene planktic foraminiferal stratigraphic ranges at the Ben Gurion section, the Negev, Israel. Note presence of rare Paleocene species in Upper Cretaceous sediment probably due to reworking.

tigraphic interval (Monechi, 1985; Gerstel et al., 1987) (Fig. 5). Chemostratigraphically, the neighboring Hole 577B contains several small irridium anomalies with a broad peak centered on the K/T boundary (Michel et al., 1985). Additionally, large decreases in carbonate accumulation and the surface-to-deep $\delta^{13}C$ gradient occur at the K/T boundary in the Site 577 sequence (Zachos et al., 1989).

The Chronostratigraphic Framework

Several previous studies indicate that the K/T boundary occurs within the 29R magnetochron (i.e. Alvarez et al., 1977; Premoli Silva, 1977; Chave, 1984; Berggren et al., 1985a,b; Bleil, 1985; Monechi and Thierstein, 1985; Keller, 1989a, Wei and Wise, 1989). Berggren et al. (1985a) estimated the duration of the 29R magnetochron as 570 ky, with 340 ky preceding the K/T boundary and 230 ky following the K/T boundary. The accuracy of these estimates has been recently confirmed by Herbert and D'Hondt (1990) through the application of Milankovich-band (~21 ky) cyclostratigraphy to South Atlantic K/T boundary sections. However, the FAD's of *M. pseudobulloides* and *C. primus* within the

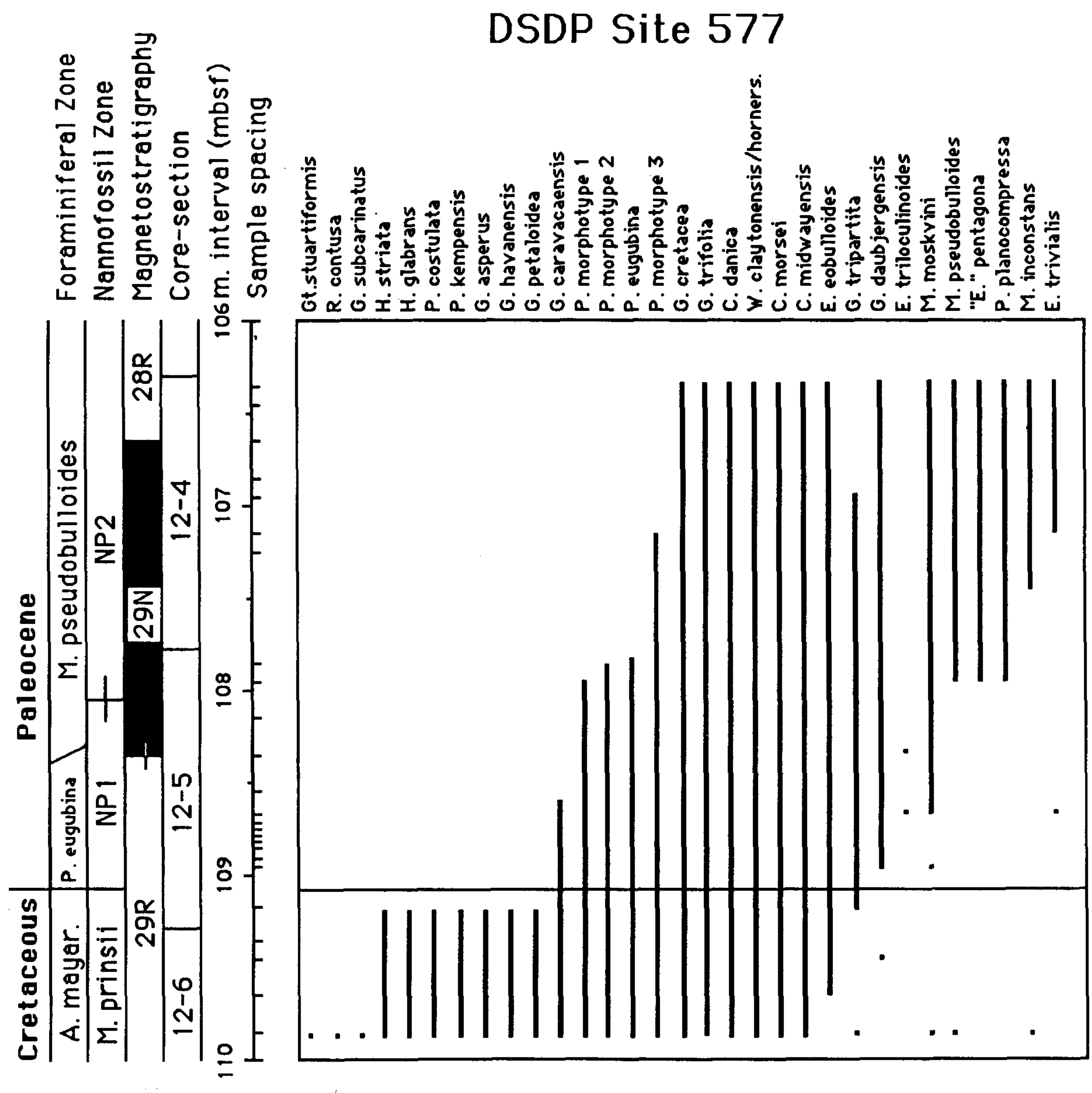
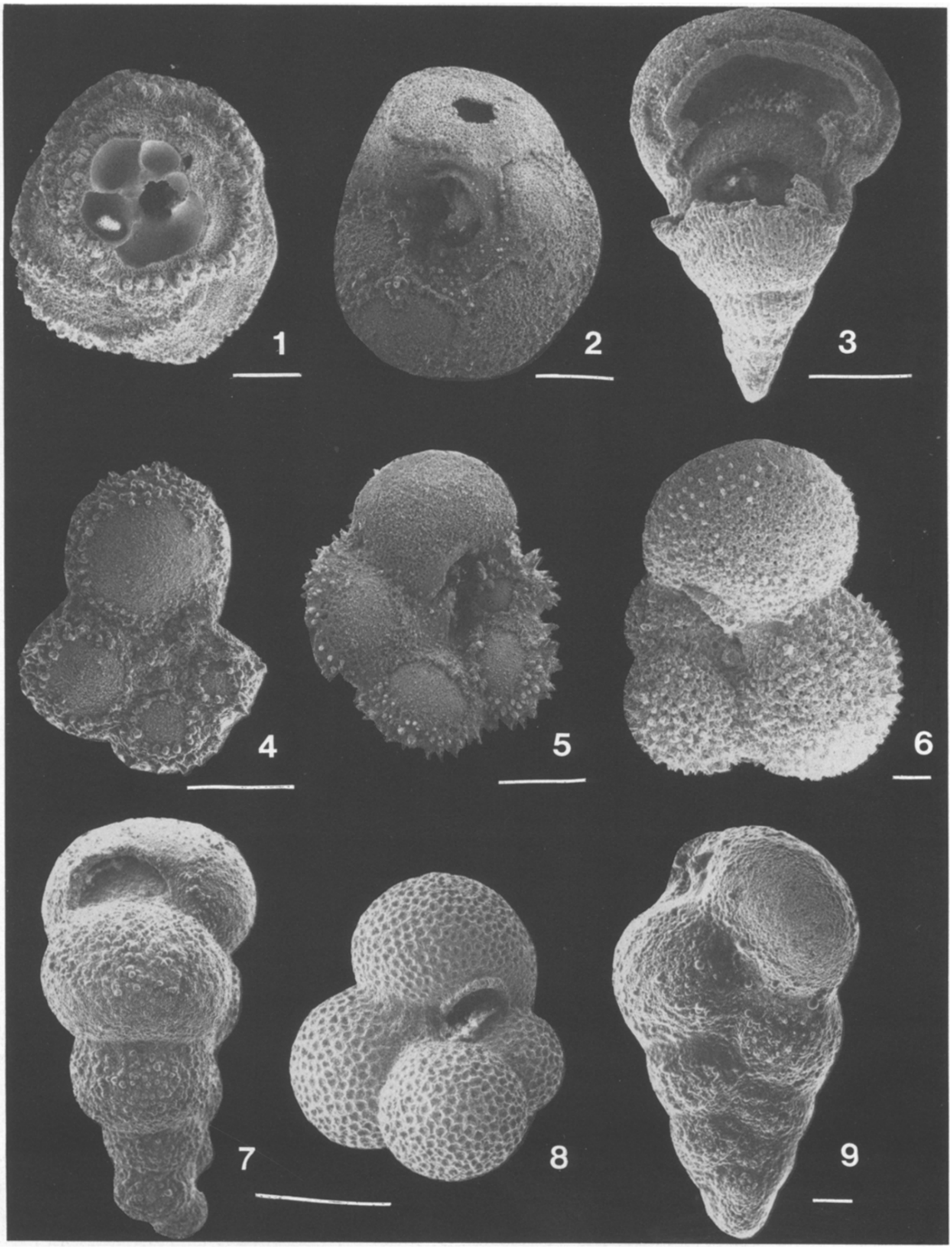


Fig. 5. Earliest Paleocene planktic foraminiferal stratigraphic ranges at DSDP Site 577. The Site 577 nannofossil zonation and paleomagnetic zonations are from Monechi (1985) and Bleil (1985). Planktic foraminiferal zonation from this study. Depth measured in meters below seafloor (mbsf). Note presence of Paleocene species in Upper Cretaceous sediment probably due to reworking and/or drilling disturbance.

29R magnetostratigraphic interval at Sites 528 and 577 are not consistent with the standard time-scale of Berggren et al. (1985b), which places these datums in the basal 29N interval at 66.1 Ma (300 ky following the K/T boundary). The FADs of *C. primus* and *M. pseudobulloides* also appear within the 29R interval at the Gubbio sequence (Premoli Silva, 1977; Monechi and Thierstein, 1985) and DSDP Site 516 (Pujol, 1983; Wei and Wise, 1989). In addition, the FAD of *M. pseudobulloides* occurs within the 29R interval at the Agost, Spain sec-

PLATE I



All specimens are from DSDP Site 577, core-section 12-6, 54–56 cm. Note the relatively poor preservation of Cretaceous taxa (1 though 6) and good preservation of Paleocene taxa (7 through 9). (1) *Rosita contusa* (Cushman). Scale bar is 100 μm. (2) *Globotruncanita sp.* Scale bar is 100 μm. (3) *Pseudotextularia elegans* (Rzehak). Scale bar is 100 μ. (4) *Globotruncanella petaloidea* (Gandolfi). Scale bar is 100 μm. (5) *Globotruncanella havanensis* (Voorwijk). Scale bar for is 20 μm. (6) *Globotruncanella* aff. *petaloidea* (Gandolfi). (7) *Woodringina claytonensis* Loeblich and Tappan. Scale bar for 7 and 8 is 100 μm. (8) *Eoglobigerina eobulloides* Morozova. (9) *Chiloguembelina midwayensis* (Cushman). Scale bar for 9 is 20 μm.

tion (Groot et al., 1989). The within-29R magnetochron FAD of *M. pseudobulloides* indicates a duration of 150 ky or less for the combined P0 and *P. eugubina* Zones. Hence, the P0 and *P. eugubina* foraminiferal Zones appear to be demonstrably shorter in temporal duration than are sometimes assumed (Berggren et al., 1985b; D'Hondt and Keller, 1987; Keller, 1988, 1989a,b).

Results

Carbonate Accumulation Rates

Averaged carbonate accumulation rates for DSDP Sites 528 and 577 (Fig. 6) were calculated using physical properties data from the DSDP Leg 64 (Site 528) and Leg 86 (Site 577) site reports (Moore et al., 1984; Heath et al., 1985), the magnetostratigraphic data of Chave (1984) and Bleil (1985), the paleomagnetic chronostratigraphy of Berggren et al. (1985a) and the accumulation rate equation of Zachos et al. (1985):

$$CAR = (\%\mathrm{CaCO_3}/100)\{[(W\,\mathrm{g/cm^3}) - (P/100)(1.01\,\mathrm{g/cm^3})](S\,\mathrm{cm\,yr})\}$$

where *CAR* is the carbonate accumulation rate, *W* is wet bulk density, *P* is porosity and *S* is the average sedimentation rate. Comparable carbonate accumulation rates are indeterminable for the Ben Gurion sequence, due to the absence of magnetostratigraphy and appropriate physical data (porosity and density measurements).

Latest Cretaceous carbonate accumulation rates at the mid-latitude South Atlantic DSDP Site 528 are relatively stable and average 1.8 $\mathrm{g/cm^2/ky}$ (Fig. 6). Over the same interval, carbonate accumulation rates at the then equatorial mid-Pacific DSDP Site 577 are also quite stable, but average only 1.1 $\mathrm{g/cm^2/ky}$. The much lower carbonate accumulation rates at Site 577 appear primarily to result from deposition at lysoclinal depths in the latest Cretaceous (Zachos et al., 1989).

At the K/T boundary, the DSDP Site 528 carbonate accumulation rate decreases radically. Average carbonate accumulation drops suddenly to nearly 0.0 $\mathrm{g/cm^2/ky}$ and remains at the low average level of 0.4 $\mathrm{g/cm^2/ky}$ for the remainder of the 29R magnetochron (approximately 230 ky). For the 29N magnetochron (approximately 670 ky), carbonate accumulation rates climb to an average of 0.9 $\mathrm{g/cm^2/ky}$. For the 28R magnetochron, average Site 528 carbonate accumulation rates again decrease to about 0.25 $\mathrm{g/cm^2/ky}$ (Fig. 6).

At DSDP Site 577, carbonate accumulation rates also decrease strongly at the K/T boundary, dropping to about 0.4 $\mathrm{g/cm^2/ky}$ by the lower *P. eugubina* Zone and remaining stable at approximately 0.35 $\mathrm{g/cm^2/ky}$ through the basal 28R magnetochron (Zachos et al., 1985) (Fig. 6). There is little evidence of dissolution in the basal Paleocene samples of this site, indicating that for this interval, DSDP Site 577 lay above lysoclinal depths (Smit and van Kempen, 1987).

The relatively lower and more stable Paleocene carbonate accumulation rates at Site 577 than at Site 528 indicate less variable and generally lower levels of carbonate productivity at the former site than at the latter for at least the first million years of the Paleocene.

