The Eocene–Oligocene planktic foraminiferal transition: extinctions, impacts and hiatuses

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Abstract – Biostratigraphic study and re-examination of 22 late Eocene to early Oligocene sections provides data in support of three and possibly a fourth late Eocene impact events in the *G. index* Zone during a period of about 1 Ma of the middle Priabonian between 34.7 and 35.7 Ma. No major species extinctions or significant species abundance changes directly coincide with these impact events. Species extinctions are gradual and selective, affecting primarily cool-temperature-intolerant surface dwellers. These extinctions began with the onset of global cooling during the early middle Eocene and culminated near the Eocene/Oligocene boundary. The global cooling was associated with the isolation of Antarctica as Australia moved northward, the development of a circum-Antarctic circulation, growth of Antarctic ice sheet beginning by late middle Eocene time and a change from a thermospheric to thermohaline circulation. We find no evidence that the multiple late Eocene impact events directly contributed to the climatic deterioration already in progress.

1. Introduction

The Eocene–Oligocene (E/O) transition forms one of the three major mass extinction events during the past 65 Ma with the earlier two extinction events at the Palaeocene/Eocene (P/E) and Cretaceous/Tertiary (K/T) boundaries. During the E/O transition spanning from the late middle Eocene to early Oligocene, global temperatures cooled more than any time since the Mesozoic leading to the formation of the first Antarctic ice sheets. During this time a circum-Antarctic circulation pattern was established as Australia separated from Antarctica and the oceans changed from a thermospheric to thermohaline circulation as a result of Antarctic glaciation (Kennett, 1977, 1980). Associated with these climatic and oceanic circulation changes are major waves of extinctions among terrestrial and marine organisms (Berggren & Prothero, 1992). Several extra-terrestrial impacts occurred during the late Eocene, but are not associated with major extinctions (Keller, 1986), and their relationship to climate change (if any) is unclear.

During the last decade numerous studies have dealt with the climatic and biotic changes across the E/O transition (see volumes edited by Pomerol & Premoli Silva, 1986; Premoli Silva, Coccioni & Montanari, 1988 and Prothero & Berggren, 1992) in an effort to elucidate the environmental effects of this crisis, to determine the precise timing and nature of extinctions and climatic shifts, and to determine a possible cause-and-effect relationship between extra-terrestrial impacts and climate change and extinctions (Keller, 1986; Keller, D'Hondt & Vallier, 1983; Keller *et al.* 1987*a*; Montanari, 1990). These studies have resulted

in a wealth of data rivalled only by the K/T boundary interval. More importantly, however, they have resulted in a revised geochronology due to detailed biostratigraphic and magnetostratigraphic studies and radiometric dating (Odin, Clauser & Renard, 1988; Odin *et al.* 1988, 1991; Prothero & Swisher, 1992), and a section at Massignano (Italy) was officially designated as Eocene/Oligocene boundary stratotype.

The purpose of this study is to evaluate the planktic foraminiferal turnover in the Massignano stratotype and to correlate and compare this section with the similarly complete Torre Cardela, Fuente Caldera and Molino de Cobo sections of Spain, the Barbados section and the most complete deep-sea sections in the Atlantic, Pacific and Indian Oceans (Fig. 1). This will allow us to evaluate (1) whether the Massignano stratotype is globally representative of the faunal turnover, (2) whether extinctions are synchronous, (3) the number and stratigraphic position of impact horizons and (4) the presence of hiatuses and their relationship to climate and sea level changes. In addition, we have re-evaluated the biostratigraphy of 21 deep-sea and onshore marine sections in order to determine the stratigraphic completeness, the presence of hiatuses and the chronostratigraphical position of impact horizons. Based on these data we re-evaluated the number of impact horizons and their relationship to species extinctions, faunal turnover, hiatuses and sea level changes.

2. Methods

Sediment samples were disaggregated by soaking in Calgon water overnight with the addition of a small
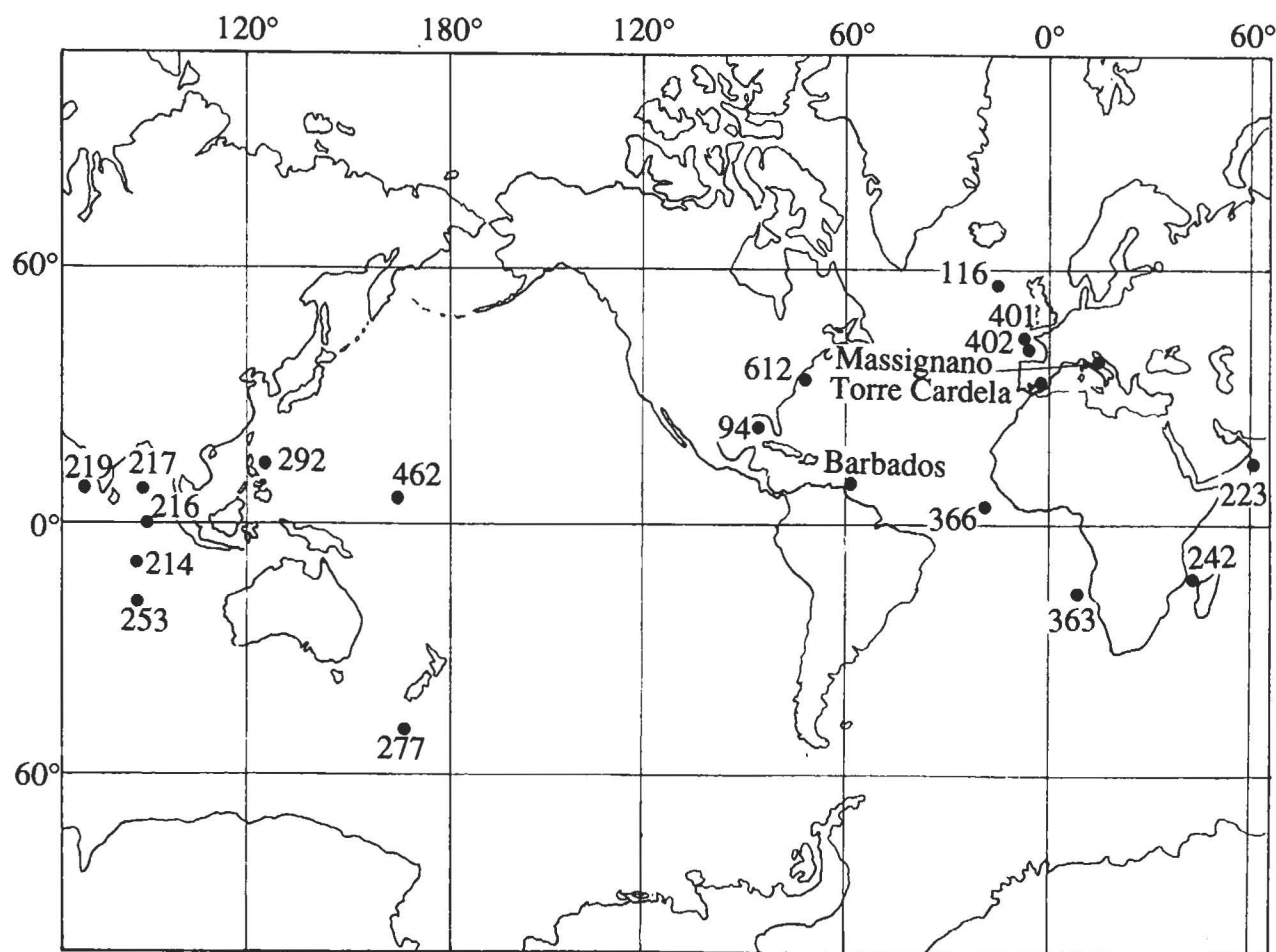
Figure 1. Geographical location of DSDP sites and land sections restudied.

amount of 10% hydrogen peroxide. Samples were then washed with tap water over 63 and 150 μm screens and dried in the oven. Quantitative counts for faunal analysis were obtained from aliquots (using a modified Otto microsplitter) of approximately 300–500 specimens in the size fraction greater than 150 μm. The remaining sample was scanned for rare species and the fractions between 63 and 150 μm were examined for smaller species. All specimens picked from the aliquot and the rare taxa from the rest of the sample were mounted on a microslide for a permanent record and identified. For palaeoecological analysis taxa were grouped into surface, intermediate and deep water dwellers based on oxygen and carbon isotope ranking by Keller & MacLeod (1992).
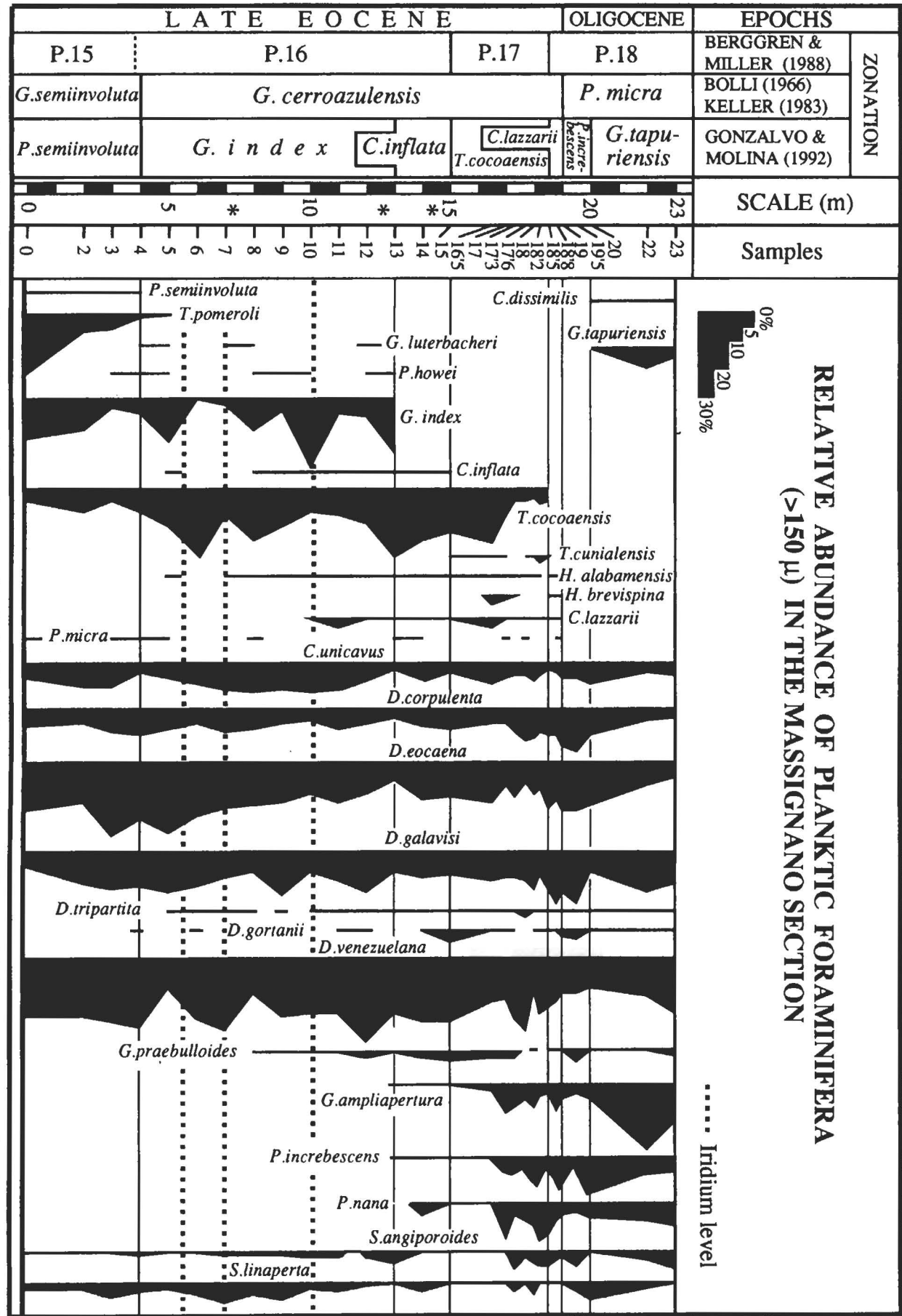
3. Chronostratigraphy and biostratigraphy