Faunal Succession

DSDP Site 528

The uppermost Cretaceous samples of DSDP Site 528 contain relatively diverse assemblages of abundant biserial (*Heterohelix, Pseudoguembelina* and *Pseudotextularia* species), multiserial (*Planoglobulina* species), planispiral (*Globigerinelloides* species) and trochospiral foraminifera (*Hedbergella, Globotruncanella, Rugoglobigerina* and *Globotruncana* species). The faunal populations of these samples are dominated by heterohelicid species (predominantly *Heterohelix globulosa, H.*

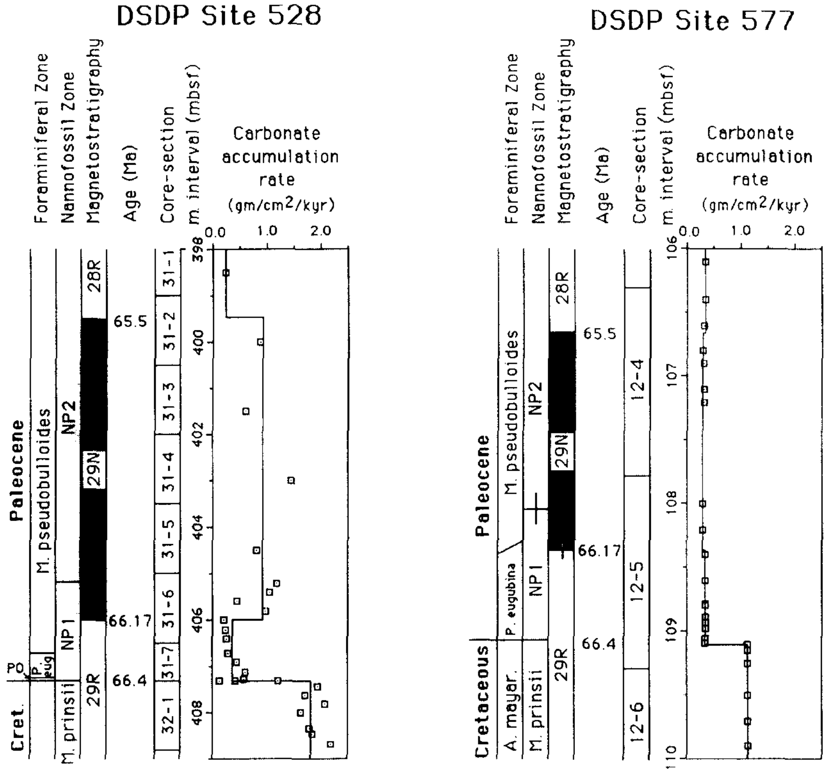


Fig. 6. Carbonate accumulation rates for DSDP Sites 528 and 577. The figured interval spans the latest Cretaceous and the first million years of the Paleocene. Note the generally higher and more variable accumulation rates at South Atlantic Site 528 than at mid-Pacific Site 577. The Site 577 data is from Zachos et al. (1985). The Site 528 nannofossil and the paleomagnetic zonations are from Manivit (1984), Bralower (unpubl.) and Chave (1984). The Site 577 nannofossil zonation and paleomagnetic zonations are from Monechi (1985) and Bleil (1985).

striata, H. navarroensis and *H. glabrans*) with large numbers of pseudoguembelinids (primarily *Pseudoguembelina costulata*) and globigerinelloid species (*Globigerinelloides asperus, G. subcarinatus* and *G. ultramicrus*) (Fig. 7a, Table Ia, Plate II). Some between-sample variation appears within the Cretaceous sequence: relative to the other Site 528 samples, samples at 408 and 408.48 m below the seafloor (mbsf) contain lower numbers of *H. globulosa, Heterohelix pulchra* and *Hedbergella holmdelensis* and greater numbers of *heterohelix semicostata, G. asperus, Globotruncanella havanenesis* and *Globotruncana arca* (Fig. 7a, Table Ia). Many of the latter species are known to be dissolution-resistant relative to the former species (Malmgren, 1987). With the exception of these apparently dissolution-affected faunas, dominant foraminiferal faunas appear stable throughout the sampled Cretaceous sequence. Sediment accumulation rates calculated from average 21-ky cm-wavelengths (Herbert and D'Hondt, 1990) and from the length of the Cretaceous 29R magnetochron indicate that this sampled interval spans the last ~75 ky of the Cretaceous. The last sampled Cretaceous population, from sediments deposited ~7.5 ky prior to the K/T boundary, does not appreciably differ from preceding assemblages with respect to dominant fauna (Fig. 7a).

The P0 Zone at this site occurs within the 0.5 cm thick "boundary clay". The faunal assemblage of this zone is dominated by the tris-

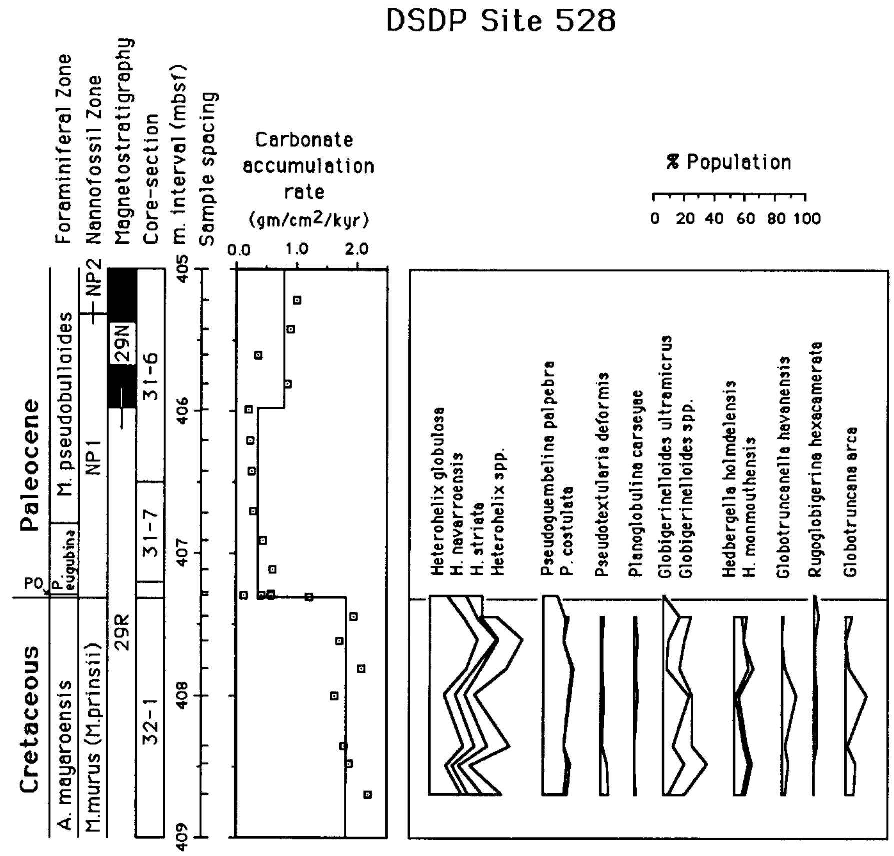


Fig. 7(a). Latest Cretaceous planktic foraminiferal turnover (> 63 μm fraction) and carbonate accumulation at South Atlantic DSDP Site 528. Population turnover is expressed by relative percentages of abundant genera and species. The nannofossil zonation is from Manivit (1984) and the paleomagnetic zonation from Chave (1984). The planktic foraminiferal zonation is from this study. Depth is in meters below seafloor (mbsf).

erial K/T boundary survivors *Guembelitria cretacea* and *Guembelitria trifolia* (Fig. 7b, Table Ib, Plate III). Prior to the K/T boundary, > 63 μm specimens of these species were not consistently present at this open-ocean site. The Site 528 P0 Zone assemblage also contains subsidiary numbers of "dwarfed" *Heterohelix globulosa, H. striata, H. navarroensis, Pseudoguembelina costulata, Globigerinelloides subcarinatus* and *Rugoglobigerina hexacamerata* (Fig. 7a, Table Ia). These latter species have been previously described as K/T boundary survivors at other sites (Keller, 1988, 1989a). In addition to these possible Cretaceous survivors, the P0 Zone assemblage of this site includes rare specimens of the earliest Paleocene forms *Parvularugoglobigerina morphotype 2* and *Parvularugoglobigerina morphotype 3* (Fig. 7b, Table Ib, Plates III, IV).

With the exception of *G. cretacea* and *G. trifolia*, no Cretaceous species range above the P0 Zone at this site. The basal *P. eugubina* Zone assemblages contain a populational abundance peak of *P. longiapertura* (10%), *P. eugubina* (4%), *P. morphotype 2* (7%) and *P. morphotype 3* (5%) (Fig. 7b, Table Ib, Plates III, IV). Faunal assemblages of the lower *P. eugubina* Zone are dominated by earliest Paleocene biserial species. 50 to 60% of the fauna in these samples is composed of *Woodringina claytonensis*, 15 to 30% is *Chiloguembelina morsei* and 5 to 12% is *Chiloguembelina*

TABLE Ia

DSDP Site 528 latest Cretaceous sample interval, percent carbonate and representative planktic foraminiferal counts (> 63 μm size fraction)

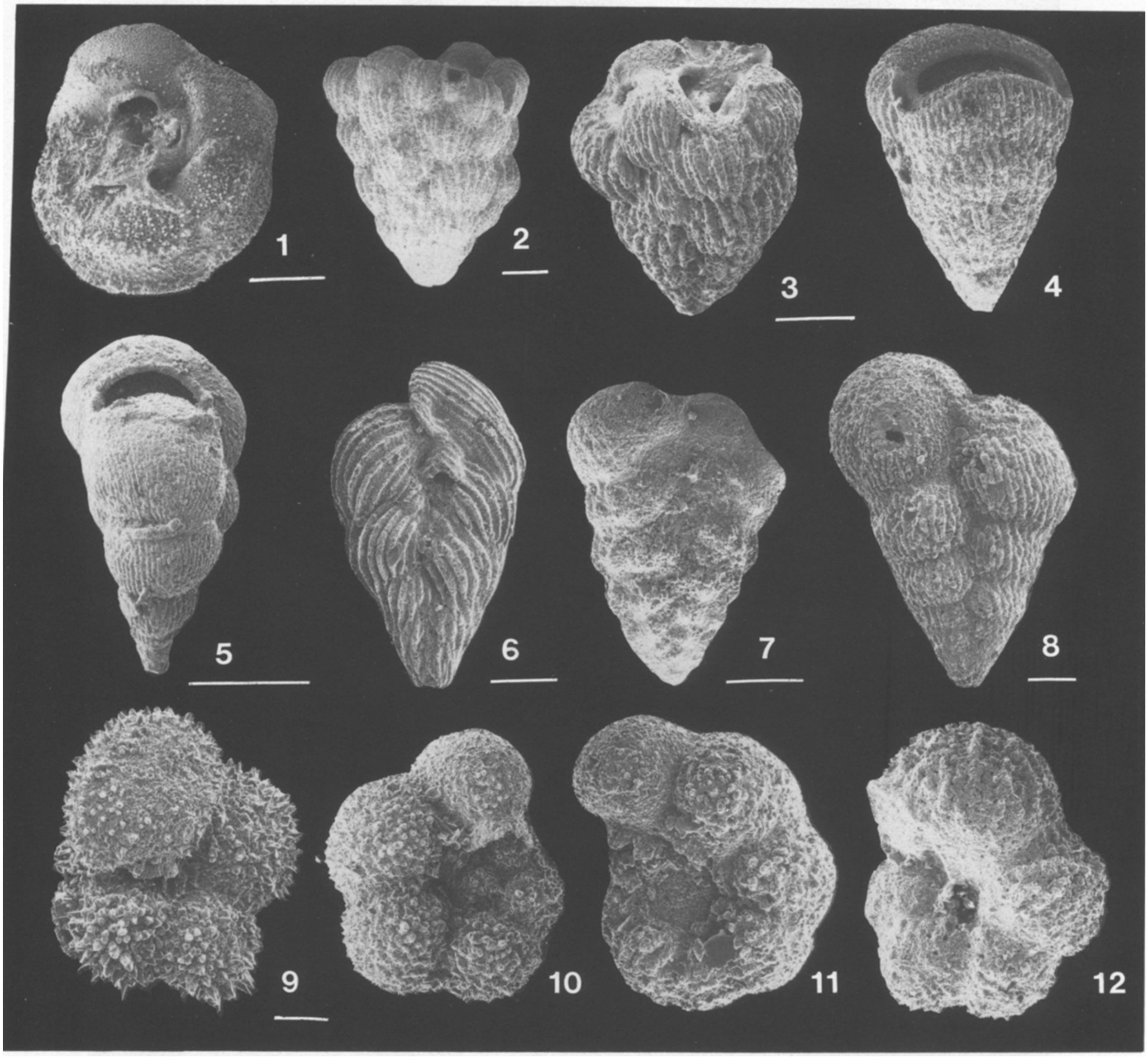
Sample	% Carbonate	*Heterohelix globulosa* (Ehrenberg)	*Heterohelix navarroensis* Loeblich	*Heterohelix striata* (Ehrenberg)	*Heterohelix pulchra* (Brotzen)	*Heterohelix glabrans* (Cushman)	*Heterohelix semicostata* (Cushman)	*Pseudoguembelina costulata* (Cushman)
32-1(139-141)	75.8	95	48	21	30	32	7	65
32-1(118-120)	64.5	30	16	9	5	8	5	40
32-1(105-107)	61.8	160	72	45	44	70	3	98
32-1(69-71)	56.6	19	5	17	1	2	13	30
32-1(50-52)	71.8	135	13	34	39	32	4	87
32-1(30-32)	59.3	215	6	98	39	64	1	92
32-1 (13-15)	67.4	122	14	47	14	36	11	78
31cc 15cm	15.0	15	12	17				12
31cc 15-cm	46.8	1						1
31cc(14-15)	64.3							

Sample	*Pseudoguembelina palpebra* Brönnimann and Brown	*Pseudotextularia elegans* (Rzehak)	*Planoglobulina carseyae* (Plummer)	*Planoglobulina brazoensis* Martin	*Racemiguembelina intermedia* (de Klasz)
32-1(139-141)	13	17	2	4	1
32-1(118-120)	8	2			
32-1(105-107)	5	1	2		
32-1(69-71)	4		1	3	
32-1(50-52)	13	2		4	2
32-1(30-32)	4	2	1	11	
32-1 (13-15)	11	2	4	4	3
31cc 15cm					
31cc 15-cm					
31cc(14-15)					

Sample	*Racemiguembelina fructicosa* (Egger)	*Globigerinelloides subcarinatus* (Brönnimann)	*Globigerinelloides asperus* (Ehrenberg)	*Globigerinelloides ultramicrus* (Subbotina)	*Hedbergella monmouthensis* (Olsson)	*Hedbergella holmdelensis* (Olsson)
32-1(139-141)		39	18	10	4	27
32-1(118-120)		33	38	5	3	24
32-1(105-107)		71	37	33	18	45
32-1(69-71)			30	7	3	3
32-1(50-52)		33	10	9	16	50
32-1(30-32)		33	22	38	4	41
32-1 (13-15)	1	14	57	27	13	30
31cc 15cm		2				
31cc 15-cm						
31cc(14-15)						

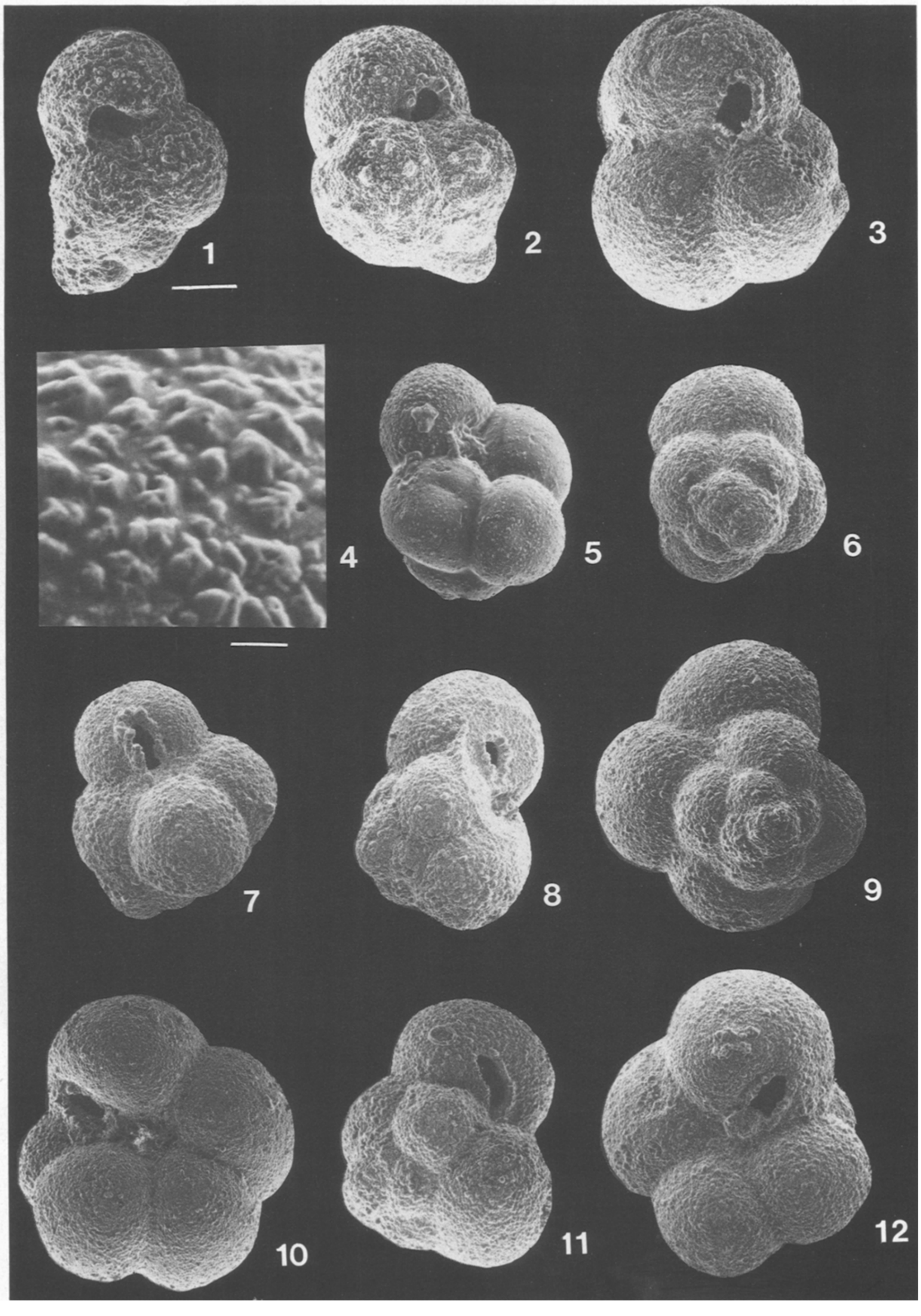
Sample	*Schackoina multispinata* (Cushman and Wickenden)	*Rugoglobigerina rugosa* (Plummer) and *hexacamerata* Brönnimann	*Globotruncana arca* (Cushman)	*Globotruncanita stuarti* (de Lapparent)	*Rosita contusa* (Cushman)	*Guembelitria cretacea* Cushman	*Parvularugoglobigerina* species 1	Total
32-1(139-141)	1		28	3		5	1	487
32-1(118-120)			17		1			268
32-1(105-107)		13	10					745
32-1(69-71)		5	26					192
32-1(50-52)		7	11					513
32-1(30-32)	1	9	3					693
32-1 (13-15)		16	24	3	1			543
31cc 15cm		1						59
31cc 15-cm								2
31cc(14-15)								0

PLATE II



All samples from DSDP Site 528 core-section 32-1, cm interval 13–15. Scale bars for 1, 2, 5, 6 and 7 are 100 μm. (1) *Globotruncana arca* (Cushman). (2) *Racemiguembelina fructicosa* (Egger). (3) *Racemiguembelina powelli* Smith and Pessagno. Scale bar for 3 and 4 is 100 μm. (4) *Pseudotextularia deformis* (Kikoine). (5) *Pseudotextularia elegans* (Rzehak). (6) *Pseudoguembelina costulata* (Cushman). (7) *Heterohelix semicostata* (Cushman). (8) *Heterohelix striata* (Ehrenberg). Scale bar is 20 μm. (9) *Globotruncanella havanensis* (Voorwijk). Scale bar for 9 through 12 is 20 μm. (10) *Globigerinelloides asperus* (Ehrenberg). (11) *Globigerinelloides ultramicrus* (Subbotina). (12) *Ruguglobigerina rugosa* (Plummer), note uncharacteristically narrow umbilicus and absence of final chamber.

PLATE III



midwayensis (Fig. 7b, Table Ib, Plate V). During this interval, subsidiary faunal elements include *Globoconusa tripartita, Eoglobigerina eobulloides* and *Morozovella moskvini* (Fig. 7b, Table Ib, Plate VI).

In the upper *P. eugubina* Zone, a pronounced decline in the dominance of *Woodringina* and *Chiloguembelina* and a pronounced increase in the dominance of *Guembelitria* species occurs (Fig. 7b). Over this second earliest Paleocene *Guembelitria* abundance peak, *G. cretacea* comprises up to 23% of the assemblage and *G. trifolia* comprises up to 31% of the foraminiferal fauna. In contrast, the combined *Woodringina* and *Chiloguembelina* species drop to as low as 15% of the total assemblage in the upper *P. eugubina* Zone. Throughout this interval, subsidiary faunal elements include low abundances of *P. longiapertura* and *P. morphotype 3*, stable small populations of *G. tripartita* and *E. eobulloides* (< 10% of the total fauna belong to each species) and stable or increasing proportions of the newly appearing *Globoconusa daubjergensis, Eoglobigerina trivialis, M. moskvini, Morozovella pseudobulloides, Planorotalites planocompressa* and *"Eoglobigerina" pentagona* (Fig. 7b, Table Ib, Plate VI).

Within the *M. pseudobulloides* Zone, *P. eugubina, P. Morphotype 2* and *P. morphotype 3* undergo their final decline and become extinct. Throughout this zone, *W. claytonensis, Ch. midwayensis, M. pseudobulloides* and *G. daubjergensis* populations increase to levels as high as32%, 24%, 20% and 17% respectively of the total foraminiferal assemblage. Over the same interval, guembelitriid and eoglobigerinid faunal elements decline to less than 2% of the total counted assemblage. Throughout this interval, stable or slightly increasing subsidiary faunal elements include *M. moskvini, P. planocompressa, "E." pentagona* and *Woodringina hornerstownensis* (Fig. 7b, Table Ib).

Approximately 230 ky after the K/T boundary (at the 29R/29N paleomagnetic reversal), carbonate accumulation rates increase. This increase in carbonate accumulation is paralleled by increased proportions of *W. claytonensis, M. pseudobulloides* and *G. daubjergensis.* Also during this increase in carbonate accumulation, *Morozovella inconstans* makes its first appearance, increasing to 5% of the total assemblage (Fig. 7b, Table Ib, Plate VI).

The Ben Gurion Section, Israel

The uppermost Cretaceous samples of the Ben Gurion section contain relatively diverse assemblages of abundant biserial (*Heterohelix* and *Pseudoguembelina*), multiserial (*Planoglobulina*), triserial (*Guembelitria*), trochospiral (*Rugoglobigerina, Globotruncanella and Hedbergella*) and planispiral (*Globigerinelloides*) species (Fig. 8a,b, Tables IIa,b). The dominant species within these foraminiferal populations are *Heterohelix globulosa* (20% to 44% of the total populations) and *Pseudoguembelina costulata* (9% to 24% of the total populations). Significant proportions of *Heterohelix navarroensis, Heterohelix glabrans, Guembelitria cretacea, Planoglobulina carseyae, Globigerinelloides asperus, Globigerinelloides subcarinatus, Globigerinelloides volutus* and *Rugoglobigerina rugosa* are also present. Some between-sample variation appears within the Ben Gurion uppermost Cretaceous se-

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PLATE III

The scale bar for all specimens, excluding 4, is 20 μm. Unless otherwise noted, all specimens are from DSDP Site 577, core-section 12-5, 115–117 cm. (1) *Guembelitria cretacea* Cushman, DSDP Site 528, core-section 31cc, 14–15 cm. (2) *Guembelitria trifolia* (Morozova). (3) morphotype intermediate between *G. trifolia* and *Parvularugoglobigerina morphotype 1.* (4) *Parvularugoglobigerina morphotype 1,* close-up of 5. Note presence of guembelitriid pore-volcanoes. Scale bar is 2 μm. (5) *Parvularugoglobigerina morphotype 1,* Brazos Core sample 264. (6) morphotype intermediate between *G. trifolia* and *Parvularugoglobigerina morphotype 1.* (7) *Parvularugoglobigerina morphotype 1.* (8) *Parvularugoglobigerina morphotype 1.* (9) *Parvularugoglobigerina morphotype 1.* (10) *Parvularugoglobigerina morphotype 3.* (11) *Parvularugoglobigerina morphotype 3.* (12) *Parvularugoglobigerina morphotype 1.*

TABLE Ib

DSDP Site 528 earliest Paleocene sample interval, percent carbonate and representative planktic foraminiferal counts (> 63 μm size fraction)

Sample	% Carbonate	*Guembelitria cretacea* Cushman	*Guembelitria trifolia* (Morozova)	*Chiloguembelitria danica* Hofker	*Parvularugo-globigerina morphotype 1*	*Parvularugo-globigerina morphotype 2*	*Parvularugo-globigerina eugubina* (Luterbacher and Premoli Silva)	*Parvularugo-globigerina longiapertura* (Blow)	*Parvularugo-globigerina morphotype 3*
31cc 15cm	15.0	38	13	4		10	6		
31cc 15-cm	46.8	14	6	1	1	6	19	10	4
31cc(14-15)	64.3	29	13			6	6	23	10
31cc(13-14)	63.6	41	14	1		6	1	50	24
31-7(60-62)	67.1	15	7	1		10	13		15
31-7(40-42)	50.3	125	129	9					16
31-7(20-22)	31.3	138	227	5		1	16		31
31-6(141-143)	28.0	96	140				13	2	9
31-6(120-122)	24.8	30	47	1			7	2	10
31-6(98-100)	23.9	23	66						
31-6(80-82)	55.4	5	13				3		
31-6(59-61)	24.6								
31-6(41-43)	59.6	3	8						
31-6(21-23)	66.8	3	3						

Sample	*"Eoglobigerina" taurica* Morozova	*Woodringina claytonensis* Loeblich and Tappan	*Woodringina hornerstownensis* Olsson	*Chiloquembelina midwayensis* (Cushman)	*Globoconusa tripartita* Morozova	*Chiloquembelina morsei* (Kline)	*Globoconusa daubjergensis* (Brönnimann)	*Eoglobigerina eobulloides* Morozova
31cc 15cm								
31cc 15-cm		210		30		126		
31cc(14-15)		188		44	3	63		2
31cc(13-14)		231		39	1	73		16
31-7(60-62)		277		23	30	36	9	18
31-7(40-42)		137		43	24	19	4	15
31-7(20-22)	1	56		24	41	27	64	40
31-6(141-143)		77		64	43	14	15	26
31-6(120-122)	1	79		35	21	6	15	15
31-6(98-100)		37		51	18	49		18
31-6(80-82)		99		85	20	9	18	7
31-6(59-61)		121	1	51	23	10	75	
31-6(41-43)		132	5	41	18	9	71	1
31-6(21-23)		75	5	31	5	3	35	1

Sample	*Eoglobigerina trivialis* (Subbotina)	*Eoglobigerina trilocalinoides* (Plummer)	*Morozovella moskvini* (Shutskaya)	*Morozovella pseudobulloides* (Plummer)	*Morozovella inconstans* (Subbotina)	*Planorotalites planocompressa* (Shutskaya)	*"Eoglobigerina" pentagona* (Morozova)	Total (Cretaceous and Paleocene)
31cc 15cm								130
31cc 15-cm								429
31cc(14-15)						2		391
31cc(13-14)						3		500
31-7(60-62)			5					459
31-7(40-42)			13			4		538
31-7(20-22)	5		30	9		12		727
31-6(141-143)	15		106	27		11	10	668
31-6(120-122)	9		44	23		11	16	372
31-6(98-100)	18		19	32	3	7	7	357
31-6(80-82)	4	4	31	24	10	14	7	353
31-6(59-61)	6		31	91	1	37	4	451
31-6(41-43)	5		34	36	20	22	9	414
31-6(21-23)			29	24	8	17	3	242