New radioisotopic dates from volcanic ashes in sections of the Marche–Umbria basin of Italy (including the Massignano stratotype section) which have both magneto- and biostratigraphic control (Montanari, 1988; Montanari *et al.* 1988; Odin *et al.* 1988) and from microtektite horizons on Barbados,

Site 94 and Site 612 (Glass & Crosbie, 1982; Glass, Hall & York, 1986; Glass, 1989) have necessitated a revision of the commonly used late Eocene to early Oligocene time scale of Berggren, Kent & Flynn (1985). In a recent summary of this new data Berggren *et al.* (1992) revised the E/O boundary from their earlier 36.6 Ma age to 34 Ma. The ages for the Oligocene/Miocene (24 Ma) and Palaeocene/Eocene (55 Ma) boundaries remain unchanged. The main effect of this younger revision of the E/O boundary is to shorten the Oligocene and lengthen the late Eocene by 2.6 Ma.

Based on detailed stratigraphic studies of the Massignano (Italy) and Torre Cardela (Spain) sections Gonzalvo & Molina (1992) have refined the most commonly used biozonations of Bolli (1966) and Berggren & Miller (1988). The following biozonation was established: *Porticulasphaera semiinvoluta, Globigerapsis index, Cribrohantkenina inflata, Turborotalia cocoaensis, Cribrohantkenina lazzarii, Paragloborotalia increbescens* and *Globigerina tapuriensis* Biozones. The index species used to define these biozone boundaries are shown in Figure 10. This stratigraphic refinement improves the relative age correlation and in

Figure 2. Relative abundance of planktic foraminifera in the Massignano section (Italy). Dotted lines mark Ir anomalies. Asterisks in metre column mark position of radiometric ages of Montanari, 1988, 1990, Odin & Montanari, 1988, and Odin *et al.* 1988, 1991.

RELATIVE ABUNDANCE OF PLANKTIC FORAMINIFERA (>150 μ) IN THE MASSIGNANO SECTION

	LATE EOCENE			OLIGOCENE	EPOCHS	
P.15	P.16		P.17	P.18	BERGGREN & MILLER (1988)	ZONATION
G.semiinvoluta	G. cerroazulensis			P. micra	BOLLI (1966) KELLER (1983)	
P.semiinvoluta	G. i n d e x	C.inflata	C.lazzarii / T.cocoaensis	P.incre-bescens / G.tapu-riensis	GONZALVO & MOLINA (1992)	

SCALE (m): 0   5   *   10   *   *   15   20   23

Samples: 0 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 17 173 176 18 182 185 188 19 195 20 22 23

P.semiinvoluta
T.pomeroli
G. luterbacheri
P.howei
G. index
C.inflata
T.cocoaensis
T.cunialensis
H. alabamensis
H. brevispina
C.lazzarii
P.micra
C.unicavus
D.corpulenta
D.eocaena
D.galavisi
D.tripartita
D.gortanii
D.venezuelana
G.praebulloides
G.ampliapertura
P.increbescens
P.nana
S.angiporoides
S.linaperta
C.dissimilis
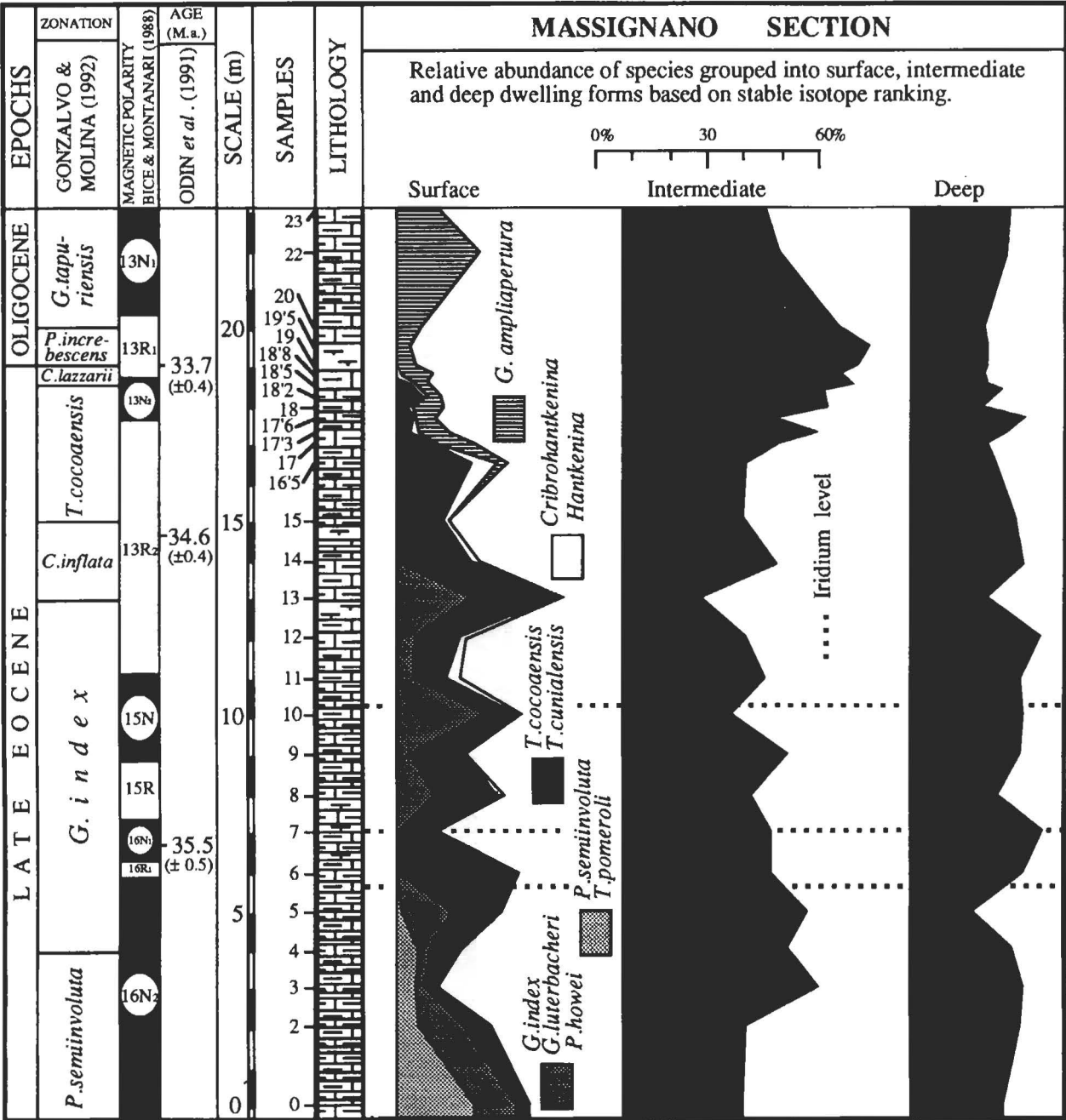G.tapuriensis