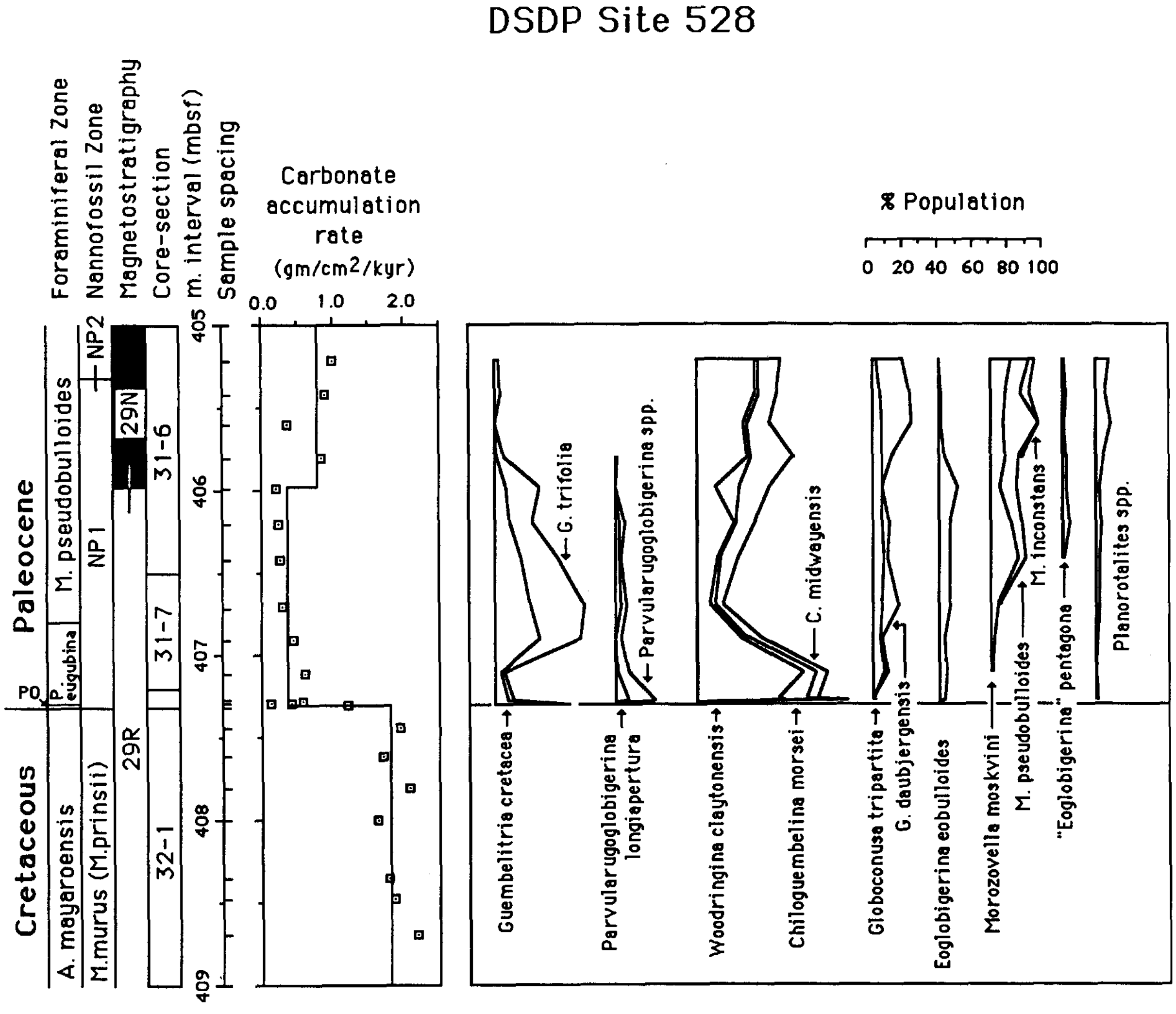
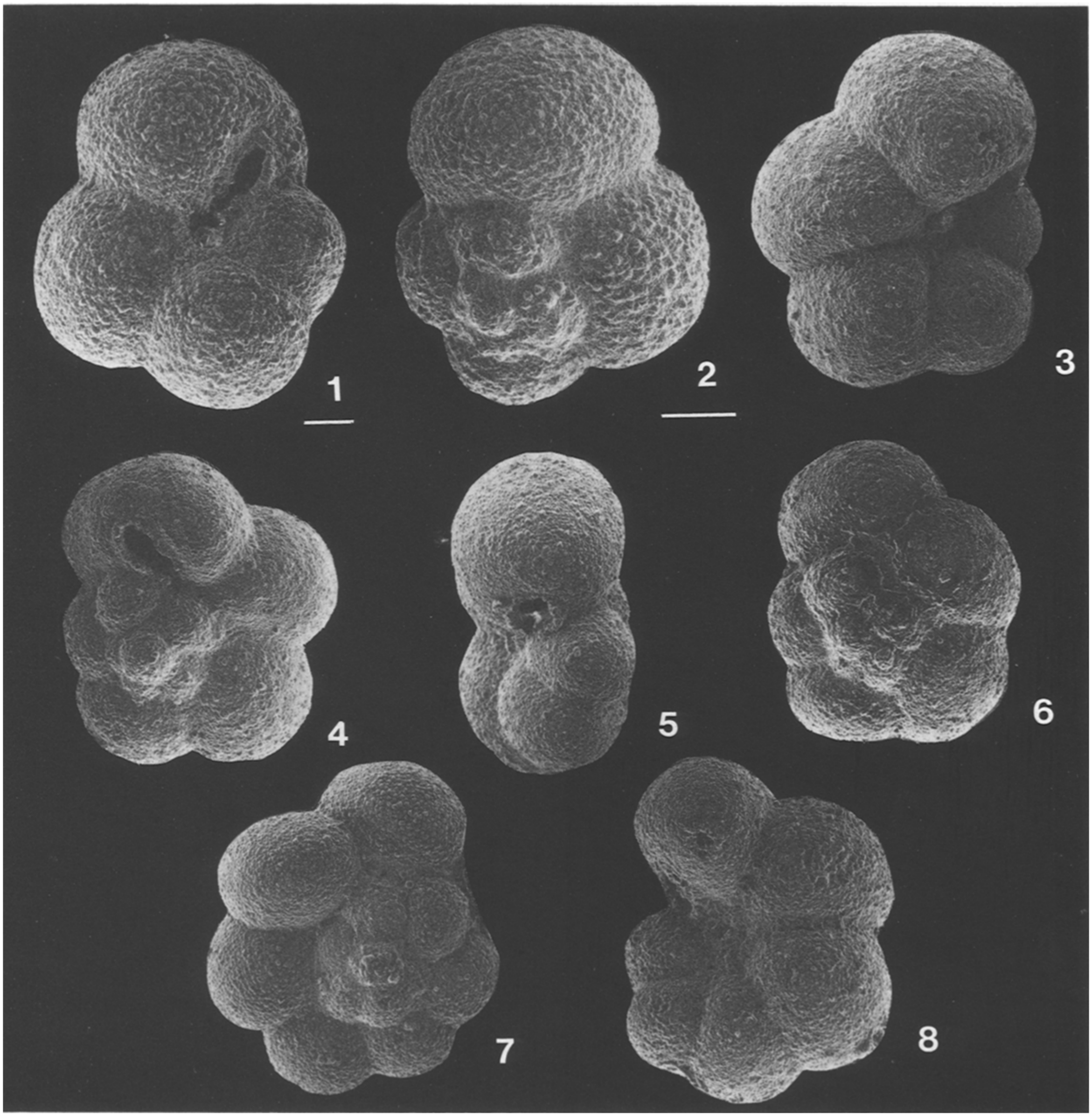


Fig. 7(b). Earliest Paleocene planktic foraminiferal assemblage turnover (> 63 μm fraction) and carbonate accumulation at DSDP Site 528. The nannofossil zonation is from Manivit (1984) and the paleomagnetic zonation from Chave (1984). The planktic foraminiferal zonation is from this study. Depth is in meters below seafloor (mbsf).

quence: *H. globulosa* and *H. navarroensis* populations alternate noticeably in abundance relative to *P. costulata* and *P. carseyae* (Fig. 8a). Despite these populational alternations, the dominant foraminiferal faunas do not demonstrate directional change prior to the K/T boundary and appear to be relatively stable throughout the uppermost Cretaceous sequence of the Ben Gurion section (Fig. 8a). Occasional individuals belonging to typical P0 Zone taxa (*W. Claytonensis, P. morphotype 2, P. morphotype 3, P. eugubina*) are also rarely present in the upper 10 to 15 cm of the Ben Gurion Cretaceous sequence (Fig. 8b, Table IIb). The presence of these rare specimens may be due to bioturbation, an interpretation supported by the presence of Cretaceous lithic fragments and worn discolored Cretaceous foraminifera in basal Paleocene samples of this

PLATE IV



The scale bar for all specimens, excluding 2, is 20 μm. All specimens are from DSDP Site 577, core-section 12-5, 115–117 cm. (1) *Parvularugoglobigerina morphotype 2.* (2) *Parvularugoglobigerina morphotype 2.* Scale bar is 10 μm. (3) *Parvularugoglobigerina eugubina* (Luterbacher and Premoli Silva). (4) *Parvularugoglobigerina eugubina* (Luterbacher and Premoli Silva). Note aberrant aperture. (5) *Parvularugoglobigerina eugubina* (Luterbacher and Premoli Silva). (6) *Parvularugoglobigerina eugubina* (Luterbacher and Premoli Silva). (7) *Parvularugoglobigerina longiapertura* (Blow). (8) *Parvularugoglobigerina longiapertura* (Blow).

PLATE V

Unless otherwise noted, all specimens are from DSDP Site 577, core-section 12-5, 94–96 cm. (1) *Guembelitria cretacea* Cushman, DSDP Site 528, 31 cc, 14–15 cm. Scale bar for 1 through 4 is 20 μm. (2) *Woodringina claytonensis* Loeblich and Tappan. (3) *Woodringina claytonensis* Loeblich and Tappan. (4) aberrant *Woodringina claytonensis* Loeblich and Tappan. (5) *Woodringina hornerstownensis* Olsson, DSDP Site 577, 12-4, 34–36. Scale bar for 5, 6 and 7 is 20 μm. (6) *Woodringina hornerstownensis* Olsson, Hornerstown Formation. (7) *Woodringina hornerstownensis* Olsson, Hornerstown Fm. (8) *Woodringina hornerstownensis* Olsson, DSDP Site 577, 12-4, 34–36. Scale bar for 8 is 50 μm. (9) *Chiloguembelina morsei* (Kline), DSDP Site 528, 31 cc, 14–15 cm. Scale bar for 9, 10 and 11 is 20 μm. (10) *Chiloguembelina Morsei* (Kline). (11) *Chiloguembelina morsei* (Kline). (12) *Chiloguembelina midwayensis* (Cushman), DSDP Site 528, DSDP Site 528, 31 cc, 14–15 cm. Scale bar for 12, 13 and 14 is 20 μm. (13) *Chiloguembelina midwayensis* (Cushman), DSDP Site 577, 12-5, 34–36 cm. (14) *Chiloguembelina midwayensis* (Cushman), DSDP Site 577, 12-5, 34–36 cm. (15) *Chiloguembelina midwayensis* (Cushman). Scale bar for 15 is 20 μm.

PLATE V

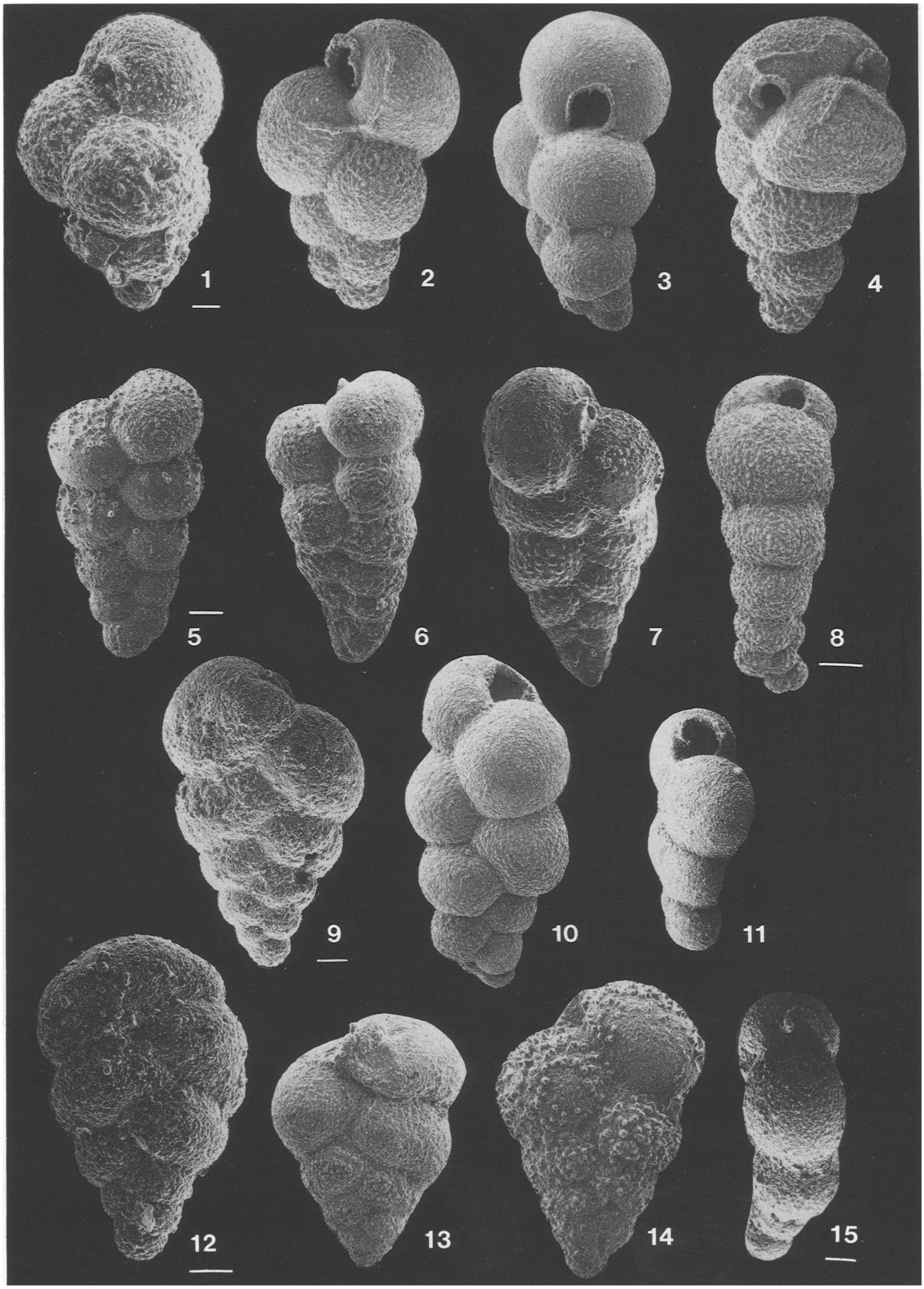
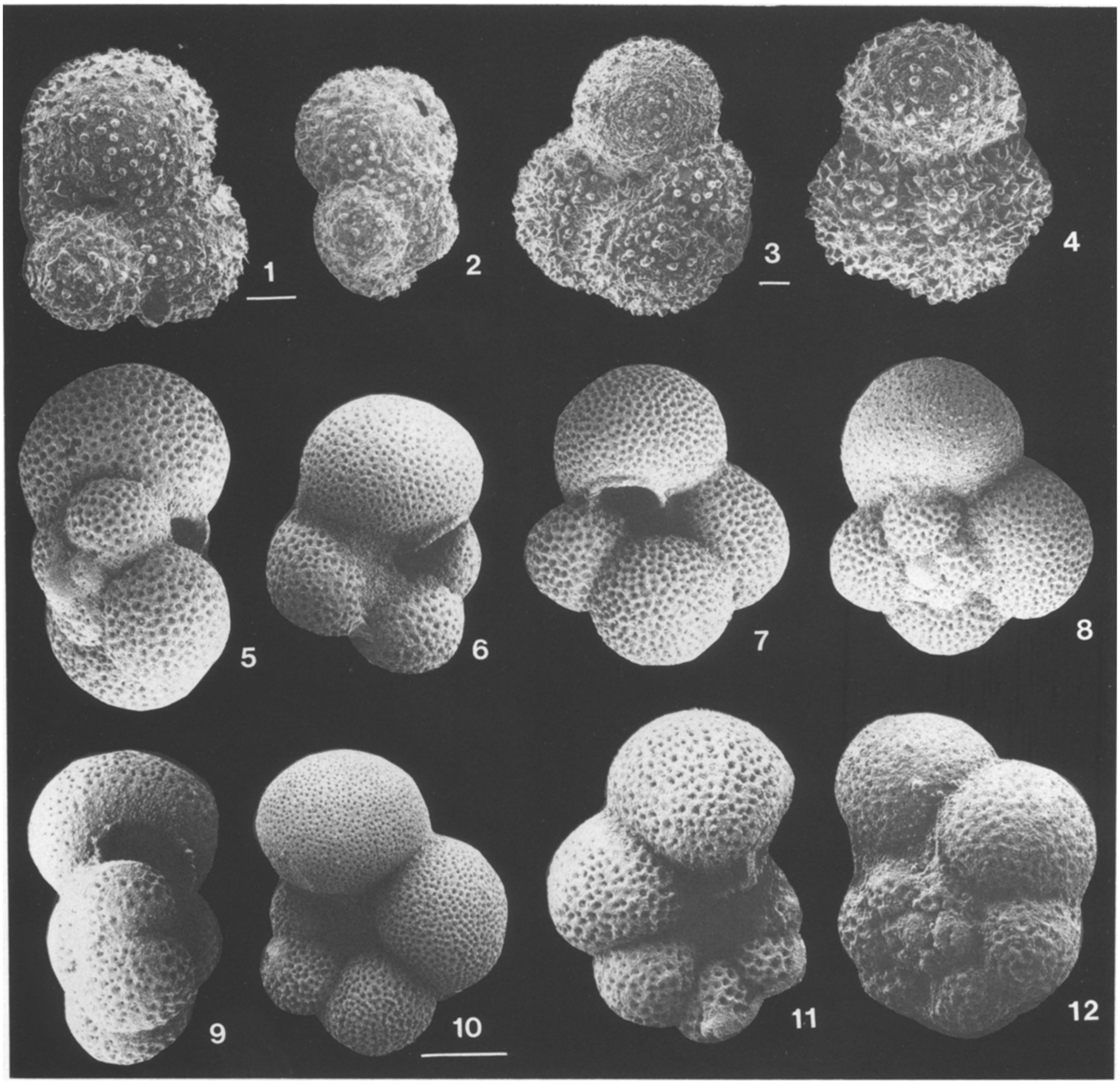


PLATE VI



The scale bar for all specimens, excluding 10, is 20 μm. (1) *Globoconusa tripartita* Morozova. Specimens 1 and 2 are from DSDP Site 528, core-section 31-7, 60–62 cm. (2) *Globoconusa tripartita* Morozova. (3) *Globoconusa daubjergensis* (Brönnimann). Specimens 3 and 4 are from DSDP Site 528, core-sections 31-7, 20–22. (4) *Globoconusa daubjergensis* (Brönnimann). (5) *Morozovella moskvini* (Shutskaya). Specimens 5 through 12 are from DSDP Site 577, core-section 12-4, 54–56 cm. (6) *Morozovella moskvini* (Shutskaya). (7) *Eoglobigerina eobulloides* Morozova. (8) *Eoglobigerina eobulloides* Morozova. (9) *Morozovella pseudobulloides* (Plummer). (10) *Morozovella pseudobulloides* (Plummer). Scale bar is 100 μm. (11) *Morozovella inconstans* (Subbotina). (12) *Morozovella inconstans* (Subbotina).

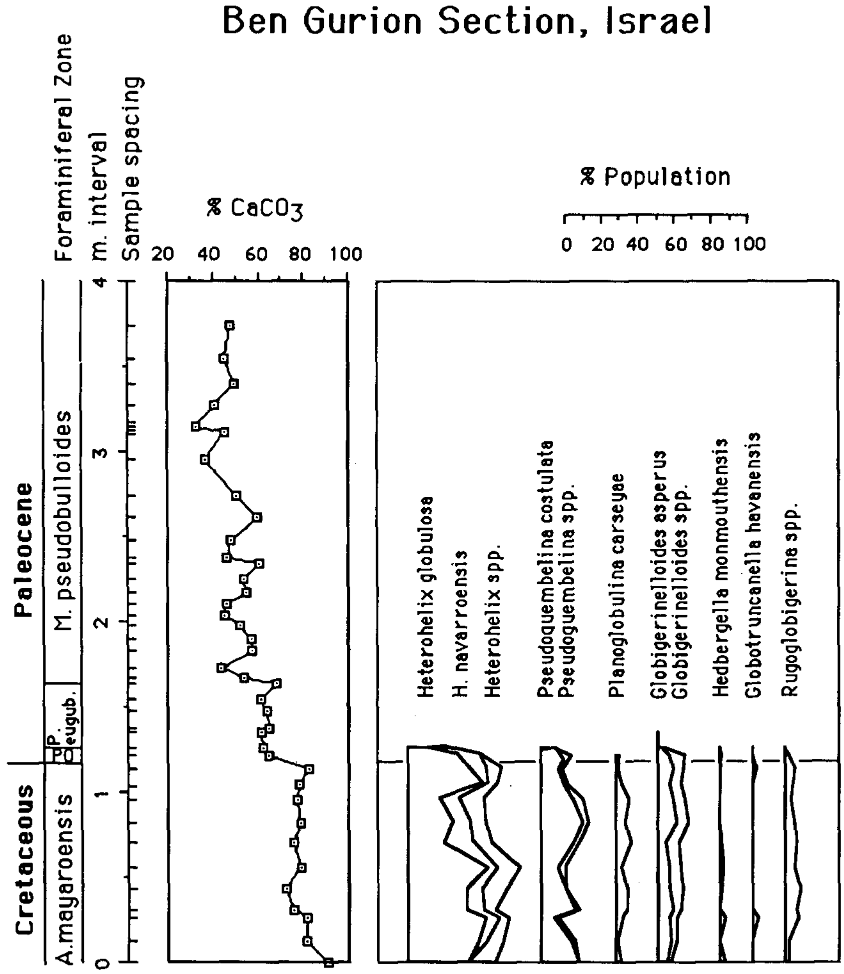


Fig. 8(a). Latest Cretaceous planktic foraminiferal assemblage turnover (> 63 μm fraction) and carbonate content at the Tethyan Ben Gurion section, the Negev, Israel. The planktic foraminiferal zonation is from this study.

and other Negev K/T boundary sections (Keller et al., in press).

At the Ben Gurion section, sedimentary carbonate content drops suddenly from 82% to 65% at the level of the K/T boundary (Fig. 8a). This decrease is consistent with the findings of decreased carbonate content at other K/T boundary sections worldwide (Zachos et al., 1985, 1989; Herbert and D'Hondt, 1988, 1990; Keller and Lindinger, 1989; Keller et al., in press). In the absence of Cretaceous chronostratigraphic datums and of porosity and density data, it is not possible to assess the relative importance of changes in carbonate and non-carbonate sedimentation at the Ben Gurion K/T boundary. The low level of the K/T boundary decrease in carbonate content could reflect a number of factors, including covarying carbonate and non-carbonate sedimentation and bioturbation of uppermost Cretaceous sediments into basal Paleocene sediments.

The Ben Gurion P0 Zone and basal *P. eugubina* Zone faunal assemblage is characterized by a small peak in the abundance of the triserial K/T boundary survivors *Guembelitria cretacea* and *Guembelitria trifolia* (Fig. 8b). The Ben Gurion P0 Zone samples also contain a large but rapidly decreasing proportion of other Cretaceous taxa, including 27% to 12% *H. globulosa*, 9% to 6% *H. navarroensis*, 11%

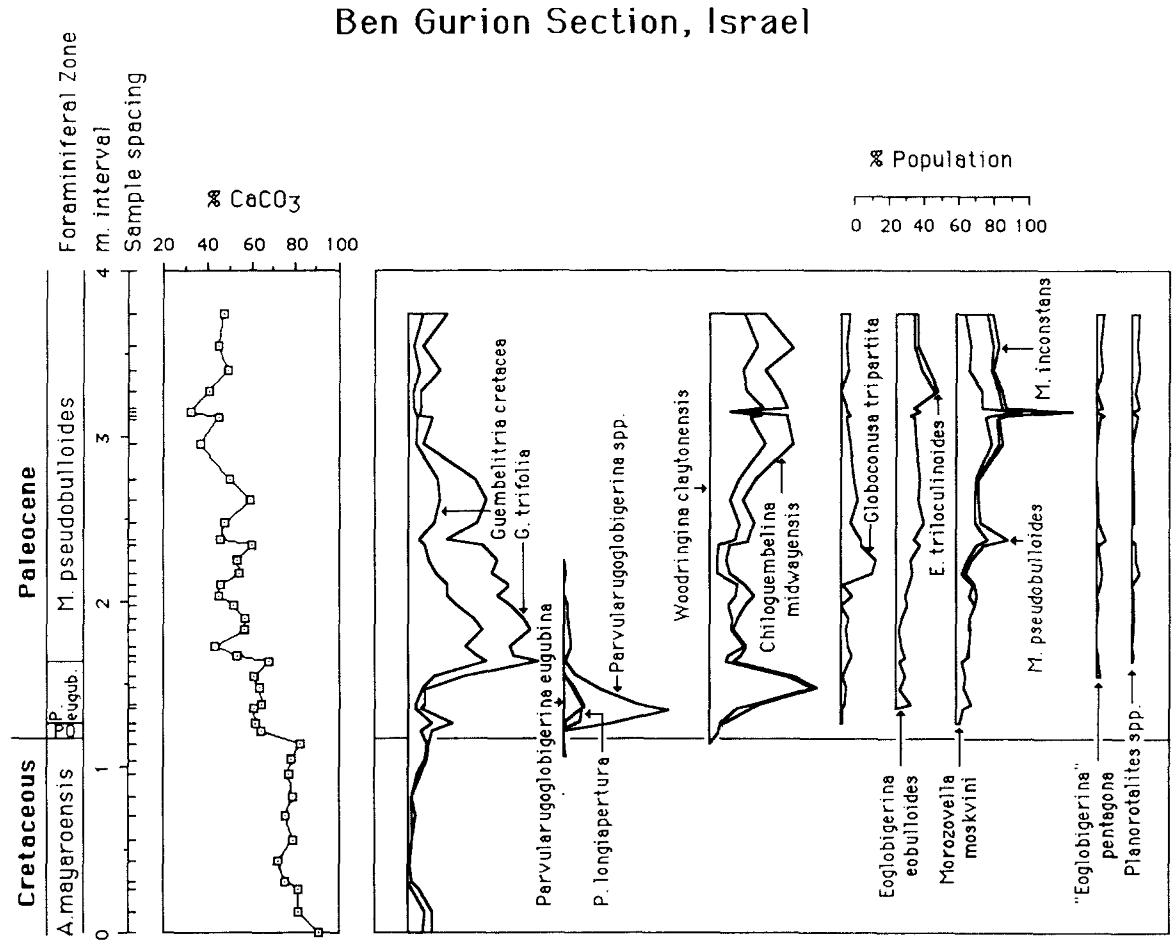


Fig. 8(b). Earliest Paleocene planktic foraminiferal assemblage turnover (> 63 μm fraction) and carbonate content at the Tethyan Ben Gurion section, the Negev, Israel. The planktic foraminiferal zonations is from this study.

to 6% *P. costulata*, 7% to 1% *G. asperus*, 5% to 1% *G. subcarinatus* and 4% to 1% *G. volutus* (Fig. 8a, Table IIa). Although some of the latter species have been previously described as K/T boundary survivors at other sites (Keller, 1988, 1989a), the presence of these and other Cretaceous taxa in the basal 10 cm of the Paleocene Ben Gurion sequence may also result from the previously mentioned bioturbation and reworking of the K/T boundary sediments. In addition to these Cretaceous taxa, the P0 Zone assemblage of this site includes trace populations of the earliest Paleocene species *Parvularugoglobigerina morphotype 1, Parvularugoglobigerina morphotype 2, Parvularugoglobigerina morphotype 3, Woodringina claytonensis* and *Chiloguembelina morsei* (Fig. 8b, Table IIb).

Faunal assemblages of the basal *P. eugubina* Zone are characterized by local maxima in the populational abundance of *P. morphotype 1* (25%), *P. morphotype 2* (10%), *P. eugubina* (12%), *P. longiapertura* (9%) and *P. morphotype 3* (13%). *G. cretacea* and *G. trifolia* are the only Cretaceous species which range into the *P. eugubina* Zone at this locality. The remaining *P. eugubina* Zone is dominated by earliest Paleocene biserial species: 24% to 59%

TABLE IIa

Ben Gurion latest Cretaceous sample interval, percent carbonate and representative planktic foraminiferal counts (> 63μm size fraction)

Sample	m. depth	% carbonate	*Heterohelix globulosa*	*Heterohelix navarroensis*	*Heterohelix striata*	*Heterohelix glabrans*	*Heterohelix americana* (Ehrenberg)	*Pseudoguembelina costulata*	*Pseudoguembelina palpebra*	*Pseudoguembelina kempensis* Esker	*Pseudotextularia elegans*	*Planoglobulina carseyae*	*Planoglobulina multicamerata* (de Klasz)	*Globigerinelloides subcarinatus*	*Globigerinelloides asperus*	*Globigerinelloides volutus* (White)
69	0.00	90.49	83		4	33		51				7		6	12	
68	0.12	81.30	103	2	3	30	4	48	1	1		3		1	21	7
67	0.26	81.11	88	14		10	3	18	1	1		9		7	14	1
66	0.31	75.87	64	17		14	1	40		2	1	13		4	17	3
65	0.43	72.20	63	14	4	26	1	27		1		13		12	13	3
64	0.56	78.87	106	4	7	25	6	27		5		8		9	15	6
63	0.71	75.20	45	32	5	23	3	46		4	2	19		8	11	8
62	0.82	79.04	87	25	1	28	3	79	4	4	4	19	0	12	35	10
61	0.96	77.41	37	17	2	24	5	39		7		15	0	6	17	6
60	1.05	78.33	95	10	1	3	12	32		3	3	8		7	16	7
59	1.14	81.98	61	15	0		14	16	4		2	1		5	16	4
58	1.22	64.91	60	21			4	25	9	3	1	5	2	12	16	10
57	1.26	61.74	23	11	4		7	11	1	4				2	2	1
56	1.35	61.05													1	
55	1.38	64.67														
54	1.48	63.84		1												
53	1.54	61.10														
52	1.64	68.40														
51	1.67	54.00														
50	1.73	43.31														
49	1.83	56.89														
48	1.90	56.64		1	1											
47	1.98	51.69														
46	2.03	45.58													1	
45	2.10	45.90														

Sample	*Hedbergella monmouthensis*	*Hedbergella holmdelensis*	*Schackoina multispinata*	*Globotruncanella petaloidea* (Gandolfi)	*Globotruncanella caravacaensis* Smit	*Rugoglobigerina rugosa*	*Rugoglobigerina macrocephala* Brönnimann	*Rugoglobigerina hexacamerata*	*Rugoglobigerina hantkeninoides* Bronnimann	*Guembelitria cretacea*	*Guembelitria trifolia*	Cretaceous Total	Guembelitria Total	Paleocene Total	Total
69		9	3	0		6				20	13	214	33	0	247
68		1	0			3	3	0	1	25	11	232	36	0	268
67		6			7	14			1	5	7	194	12	0	206
66	0	0			1	11		3	1	3	2	192	5	0	197
65		2			0	8		2	7	1	1	196	2	0	198
64	1	4		0	0	8		2	2	3	1	235	4	0	239
63	2	0		1	0	8	1	3	3	7	2	224	9	0	233
62		0			0	16		0	2	6	1	329	7	4	340
61		0	3		1	1		5	1	10	4	186	14	0	200
60		0	3		1	3	1	5		23	4	210	27	9	246
59		0			4	4		5		20	3	151	23	9	183
58	0	3			0	3		2		17	16	176	33	16	225
57					2	3				25	23	71	48	78	197
56										11	4	1	15	177	193
55										8	11	0	19	172	191
54										24	4	1	28	270	299
53										28	40	0	68	164	232
52										249	172	0	421	154	575
51										89	48	0	137	96	233
50										108	89	0	197	156	353
49										213	143	0	356	162	518
48										212	166	2	378	206	586
47										69	79	0	148	107	255
46										86	109	0	195	192	387
45										114	194	1	308	249	558

of the fauna in these samples is composed of *Woodringina claytonensis* and 1% to 8% is *Chiloguembelina midwayensis*. First appearances and low relative abundances of the following taxa occur during the *P. eugubina* interval of the Ben Gurion sequence: *Globoconusa tripartita, Globoconusa daubjergensis, Eoglobigerina eobulloides* and *Morozovella moskvini* (Fig. 8b, Table IIb).

In the uppermost *P. eugubina* Zone, a pronounced decline in the dominance of *W. claytonensis* and *Ch. midwayensis* and a pronounced increase in the dominance of *Guembelitria cretacea* and *Guembelitria trifolia* begins, similar to that observed at Site 528 (Fig. 8b). This decline of biserial species dominance continues into the basal *M. pseudobulloides* Zone and is immediately followed by a second earliest Paleocene drop in sedimentary carbonate content. *Guembelitria* species continue to dominate foraminiferal populations for the first 1.2 m of the *M. pseudobulloides* Zone. Over this interval, *G. cretacea* and *G. trifolia* comprise up to 43% and 39% respectively of the foraminiferal fauna. In contrast, the combined *Woodringina* and *Chiloguembelina* species drop to as low as 5% of the total assemblage and never rise above 20% of the total assemblage for the duration of the *M. pseudobulloides* Zone *Guembelitria* abundance peak (Fig. 8b).