0%
5
10
20
30%

······ Iridium level

485

Figure 3. Relative abundance of species grouped into surface-, intermediate- and deep-dwelling forms based on stable isotope ranking in the Massignano section (Italy). Intermediate-dwelling taxa include *D. corpulenta*, *D. eocaena*, *D. galavisi*, *S. linaperta*, *S. angiporoides*. Deep dwellers include *C. unicavus* and *D. venezuelana* (see Fig. 2).

particular aids in the stratigraphic placement of the impact horizons which were found in the late Eocene.

3.a. Massignano stratotype section (Italy)

The Massignano section is located in an abandoned quarry placed near Massignano village (Ancona, Italy). Geologically this section is part of the Marche–Umbria basin of the northeastern Apennines and belongs to the Scaglia Variegata and Scaglia Cinerea

lithostratigraphic units, which has been discussed by Alvarez & Montanari (1988) and Coccioni *et al.* (1988).

The Massignano section consists of a 23 m thick pelagic carbonate sequence of reddish and greenish-gray marls and calcareous marls. Several thin biotite-bearing layers of volcanic origin are present near the boundary between the Scaglia Variegata and Scaglia Cinerea. These biotite-bearing layers were studied by Montanari (1988, 1990), Odin & Montanari (1988),

Odin, Clauser & Renard (1988), and Odin *et al.* (1991) and yielded radioisotopic ages of 34.6 ± 3 Ma (at 14.7 m), 34.3 ± 2 Ma (at 12.7 m) and 35.5 ± 3 Ma (at 7.2 m) (see Figure 2 for metre location of these biotite-bearing layers marked by asterisks). In addition, an age of 33.7 ± 0.5 Ma was estimated for the Eocene/Oligocene boundary, and the age of the Priabonian stage between 37.5 Ma and 33.7 ± 0.5 Ma based on the study of six sections from the Apennines (Odin *et al.* 1991). Earlier magneto- and biostratigraphic studies were published by Bice & Montanari (1988) and Coccioni *et al.* (1988) respectively. Recently, the Eocene/Oligocene Boundary Stratotype has been officially designated in the Massignano section at metre 19, which appears to coincide with the hantkeninid extinction event, marking the Priabonian/Rupelian boundary.

Figure 2 illustrates the biostratigraphy and relative abundance changes of planktic foraminifera in the Massignano section. The two most commonly used zonal schemes are shown for comparison with the more detailed Gonzalvo & Molina (1992) biozonation. Note that the Massignano section shows a relatively gradual faunal turnover throughout the late Eocene, beginning with the extinction of *Porticulasphaera semiinvoluta* which marks the *P. semiinvoluta/G. index* boundary. In the following *G. index* Zone two taxa disappear at the top of the Zone including *G. index*. Montanari (1991) reported three small iridium anomalies in this interval, two in the upper part of Chron 16N (at 5.5 m and at 7.0 m) and one in the middle part of Chron 15N (at 10 m) although no impact related microspherules have been found. If these Ir anomalies represent three impact horizons as Montanari suggests, then these impacts may have been responsible for at most one species extinction (*Turborotalia pomeroli*). Moreover, no major species abundance changes can be directly attributed to these impact events (the abundance peak of *G. index* at 10 m is likely due to preservational changes).

The major faunal turnover occurs near the E/O boundary (*Turborotalia cocoaensis* and *Cribrohantkenina lazzarii* zones) where six species disappear over a short time interval and major abundance changes are observed in five taxa (*T. cocoaensis*, *P. increbescens*, *P. nana*, *G. ampliapertura*, *S. angiporoides*). A clue to the nature of this faunal turnover can be gained from Figure 3, which groups taxa into surface (0–100 m), intermediate or thermocline (100–200 m) and deep dwellers (> 200 m) based on the stable isotope ranking of Keller & MacLeod (1992). Note that throughout the late Eocene the major faunal turnovers occur in the surface dwelling group where temperature intolerant species successively disappear. A gradual climatic cooling is recorded throughout this interval in high and low latitude stable isotope records (Barrera & Huber, 1991; Keller, MacLeod & Barrera, 1992). Intermediate dwelling taxa which consist predominantly of globigerinid morphologies (*D. eocaena*, *D. corpulenta*, *D. galavisi*, *S. linaperta*, *S. angiporoides*) respond to this cooling by expanding their relative population size as is particularly evident during the maximum cooling across the E/O boundary (Fig. 3). In contrast, deep dwellers (*C. unicavus*, *D. venezuelana*) remain relatively unchanged indicating that major temperature changes were restricted to the surface and thermocline layers.