Throughout the basal 60 cm of the *M. pseudobulloides* Zone, subsidiary faunal elements include low proportions of *P. morphotype 3*, stable small populations of *G. daubjergensis, Planorotalites planocompressa* and *"Eoglobigerina" pentagona* (< 5% of the total fauna belongs to each species), variable populations of *G. tripartita* (3% to 20%) and *M. pseudobulloides* (1% to 9%) and slightly increasing populations of *E. eobulloides* (2% to 9%) and *M. moskvini* (6% to 9%) (Fig. 8b, Table IIb).

In the lower part of the *M. pseudobulloides* Zone, *P. morphotype 3* becomes extinct. Following the interval of the *M. pseudobulloides* Zone *Guembelitria* abundance peak, *W. claytonensis* and *Ch. midwayensis* increase in relative abundance to levels fluctuating between 16% and 30% and between 12% and 22%, respectively (Fig. 8b). Over the same interval, *M. moskvini* increases to 20% of the total assemblage and then decreases to 5% as *M. pseudobulloides* and *Morozovella incônstans* increase in relative abundance to 14% and 3%, respectively. Within this interval of morozovellid and biserial foraminiferal relative abundance, small populations of *Eoglobigerina varianta* appear, *E. eobulloides* fluctuates between 10% and 20%, *G. tripartita* populations decrease to between 3% and 6% and *Guembelitria* relative abundance fluctuates between 7% and 22% of the total population. Throughout the analyzed interval, *Planorotalites planocompressa* and *"Eoglobigerina" pentagona* populations never comprise more than 4% to 5% of the foraminiferal assemblage (Fig. 8b, Table IIb).

The *Woodringina* and *Morozovella* dominated interval is punctuated by a pronounced ~2 cm thick black shale horizon approximately 1.5 m above the base of the *M. pseudobulloides* Zone. This dark shale serves as a regional stratigraphic marker (Keller et al., in press) and is characterized at the Ben Gurion and other Negev sections by a biserial-poor *Morozovella*-dominated population containing 37% *M. moskvini* and 27% *M. pseudobulloides* (Fig. 8b, Table IIb).

DSDP Site 577

Due to extensive carbonate dissolution in uppermost Cretaceous sediments at this site, the Cretaceous planktic foraminifera consistently present in these samples are minor populations of dissolution-resistant *Globotruncanella havanensis* and scattered, poorly preserved pseudoguembelinids, heterohelicids and globigerinelloids (Fig. 9, Table IIIa, Plate I). Gerstel et al. (1986) have previously reported a significant increase in latest Cretaceous >106 μm heterohelicids immediately below the boundary at this site. In the present

TABLE IIb

Ben Gurion earliest Paleocene sample interval, percent carbonate and representative planktic foraminiferal counts (> 63 μm size fraction)

Sample	*Chiloguembelina midwayensis*	*Globoconusa tripartita*	*Globoconusa daubjergensis*	*Eoglobigerina eobulloides*	*Eoglobigerina trivialis*	*Eoglobigerina triloculinoides*	*Eoglobigerina varianta* (Subbotina)	*Morozovella moskvini*	*Morozovella pseudobulloides*	*Morozovella inconstans*	*Planorotalites planocompressa*	"*Eoglobigerina*" *pentagona*	Paleocene Total	Guembelitria Total	Cretaceous Total	Total
69													69	69	214	352
68													68	81	232	381
67													67	53	194	314
66													66	19	192	277
65													65	11	196	272
64													64	15	235	314
63													63	20	224	307
62													66	30	329	425
61													61	48	186	295
60													69	64	210	343
59				4									68	83	151	302
58													75	105	175	355
57	1	2						4					134	97	71	302
56	16	3		1				9					233	83	1	317
55	5	1	3	13	1	2		17					227	63		290
54	3	9	2	5				12	0			2	323	122	1	446
53	10	3	1	9		2		13	0		0	5	211	528		739
52	22	25		10		3		15	2		3	5	202	638		840
51	17	14		8		4		15	3		2	2	145	767		912
50	9	15		12		3		26	1			1	200	701		901
49	9	14		9				37	8		3		208	943		1151
48	15	24	1	18	1	0		42	4		6	2	251	888	2	1141
47	25			14				24	3		3	2	154	724		878
46	37	22	2	18		1		30	15		5	2	238	661		899
45	28	7	2	34		9		51	10		2	12	284	679	1	964
44	23	51	12	33				10	10	0	13	12	227	786		1013
43	29	117		48				36	13		11	10	338	622		960
42	26	40	4	50	1			44	12	3	9	5	254	504		758
41	16	22	3	18		5		40	20	4		11	213	420		633
39	46	27	3	86	3			59	12	6		4	378	420		798
37	26	34		43				36	7	1	4	4	231	489		720
35	28	22		41	1	1		36	3	1	3		223	290		513
33	35	11		25				42	11	4	1		229	177		406
31	67	7		31	1			51	18	3	9	4	290	72		362
30	35	13		15	3	1	1	48	19	3	6	10	254	59		313
29	7	7	1	22		3	7	88	65	4			261	41		302
28	48	9		24	3	3	5	49	40	6	14	10	341	63		404
27	86	2		93	1	7	13	70	44	7	8	1	458	119		577
25	45	13	1	50	1	1	14	27	41	5	11	10	310	114		424
23	42	6		22		1	4	18	28	6	7	5	222	180		402
21	54	28		42	5	2	7	25	63	7	21	18	383	118		501

TABLE IIb (*continued*)

Sample	m. depth	% Carbonate	*Guembelitria cretacea*	*Guembelitria trifolia*	*Chiloguembelitria danica*	*Parvularugoglobigerina morphotype 1*	*Parvularugoglobigerina morphotype 2*	*Parvularugoglobigerina eugubina*	*Parvularugoglobigerina longiapertura*	*Parvularugoglobigerina morphotype 3*	*"Eoglobigerina" taurica*	*"Eoglobigerina" hemisphaerica* Morozova	*Woodringina claytonensis*	*Chiloguembelina morsei*
69	0.00	90.49	20	13										
68	0.12	81.30	25	11										
67	0.26	81.11	5	7										
66	0.31	75.87	3	2										
65	0.43	72.20	1	1										
64	0.56	78.87	3	1										
63	0.71	75.20	7	2										
62	0.82	79.04	6	1						2			2	
61	0.96	77.41	10	4										
60	1.05	78.33	23	4			4	2		3				
59	1.14	81.98	20	3			2			2				1
58	1.22	64.91	17	16			3			1			9	4
57	1.26	61.74	25	23	1	13	17	3	17	5			7	8
56	1.35	61.05	11	4		49	20	23		25			30	1
55	1.38	64.67	8	11		28	16	19	1	16			47	3
54	1.48	63.84	24	4	1	7	15	3		1	13	20	176	1
53	1.54	61.10	28	40	6		6			6			101	2
52	1.64	68.40	249	172	4					8			48	9
51	1.67	54.00	89	48	2					4			25	
50	1.73	43.31	108	89	6					11	2	4	66	
49	1.83	56.89	213	143	3					11		5	60	3
48	1.90	56.64	212	166	3					7	3	4	76	
47	1.98	51.69	69	79						3	2	3	25	3
46	2.03	45.58	86	109						1			56	3
45	2.10	45.90	114	194	10								79	5
44	2.17	54.33	46	112	8					3			15	1
43	2.25	53.34	64	231	7				1	2			25	3
42	2.34	60.36	30	121	3								18	
41	2.37	46.48	14	34									31	2
39	2.48	47.60	71	135	12								92	1
37	2.61	59.72	59	92	3								39	
35	2.74	50.21	47	66	4								52	
33	2.96	37.03	10	9									65	2
31	3.11	45.33	16	25									63	5
30	3.13		3	9									63	7
29	3.15	32.91	2	4									28	
28	3.21		10	12	1								94	8
27	3.27	40.71	13	21									94	5
25	3.40	49.66	23	39									57	9
23	3.55	45.43	7	11									57	3
21	3.74	47.61	36	63	1								84	6

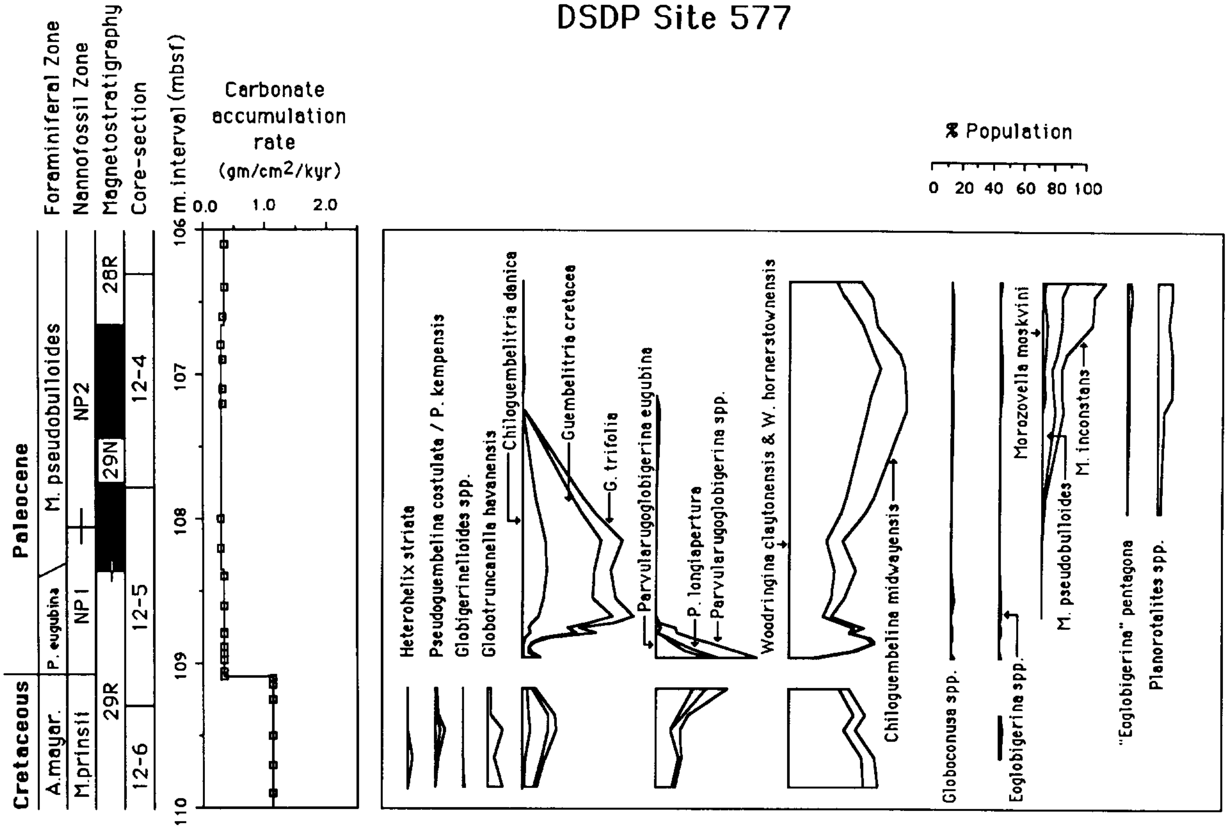


Fig. 9. K/T boundary planktic foraminiferal assemblage turnover (> 63 μm fraction) and carbonate accumulation at then-equatorial Pacific DSDP Site 577. The nannofossil zonation is from Monechi (1985) and the paleomagnetic zonation from Bleil (1985). The low species richness and relative abundance of Cretaceous specimens in the Upper Cretaceous part of the section is probably in part due to carbonate dissolution. The high relative abundance of Early Paleocene specimens and species in the same part of the core is probably due to reworking and/or downcore contamination. Depth in meters below seafloor (mbsf).

study, no noticeable increase in > 63 μm heterohelicid populations is observed immediately below the K/T boundary. Planktic foraminiferal assemblages from the last meter of Upper Cretaceous section at Site 577 contain relatively large populations of well-preserved > 63 μm *P. eugubina, W. claytonensis, Ch. Midwayensis* and small populations of *P. morphotypes 1, 2* and *3* (Fig. 9, Table IIIb, Plate I). Examination of the > 106 μm reaction from these Upper Cretaceous samples also reveals these abundant Paleocene species. The presence of a relatively diverse assemblage of well-preserved earliest Paleocene taxa in these dissolution-dominated foraminifera-poor uppermost Cretaceous samples appears to result from bioturbation and/or downward reworking. Previous stable isotopic analyses of *P. eugubina* populations from these uppermost Cretaceous sediments indicate that these specimens exhibit $\delta^{13}C$ signatures typical of earliest Paleocene oceans (Gerstel et al., 1986). Hence, preservational characteristics, populational abundances and isotopic signatures all suggest that Upper Cretaceous occurrences of *P. eugubina* at Site 577 are due to bioturbation and do not reflect a real Late Cretaceous evolutionary FAD for this species (contra Gerstel et al., 1986).

At the K/T boundary, planktic foramini-

TABLE IIIa

DSDP Site 577 latest Cretaceous sample interval and representative planktic foraminiferal counts (> 63 μm size fraction)

Sample	m. depth	*Heterohelix striata*	*Heterohelix glabrans*	*Pseudoguembelina costulata*	*Pseudoguembelina kempensis*	*Pseudotextularia elegans*	*Globigerinelloides asperus*
12-6(54-56)	109.85				3	1	1
12-6(34-36)	109.65	6	2	3	2		1
12-6(14-16)	109.45		1	8	6		1
12-6(4-6)	109.35			6	3		1
12-5(136-138)	109.17		0		3		

Sample	*Globigerinelloides subcarinatus*	*Hedbergella monmouthensis*	*Globotruncanella species*	*Globotruncanella caravacaensis*	*Globotruncanita stuartiformis* (Dalbiez)	*Schackoina multispinata*	*Guembelitria cretacea*
12-6(54-56)	1	1	23		1		16
12-6(34-36)		1	9	4			34
12-6(14-16)			19	3			27
12-6(4-6)		1	10			1	56
12-5(136-138)			7				11

Sample	*Guembelitria trifolia*	Cretaceous Total	Guembelitria Total	Paleocene Total	Total
12-6(54-56)	8	31	24	199	254
12-6(34-36)	7	28	41	234	303
12-6(14-16)	13	38	40	156	234
12-6(4-6)	16	22	72	327	421
12-5(136-138)	6	10	17	300	327

TABLE IIIb

DSDP Site 577 earliest Paleocene sample interval and representative planktic foraminiferal counts (> 63 μm size fraction)

Sample	m. depth	*Guembelitria cretacea*	*Guembelitria trifolia*	*Chiloguembelitria danica*	*Parvularugoglobigerina morphotype 1*	*Parvularugoglobigerina morphotype 2*	*Parvularugoglobigerina eugubina*	*Parvularugoglobigerina longiapertura*	*Parvularugoglobigerina morphotype I*	*"Eoglobigerina" taurica*	*Woodringina claytonensis*	*Chiloguembelina morsei*	*Chiloguembelina midwayensis*
12-6(54-56)	109.85	16	8	2		5	24		4	7	122		26
12-6(34-36)	109.65	34	7	5		2	46		3	6	145	3	22
12-6(14-16)	109.45	27	13	12		0	23	0	8	3	84	9	8
12-6(4-6)	109.35	56	16	16	1	2	62	13	15	2	178	2	30
12-5(136-138)	109.17	11	6	12	13	15	78	28	18	7	108	2	17
12-5(115-117)	108.96	51	13	2	92	24	192	35	31	5	91	3	12
12-5(110-111)	108.905	26	14	15	71	71	214	82	161		467	4	29
12-5(105-106)	108.855	23	7	5	15	28	44	20	43		231		5
12-5(99-102)	108.815	75	29	11	12	27	39	16	81		317	3	14
12-5(94-96)	108.75	132	41	20	1	19	16		28		222	3	29
12-5(91-93)	108.78	173	75	33	8		9		36		230		15
12-5(85-86)	108.715	217	91	40				3	6		202	8	22
12-5(81-82)	108.675	274	76	59							125		29
12-5(74-76)	108.55	206	97	90	0	0	1	1		1	178		61
12-5(54-56)	108.35	129	42	69		1			1		124	4	54
12-5(34-36)*	108.15	322	119	127					2		214	13	86
12-5(14-16)*	107.95	211	57	79	0			1	3	1	257	21	102
12-5(4-6)	107.85	124	40	45	2				2	1	198	8	86
12-4(114-115)	107.25	6	3	2		22				2	439	32	193
12-4(94-96)	107.15		1		0					1	493	4	223
12-4(74-75)	106.95	2	3		0					1	393	1	101
12-4((54-56)	106.85									1	612	12	177
12-4(34-36)	106.65		2								277	1	53
12-4(14-16)	106.45	1	1	1							220	17	90
12-4 (4-6)	106.35			2							234	8	112

Sample	*Globoconusa tripartita*	*Globoconusa daubjergensis*	*Eoglobigerina eobulloides*	*Eoglobigerina trivialis*	*Eoglobigerina triloculinoides*	*Morozovella moskvini*	*Morozovella pseudobulloides*	*Morozovella inconstans*	*Planorotalites planocompressa*	*"Eoglobogerina" pentagona*	Paleocene Total	Cretaceous Total	Total
12-6(54-56)	1					3		5			223	31	254
12-6(34-36)			2								275	28	303
12-6(14-16)		1	5							3	196	38	234
12-6(4-6)			6								399	22	421
12-5(136-138)	2										317	10	327
12-5(115-117)	7	2	3			1					564		564
12-5(110-111)											1154		1154
12-5(105-106)	1										422		422
12-5(99-102)	5	1	2								632		632
12-5(94-96)	3		5	1	1						521		521
12-5(91-93)	4	4 .	4								591		591
12-5(85-86)			2								591		591
12-5(81-82)	2		4			1					570		570
12-5(74-76)	12	2	3		5	2					659		659
12-5(54-56)	1										425		425
12-5(34-36)*	3	1	1			2					890		890
12-5(14-16)*		2	1			3	7		17	2	764		764
12-5(4-6)	2		1			3	7		13		532		532
12-4(114-115)		5	3				77	40	38	12	874		874
12-4(94-96)	1	5	3	2	0	21	52	43	86	9	944		944
12-4(74-75)		1	4	2		8	32	41	65	8	662		662
12-4((54-56)		11	4	3		24	76	72	111	11	1114		1114
12-4(34-36)		5	3			19	54	121	46	5	586		586
12-4(14-16)		5				9	69	126	56	20	615		615
12-4 (4-6)			3	1		17	108	187	71	18	761		761

feral preservation strongly improves (Zachos et al., 1985). Sediments with typical P0 Zone assemblages appear to be absent at this site (Gerstel et al., 1986; this report). Although the Site 577 core has been depleted at the K/T boundary, examination of equivalent samples from Hole 577A indicates that the P0 Zone is not present at that drill-hole either. The absence of P0 Zone sediments suggests either bioturbation, core disturbance or a short hiatus in the basal Paleocene record of this locality.

As at DSDP Site 528 and the Ben Gurion section, *Guembelitria cretacea* and *G. trifolia* are the only Cretaceous species which range into the *P. eugubina* Zone at DSDP Site 577. At this site, faunal assemblages of the basal *P. eugubina* Zone are characterized by local maxima in the populational abundance of *Parvularugoglobigerina morphotype 1* (16%), *P. morphotype 2* (4%), *P. eugubina* (34%), *P. longiapertura* (9%) and *P. morphotype 3* (14%). Also as at Site 528 and the Ben Gurion section, the earliest Paleocene parvulorugoglobigerinid abundance peak is quickly followed by an abundance peak of earliest Paleocene biserials, primarily *W. claytonensis* (up to 54% of the total assemblage) with minor abundances of *Ch. midwayensis* (1 to 3%) (Fig. 9, Table IIIb).

Within the *P. eugubina* Zone occurs a pronounced decline in the relative dominance of *W. claytonensis* and a pronounced increase in the dominance of *G. cretacea* (up to 48%), *G. trifolia* (up to 15%) and *Chiloguembelitria danica* (up to 16%). Through the basal 29N magnetochron, *Guembelitria* species dominate the foraminiferal assemblage with subsidiary numbers of *W. claytonensis* (including forms intergradational with *Woodringina hornerstownensis*) (up to 27%) and *Ch. midwayensis* (up to 13%) (Fig. 9). In the *M. pseudobulloides* Zone, *Guembelitria* species decrease strongly in relative abundance, dropping to less than 1% of the total assemblage by the upper 29N and lower 28R magnetochrons. Over the interval of decreasing guembelitriid assemblage dominance, *W. claytonensis* (including morphotypes intergradational with *W. hornerstownensis*) and *Ch. midwayensis* again increase in relative abundance, respectively reaching maxima of 59% and 24%. Also over the interval of decreasing *Guembelitria* assemblage dominance, *M. pseudobulloides, M. inconstans* and *P. planocompressa* all increase in relative abundance to comprise 7%, 6% and 10% of the total counted populations, respectively. Over the interval of the lower 28R magnetochron, *M. pseudobulloides* and *M. inconstans* continue to increase relative to other taxa, comprising 14% and 25% of the total assemblage by the end of the analyzed sequence. Throughout the Paleocene 29R through lower 28R magnetochrons at DSDP Site 577, the following taxa are present only in minor abundances: *Globoconusa tripartita, Globoconusa daubjergensis, Eoglobigerina eobulloides, E. trivialis, E. triloculinoides* and *Morozovella moskvini* (Fig. 9, Table IIIb).

Species richness

Species richness is the number of species present in each counted sample (MacArthur, 1972; Pianka, 1974). This parameter was determined for all foraminiferal samples discussed in this report in order to estimate local diversity trends over the examined interval. Because species richness is determined in this study from representative counts of single-site fossil assemblages, it is strictly a measure of local diversity and does not directly measure global planktic foraminiferal diversity. Since the sampled fossil assemblages are affected by sedimentation rate, bioturbation, sample thickness and other time-averaging effects, species richness as measured in this study is also not an instantaneous measure of diversity in biological populations. Rather, it is a measure of fossil assemblage diversity averaged over the temporal interval affected by bioturbation (up to a few thousand years). Additionally, estimates of species richness reflect the taxonomic philosophy of the individual paleontologist. For this reason, different workers may calculate slightly different values of species richness for identical samples, although species richness trends should not change much, assuming each taxonomist is consistent from sample to sample.

Latest Cretaceous planktic foraminiferal assemblages from DSDP Site 528 average 20 species per counted sample (300 to 600 specimens), ranging between 18 and 22. No significant increase or decrease in species richness occurs as the boundary is approached (Fig. 10). Species richness of Upper Cretaceous samples from the Ben Gurion section averages 17 ranging between 12 and 20. As at Site 528, no significant change in species richness occurs prior to the K/T boundary (Fig. 10). The apparent difference in species richness between the two sites may reflect slightly higher species richness in open-ocean sites. At both sites, these estimates probably underestimate actual species richness, due to the existence of rare Late Cretaceous species not consistently present in the counted samples but possibly present in the larger populations from which those samples were taken: some examples include *Planoglobulina* species, *Racemiguembelina* species, *Schackoina multispinata* and several globotruncanid species.

P0 Zone samples of both the Ben Gurion section and Site 528 are characterized by unusually high numbers of species: 22 to 25 species are present in P0 Zone samples of the Ben Gurion section and 12 species are present in the P0 Zone sample of DSDP Site 528 (Fig.

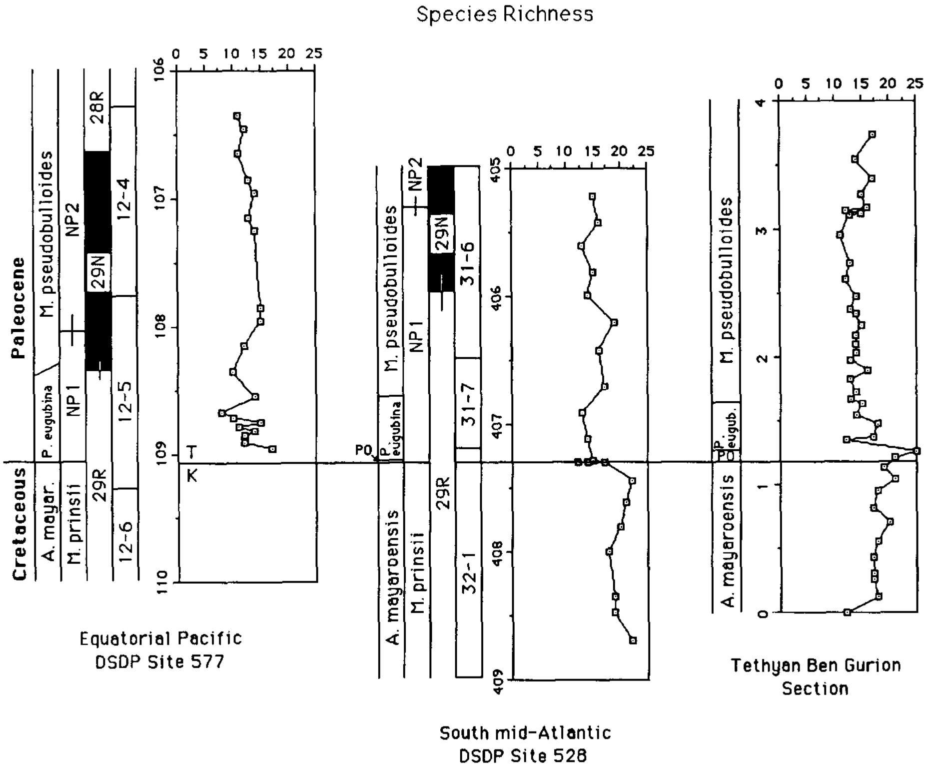


Fig. 10. Planktic foraminiferal species richness for the K/T boundary sequences of DSDP Sites 528 and 577 and the Ben Gurion section. Species richness is the number of species present in each counted sample. Site 528 nannofossil and paleomagnetic zonations are from Manivit (1984), Bralower (unpubl.) and Chave (1984). Site 577 nannofossil zonation and paleomagnetic zonations are from Monechi (1985) and Bleil (1985). Planktic foraminiferal zonation is from this study.

10). Between 14 and 19 of the species present in Ben Gurion P0 Zone samples are typically Cretaceous taxa, as are 8 of the species present in the P0 Zone sample of Site 528. It is likely that many of these are reworked. However, it is also possible that the balance between *Guembelitria* species, newly evolving Paleocene taxa (i.e. *Chiloguembelitria danica, Parvularugoglobigerina morphotype 1, Woodringina claytonensis*) and rapidly disappearing K/T boundary survivors (i.e. *Heterohelix globulosa, Heterohelix striata, Pseudoguembelina costulata*: Keller, 1988, 1989a) prevents species richness from dropping to previously suggested levels of 1 to 2 species in the earliest Paleocene (Smit, 1982; Collins, 1989). Even at the relatively expanded El Kef K/T boundary sequence, P0 Zone species richness never drops below 5 species in any given sample (Keller, 1988).

Species richness of *P. eugubina* Zone and *M. pseudobulloides* Zone samples from Site 528 fluctuates between 13 and 19, exhibiting a slight increase in average value from the *P. eugubina* Zone to the *M. pseudobulloides* Zone (from 14 to almost 16). Species richness of *P. eugubina* Zone and *M. pseudobulloides* Zone samples from the Ben Gurion section fluctuates between 11 and 18, also increasing in average value within the *M. pseudobulloides* Zone from 14 to almost 16 (Fig. 10). The latter increases in average species richness reflect an increased presence of *Morozovella* and *Eoglobigerina* species in *M. pseudobulloides* Zone assemblages (Figs. 7b, 8b). Species richness of *P. eugubina* Zone and *M. pseudobulloides* Zone samples from DSDP Site 577 ranges from 8 to 17. As at the other two sites, average species richness increases slightly from the *P. eugubina* Zone to the *M. pseudobulloides* Zone (from 12 to 13) (Fig. 10). Due to reworking, the species richness of the Site 577 foraminiferal samples may be slightly inflated. This problem is most acute in the lowermost Paleocene samples where relatively fewer foraminifera were initially present (such as the basal paleocene sample which exhibits an apparent species richness of 17). The generally low planktic foraminiferal diversity of the earliest Paleocene (Smit, 1977, 1982; Toumarkine and Luterbacher, 1985; Keller, 1988, 1989a) precludes the possibility that these earliest Paleocene estimates seriously underestimate actual species richness in the represented assemblages.