3.b. Torre Cardela section (Spain)

The Torre Cardela section is exposed in a road cut near the 186 km marker of the road (N-324) that leads from Torre Cardela to El Gobernador in the province of Granada (Spain). Geologically the section is part of the Cañada Formation (Cardela Group) of the Subbetic Zone of the Betic Cordillera. Sediments consist of calcarenites of turbidite origin rhythmically interbedded with thick hemipelagic marls. The Eocene–Oligocene transition spans about 110 m of marls with some limestone layers. The planktic foraminiferal faunas were earlier studied by Martínez-Gallego & Molina (1975), Martínez-Gallego (1977) and Molina (1979), and restudied by Gonzalvo & Molina (1992).

Figure 4 shows the biostratigraphic zonation and relative abundance changes of planktic foraminiferal species in the Torre Cardela section. Note that as in the Massignano section two significant changes are present near the E/O boundary and at the *G. index/C. inflata* Zone boundary. The *P. semiinvoluta* Zone was not recovered in this section. According to P. Martínez (pers. comm.), a small iridium anomaly is present at the extinction of *G. index* just above an interval of increased carbonate dissolution. This Ir level, if confirmed, would be near the first appearance of *G. ampliapertura* and *P. increbescens*, well above the youngest of the three iridium anomalies present in the Massignano section. No other Ir anomalies have been found to date in the Torre Cardela section and no detailed studies have been done in the much expanded interval of this section (30 m, *G. index* Zone) as compared with Massignano (9 m).

Just as at Massignano, the major faunal turnover occurs near the E/O boundary with six taxa extinct at the base and top of the *C. lazzari* Biozone (Fig. 4). Also similar to Massignano, the late Eocene faunal turnover affected primarily surface dwelling taxa most of which disappeared by E/O boundary time (Fig. 5). The decrease in the relative abundance of surface dwellers in the earliest Oligocene and increase in intermediate dwellers, coincident with the maximum global cooling (Barrera & Huber, 1991), indicate decreased vertical thermal gradients and a shallow thermocline at this time.

Although Figure 4 shows no major species extinctions coinciding with the *G. index/C. inflata* Zone boundary and Ir anomaly, a major faunal turnover is

Figure 4. Relative abundance of planktonic foraminifera in the Torre Cardela section (Spain).
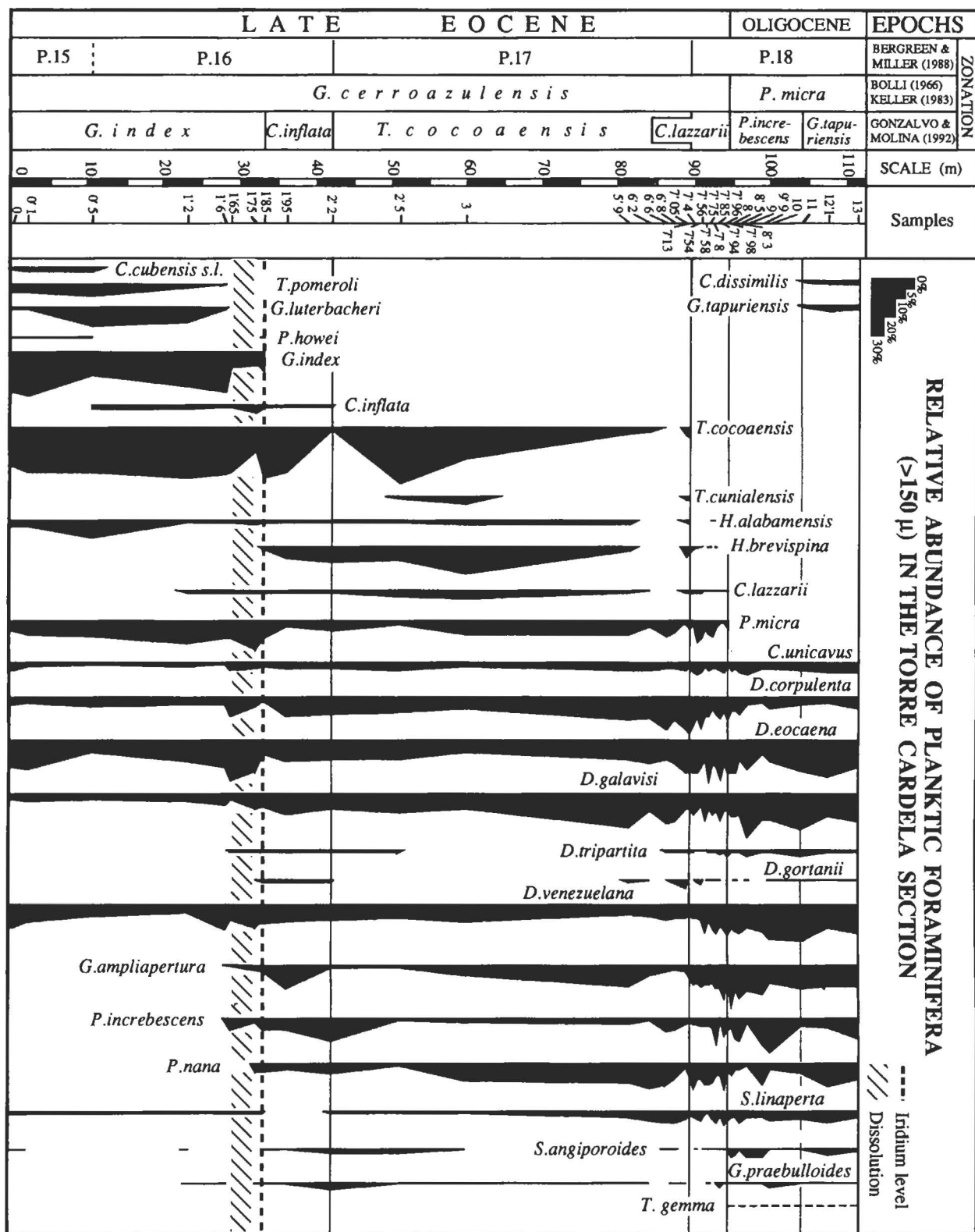
indicated in the surface dwellers. Figure 5 shows that warm water surface dwellers began to disappear through the *G. index* Zone culminating with the extinction of *G. index*. Although this trend is clearly long-term and precedes the impact horizon, it cannot be ruled out that the demise of *G. index* may have been a direct consequence of the impact.

3.c. DSDP Site 94 (Gulf of Mexico)

Site 94 is located on the continental slope of the Yucatan platform (24° 31.64′ N, 88° 26.16′ W) at 1793 m water depth. Eocene–Oligocene sediments consist of foraminiferal and nannofossil ooze and chalk which unconformably overlie Cretaceous shallow water carbonates. Planktic foraminifera were earlier studied by Keller (1985) who reported a hiatus between the middle and late Eocene (P13, P14 and part of P15 (*P. semiinvoluta*) zones missing). A microspherule layer is present in core 15 section 3, in the lower part of P16 or *G. cerroazulensis* Zone, and correlates both stratigraphically and geochemically to the microtektite horizon known as the North American tektite-strewn field (Keller *et al.* 1987*a*) that was dated by Glass & Crosbie (1982) at the age of 34.2 ± 0.6 Ma based on fission-track analysis. Microspherules from the Barbados section believed to belong to the same strewn field yielded an ^{40}Ar/^{39}Ar age of 35.4 ± 0.6 Ma (Glass, Hall & York, 1986). Those ages are well within the error margins of the radioisotopic ages from the Massignano section (Montanari, 1988, 1990; Odin *et al.* 1988).

The biostratigraphy of Site 94 has been re-studied based on the zonation of Gonzalvo & Molina (1992). Based on this analysis the microtektite layer seems to coincide with the extinction of *G. index*, similar to the *G. index* extinction and Ir anomaly present in Site 292 and in the Torre Cardela section (Figs 4, 6). However, at Massignano the *G. index* extinction occurs after the third Ir anomaly. This suggests that the *G. index* extinction datum may be diachronous disappearing early in low latitude sections and ranging higher upsection in temperate environments (Molina, 1986; Molina, Keller & Madile, 1988). In contrast, the *G. ampliapertura* and *P. increbescens* appearance datums seem to be more reliable stratigraphic markers since they occur in the same relative stratigraphic position in all sections examined (Figs 2, 4, 6). Their first appearance datums suggest that the microspherule layer of Site 94 may not be coeval with the Ir anomaly of the Torre Cardela section, although in both sections *G. index* appears at this cosmic horizon.

The biostratigraphy and relative species abundance changes in Site 94 are illustrated in Figure 6. The middle/late Eocene hiatus is marked by the sudden disappearance of 11 species between cores 17 and 16. The late Eocene interval of Site 94 is condensed and has incomplete core recovery. Species ranges may

therefore not be directly comparable to the more expanded Massignano and Torre Cardela sections. For instance, at the *P. semiinvoluta*/*G. index* Zone boundary at Site 94 four taxa disappear, but two of these, *G. luterbacheri* and *P. howei*, range through the *G. index* Zone at both Massignano and Torre Cardela. This difference is probably due to the incomplete recovery of Site 94. Nevertheless, all biozones have been identified with the exception of the very short basal Oligocene *P. increbescens* Zone, which is probably due to the condensed nature of this section.

The *G. index*/*C. inflata* Zone boundary and microtektite horizon is not marked by major species extinctions or species abundance changes and the major faunal turnover occurs near the E/O boundary similar to the Massignano and Torre Cardela sections (Figs 2, 4). At Site 94, as in the other sections, six species disappear at or near the E/O boundary marking this major cooling episode. However, one of these taxa (*P. micra*) persists elsewhere through the early Oligocene (Keller, 1983, 1985).

3.d. DSDP Site 612 (Atlantic Ocean)

Site 612 is located on the middle part of the New Jersey continental slope (38° 49.21′ N, 72° 46.43′ W) at a water depth of 1404 m. The sediments consist of light greenish-gray to grayish-yellow-green siliceous carbonate oozes and chalks. A 2.5 cm thick layer of microtektites and tektite debris is present in core 21 section 5 between 111 to 114 cm and directly overlies an unconformity that divides upper and middle Eocene sediments (Thein, 1987; Keller *et al.* 1987*a*; Glass, 1989; Miller *et al.* 1991).