Discussion

At both DSDP Site 528 and the Ben Gurion section, Late Cretaceous foraminiferal assemblages are relatively stable and dominated by *Heterohelix, Pseudoguembelina* and *Globigerinelloides*. Despite this similarity, noticeable differences occur between the Late Cretaceous faunal assemblages of these sites. Larger populations of biserial, triserial, and multiserial genera (*Heterohelix, Pseudoguembelina, Guembelitria, Planoglobulina*) relative to planispiral and trochospiral genera (*Globigerinelloides, Hedbergella, Globotruncanella, Globotruncana*) are present at the Ben Gurion Section than at DSDP Site 528 (Figs. 7a, 8a). Additionally, slightly lower species richness characterizes the Ben Gurion section than the coeval Site 528 sequence (Fig. 10). These differences indicate that the Ben Gurion section is characterized by assemblages intermediate between those of Site 528 and those of the nearshore El Kef and epicontinental Brazos sections, which are dominated by biserial and triserial *heterohelix, Pseudoguembelina* and *Guembelitria* to the near-exclusion of trochospiral forms (Figs. 7a, 8a, 11, 12) (Keller, 1988, 1989a). The differences between the latest Cretaceous faunas of these sites are consistent with the observation by Pessagno (1970), Douglas (1971, 1972), Sliter (1972a,b) and Leckie (1987) that Cretaceous biserial, triserial and multiserial forms are relatively more abundant than keeled trochospiral forms in epicontinental environments while keeled trochospiral forms are relatively more abundant

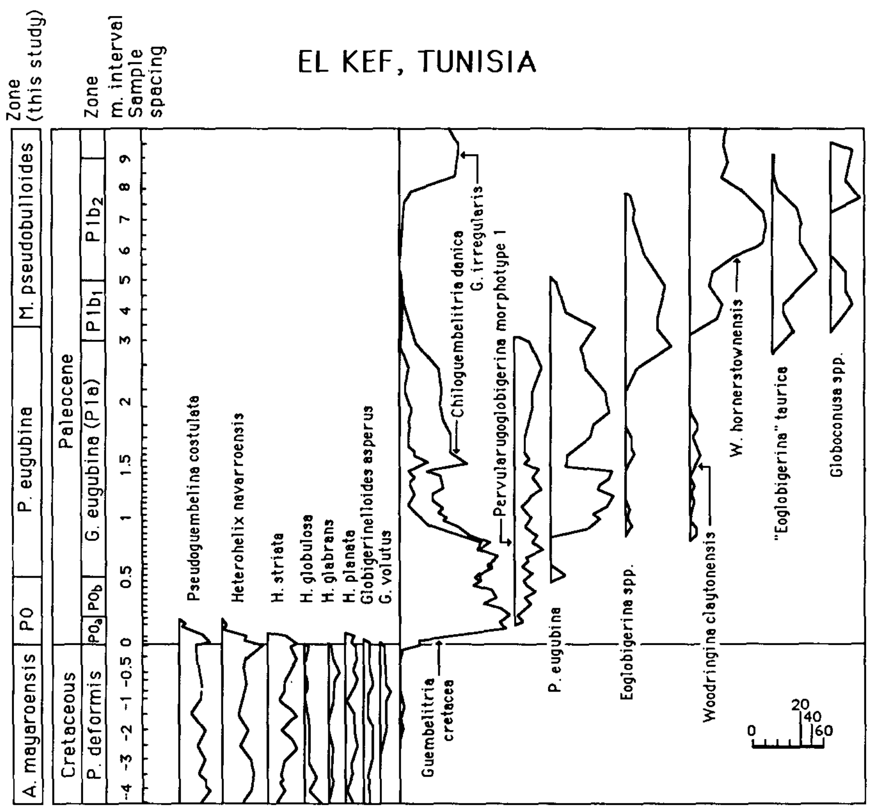


Fig. 11. K/T boundary planktic foraminiferal assemblage turnover (> 63 μm fraction) at El Kef, Tunisia. Modified from Keller, 1988.

in open-ocean environments. These differences are also consistent with the finding by Smith and Pessagno (1973) and Leckie (1987) that *Guembelitria* species are limited to shallow neritic environments and may be tolerant of relatively low salinity conditions.

At the K/T boundary, the above differences between open-ocean and epicontinental foraminiferal faunas disappear. At South Atlantic sites, this breakdown of biogeographic provincialization is stratigraphically unresolvable at time-scales less than 21,000 years (Herbert and D'Hondt, 1990). P0 Zone >63 μm assemblages of all examined sites, whether open-ocean, outer-shelf or epicontinental, are marked by abundant guembelitriids (previously rare at open-ocean sites) and the virtual absence of previously abundant open-ocean forms (Smit, 1977; this study). These previously abundant forms include most shallow-water open-ocean species [*Rugoglobigerina, Hedbergella, Globigerinelloides* and *Pseudotextularia* species (Boersma and Shackleton, 1981; Leckie, 1987)] and deeper-water open-ocean species [i.e., globotruncanid species (Boersma and Shackleton, 1981)]. The earliest Paleocene P0 Zone assemblages of DSDP Site 528, the Spanish Caravaca section, the Ben Gurion section and the El Kef section are characterized by abundance peaks of *Guembelitria* species (primarily *G. cretacea*), with secondary abundances of *Heterohelix* and *Pseudoguembelina* species (Figs. 7a,b, 8a,b, 11) (Smit, 1977, 1982; Keller, 1988). The Brazos Core P0 Zone is dominated by *Heterohelix globulosa* and *G. cretacea* with minor abundances of other *Heterohelix* and *Pseudoguembelina* species (Keller, 1989a) (Fig. 12). Minor populations of *Globigerinelloides asperus* are present in P0 Zone assemblages of the

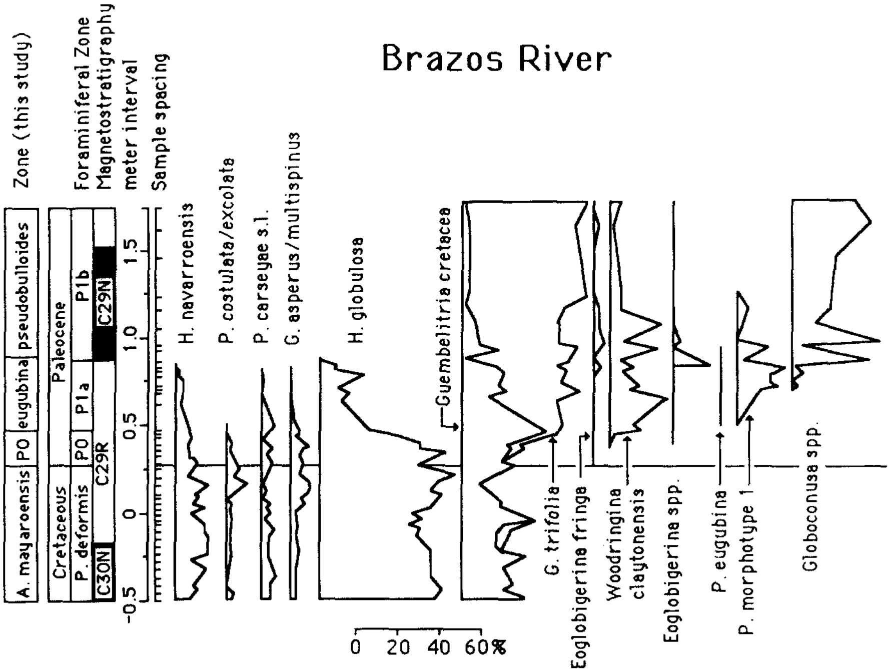


Fig. 12. K/T boundary planktic forminiferal assemblage turnover (> 63 μm fraction) at the Brazos River, Texas core. Modified from Keller, 1989. The paleomagnetic zonation is from W. Gose (unpubl., in Keller, 1989).

above sites, as are small numbers of earliest Paleocene foraminifera (*Woodringina claytonensis, Parvularugoglobigerina morphotypes 1* and *2* and *Globoconusa tripartita*). Hence, P0 Zone > 63 μm assemblages are characterized in both open-ocean and epicontinental environments by the abundance of forms previously dominant in epicontinental environments (i.e., the relatively small triserial *Guembelitria* and some biserial *Heterohelix*). Such preferential survival and assemblage dominance suggest that the K/T boundary planktic foraminiferal extinction event is not random or non-selective. While the proximal cause of this K/T boundary shift in dominant open-ocean planktic foraminiferal fauna is uncertain, it clearly coincides with the well-documented K/T boundary decrease in marine primary productivity (Hsü et al., 1982; Zachos et al., 1986, 1989; Arthur et al., 1987; D'Hondt and Lindinger, 1988; Keller and Lindinger, 1989) (Figs. 7a,b, 9).

There are several possible causes of the preferential K/T boundary survival and planktic foraminiferal assemblage dominance by previously epicontinental faunas. Some of these possible causes are: (i) selection of opportunistic forms previously adapted to an unstable environment; (ii) weaker environmental change in some or all epicontinental regions relative to open-oceans; and (iii) K/T boundary selection of specific traits previously selected for in nearshore environments. The extant triserial planktic foraminifera *Gallitellia vivans* occurs in the southern Red Sea, in Indian Ocean shelf regions (with a abundance maxima in an upwelling region immediately south of India) (Kroon and Nederbragt, 1990), in the semi-enclosed Persian Gulf [Lutze, reported in Kroon and Nederbragt (1990)], in the Huanghai Sea, a shallow sea with significant riverine input (Wang et al., 1985), in the Gulf of Mexico and in the North and South Pacific Oceans (Loeblich and Tappan, 1988). Analogy with *Gallitellia vivans* suggests that the K/T boundary survival and assemblage dominance of *Guembelitria* species reflects selection of opportunistic forms previously adapted to an unstable environment. While this analogy is consistent with present knowledge of guembelitriid paleoenvironmental associations (Smith and Pessagno, 1973; Leckie, 1987), we need a better understanding of K/T boundary environmental change and foraminiferal environmental preferences in order to definitively determine which possible causes actually apply. Regardless of cause, the preferential survival and earliest Paleocene expansion of guembelitriid species into the open-ocean exhibits a geologically short-term species-level pattern of onshore–offshore ecologic expansion. This pattern resembles longer-term ordinal and ichnogeneric patterns of evolutionary radiation observed in post-Paleozoic echinoderms (Jablonski and Bottjer, 1988), trace fossils (Bottjer et al., 1988) and Paleozoic trilobites and articulate brachiopods (Sepkoski, 1989). Whether this resemblance is coincidental or results from the operation of similar sorting processes at different taxonomic levels and geologic time-scales remains to be demonstrated.

Comparison of >63 μm earliest Paleocene foraminiferal assemblages from several sites (DSDP Sites 528 and 577, Ben Gurion, Israel, El Kef, Tunisia and Brazos River, Texas) indicates that large differences in guembelitriid dominance occur between planktic foraminiferal faunas of different localities within the P0 Zone. By the basal *P. eugubina* Zone, Cenozoic trochospiral forms are notably abundant at open-ocean sites 528 and 577 and the Ben Gurion and El Kef sections relative to the epicontinental Brazos site. The appearance of this *P. eugubina* Zone and *M. pseudobulloides* Zone difference between these faunas may mark the earliest Paleocene re-introduction of planktic foraminiferal open-ocean and epicontinental bioprovincialization.

At Site 528, Site 577 and the Ben Gurion section, the earliest *P. eugubina* Zone is marked by an abundance peak of *Parvularugoglobigerina* species. At all three sites, this early abundance peak is immediately followed by a low diversity *P. eugubina* Zone abundance peak in biserial *Woodringina* and *Chiloguembelina*, in turn followed closely by a *P. eugubina* Zone and *M. pseudobulloides* Zone *Guembelitria* abundance peak. This second Early Paleocene *Guembelitria* abundance peak is eventually followed by a second *Woodringina* and *Chiloguembelina* abundance peak and the first significant populations of *Morozovella* forms (Figs. 7b, 8b, 9).

Despite these similarities, the Site 577 *P. eugubina* and *M. pseudobulloides* Zone assemblages notably differ from coeval assemblages of Site 528 and the Ben Gurion section. Site 577 is marked by a delayed decrease in *Guembelitria* abundance, the delayed introduction of abundant *Morozovella* and the absence of relatively abundant *Globoconusa* and *Eoglobigerina*. All of these differences result in much lower species diversity at Site 577 than at Site 528 and the Ben Gurion section (Figs. 7b, 8b, 9, 11). This lower diversity at DSDP Site 577 may be related to the relatively lower carbonate productivity also typical of this site (Fig. 6).

At the Tethyan shelf El Kef section, as at DSDP Sites 528, 577 and the Ben Gurion section, the basal *P. eugubina* Zone is marked by an abundance peak of *Parvularugoglobigerina* species (Keller, 1988). The initial *Woodringina* and *Chiloguembelina* abundance peak of the El Kef *P. eugubina* Zone is greatly reduced relative to those at the open-ocean sites and the outer-shelf Ben Gurion section. Additionally, at the El Kef section, *Guembelitria* and *Parvularugoglobigerina* species remain dominant faunal constituents throughout the *P. eugubina* Zone (Fig. 11). As at DSDP Site 528 and the Ben Gurion section, the *M. pseudobulloides* Zone assemblages of the El Kef section are marked by increasing populations of Paleocene biserial (*Chiloguembelina* and *Woodringina*) and *Globoconusa* species. Unlike Site

528 and the Ben Gurion section, the basal *M. pseudobulloides* Zone assemblages of El Kef are not marked by abundant *M. moskvini*, but by abundant *"Eoglobigerina" taurica* (Keller, 1988) (Figs. 7b, 8b, 11).

As in the late Cretaceous, Early Paleocene Brazos River assemblages differ notably from coeval assemblages of the more open-ocean sections. At the Brazos River section, *Heterohelix globulosa* dominates the P0 Zone assemblages and *Guembelitria* species strongly dominate the *P. eugubina* and lower *M. pseudobulloides* Zone assemblages. This guembelitriid abundance peak appears to span the million year interval from the Paleocene 29R magnetochron through the basal 28R magnetochron (Keller, 1989a). Unlike the other sites, there appears to be no *P. eugubina* Zone *Woodringina* and *Chiloguembelina* abundance peak at the Brazos River section. The reduced abundance of *P. eugubina* Zone *Woodringina* and *Chiloguembelina* at Brazos River and El Kef relative to the more open-ocean sites may reflect a preference for deeper or less oxygenated water than is available during the *P. eugubina* Zone at those localities. Such a habitat preference is indicated by stable isotopic depth rankings of Paleocene and Eocene chiloguembelinids (Boersma and Premoli Silva, 1989). As at the three sites examined for this report, the Brazos River section is marked by upper 29R and basal 29N magnetochron abundance peaks of *Woodringina*, perhaps indicating a transgressive shift to deeper or less oxygenated water at this locality. The only other planktic foraminifera notably abundant through this interval at this site are *Parvularugoglobigerina morphotype 1, Globoconusa spp.*, and a very small abundance peak of *Eoglobigerina sp.* (Keller, 1989a) (Fig. 12). With the exception of the latter small peak, abundant populations of >63 μm trochospiral species belonging to the Cenozoic *Globigerinidae* do not appear to be present at this epicontinental site through the 28N interval (Keller, 1989a) (Fig. 12).

In short, Site 528, Site 577 and the Ben Gurion section are distinguished from the Brazos River and El Kef sections by the survival of large *H. globulosa* populations at the Brazos River section, the absence of abundant *Globigerinidae* at the Brazos River section and the damping of the open-ocean *P. eugubina* Zone biserial abundance peak at both El Kef and Brazos River sections. These differences suggest that epicontinental and open-ocean bioprovincialization is re-established soon after the K/T boundary (Figs. 7b, 8b, 9).

Conclusions

Immediately prior to the Cretaceous–Tertiary boundary, no significant change occurs in planktic foraminiferal assemblage composition or species richness of examined sequences. A geologically rapid shift in open-ocean planktic foraminiferal faunas occurs at the K/T boundary, with previously epicontinental assemblages dominant at both epicontinental and open-ocean sites. This pronounced dominance of K/T boundary assemblages by formerly epicontinental faunas is not consistent with hypotheses of random or non-selective extinctions.

The Early Paleocene re-establishment of epicontinental and open-ocean planktic foraminiferal provinces appears to be extremely rapid–occurring by the basal *P. eugubina* Zone. At open-ocean sites 528 and 577 and the outer-shelf Ben Gurion section, *P. eugubina* Zone faunal records are marked by a pronounced alternation between non-biserial and biserial-dominated assemblages. This alternation is strongly damped at previously examined shelf and epicontinental sections (Keller, 1988, 1989a). The first appearance and peak magnitude of abundant >63 μm earliest Paleocene trochospiral forms (*Parvularugoglobigerina, Eoglobigerina, Morozovella*) also vary between the epicontinental Brazos River site (Keller, 1989a) and the open-ocean and shelf sequences examined for this report.

By the mid *P. eugubina* Zone, noticeable differences appear in the relative abundance of trochospiral *Globigerinidae* at the different sites examined. These assemblage differences continue to increase throughout the earliest Paleocene, with the introduction of abundant early morozovellids delayed by almost 500,000 years at Site 577 relative to Site 528. Congruence between these relative abundance patterns and carbonate accumulation rates suggests a close dependence of newly appearing foraminiferal assemblages on levels of primary carbonate productivity.

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