A restudy of the biostratigraphy and relative abundance of planktic foraminifera is illustrated in Figure 7. The hiatus in core 21-5 is marked by the disappearance of ten species marking an estimated hiatus of 5 Ma (P12 to P16, Miller & Hart, 1987; Keller *et al.* 1987*a*). Sediments immediately above the hiatus and microtektite horizon contain common *G. index*, *T. pomeroli* and *G. luterbacheri*, which are characteristic of the *G. index* Zone in the Massignano and Torre Cardela sections (Figs 2, 4). This strongly suggests that the sediments directly overlying the unconformity are of *G. index* Zone age. This age assignment is also supported by the high relative species abundance of *T. cocoaensis*, *D. eocaena* and *S. linaperta* when compared to these other sections. Miller *et al.* (1991) restudied the biostratigraphy and tektite horizon of Site 612 and concluded that the tektite layer is not equivalent to the microtektite layers found in Barbados and other Caribbean–Gulf of Mexico locations, but is about 0.5–1.0 Ma older and located in the *P. semiinvoluta* Zone. This conclusion was based primarily on the basis of their observation of specimens of *P.* cf. *semiinvoluta* up to core 19; their illustrated specimens, however, are not
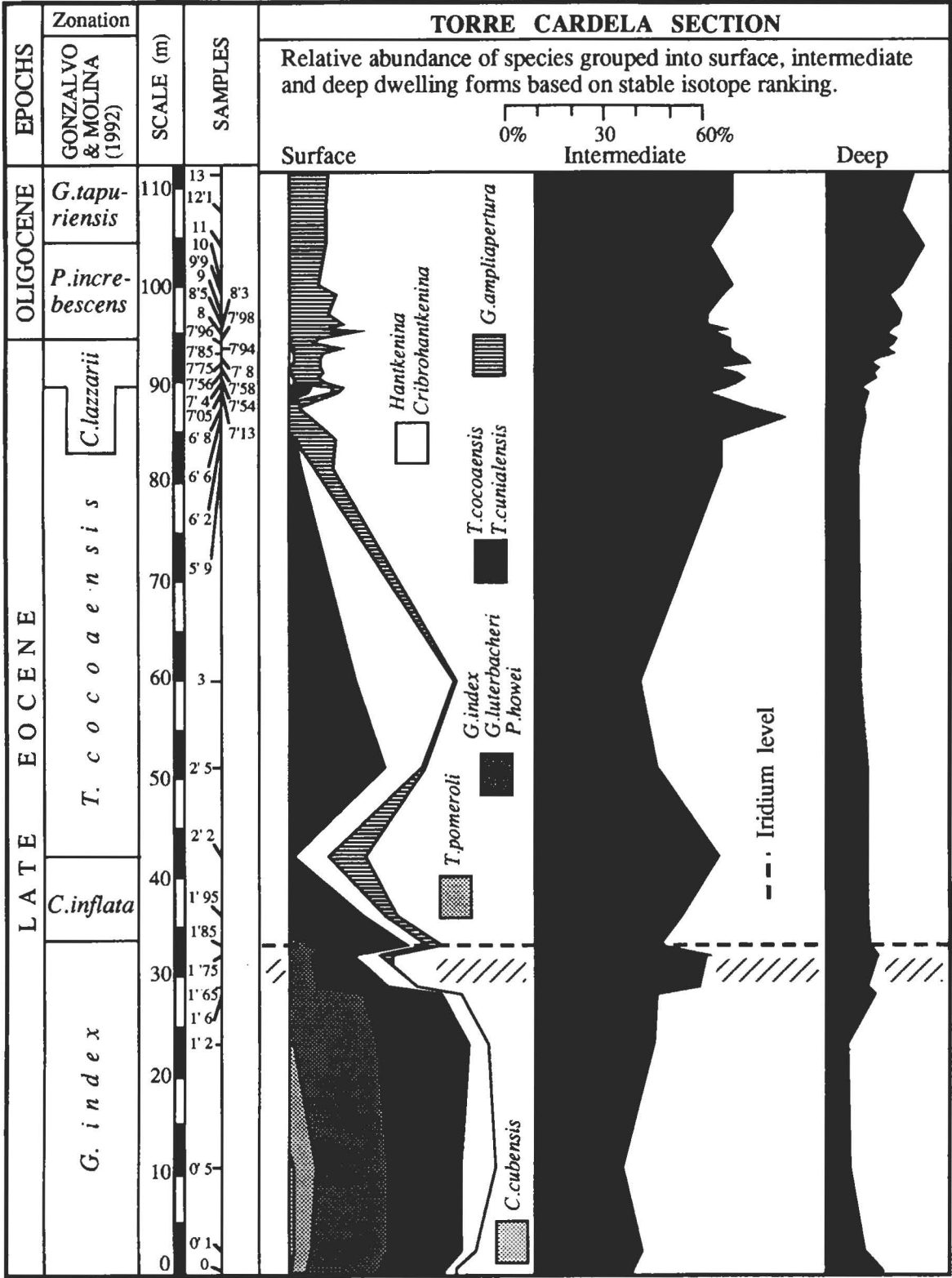
Figure 5. Relative abundance of species grouped into surface-, intermediate- and deep-dwelling forms based on stable isotope ranking in the Torre Cardela section (Spain) (see Fig. 3 for full caption).

P. semiinvoluta but *G. index*. This species is very scarce above core 21-5. At Site 612, the last appearance of *G. index* coincides with the first appearances of *G. ampliapertura* and *G. increbescens* as also observed in the Massignano, and Torre Cardela sections (Figs 2,

4). Consequently, our data indicate that the tektite layer of Site 612 is not in the *P. semiinvoluta* Zone but in the younger *G. index* Zone. We agree, however, that this tektite layer is not coeval with the microtektite layer of Barbados; this is also suggested by radiolarian

Figure 6. Relative abundance of planktic foraminifera in Site 94 (Gulf of Mexico).
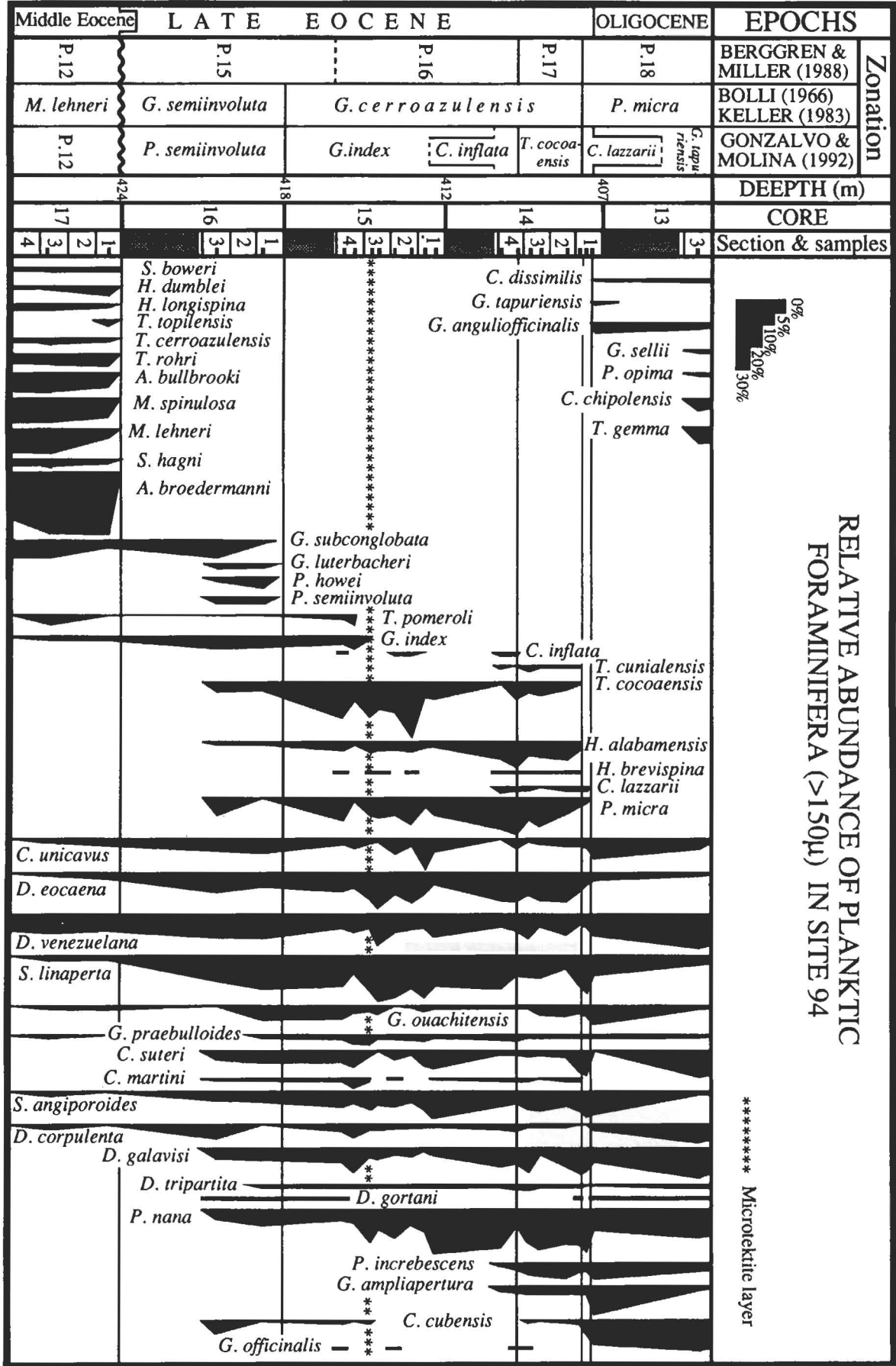
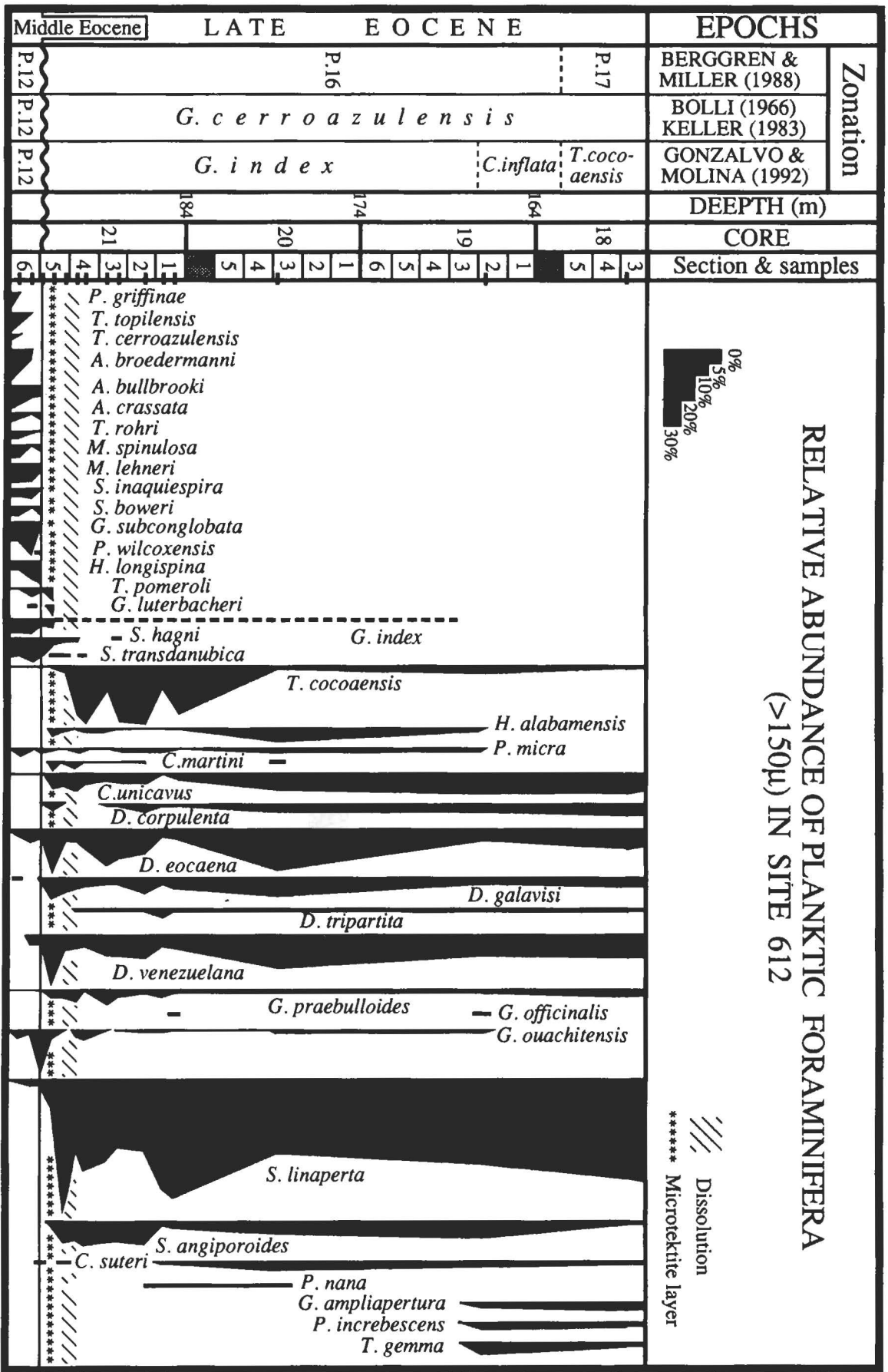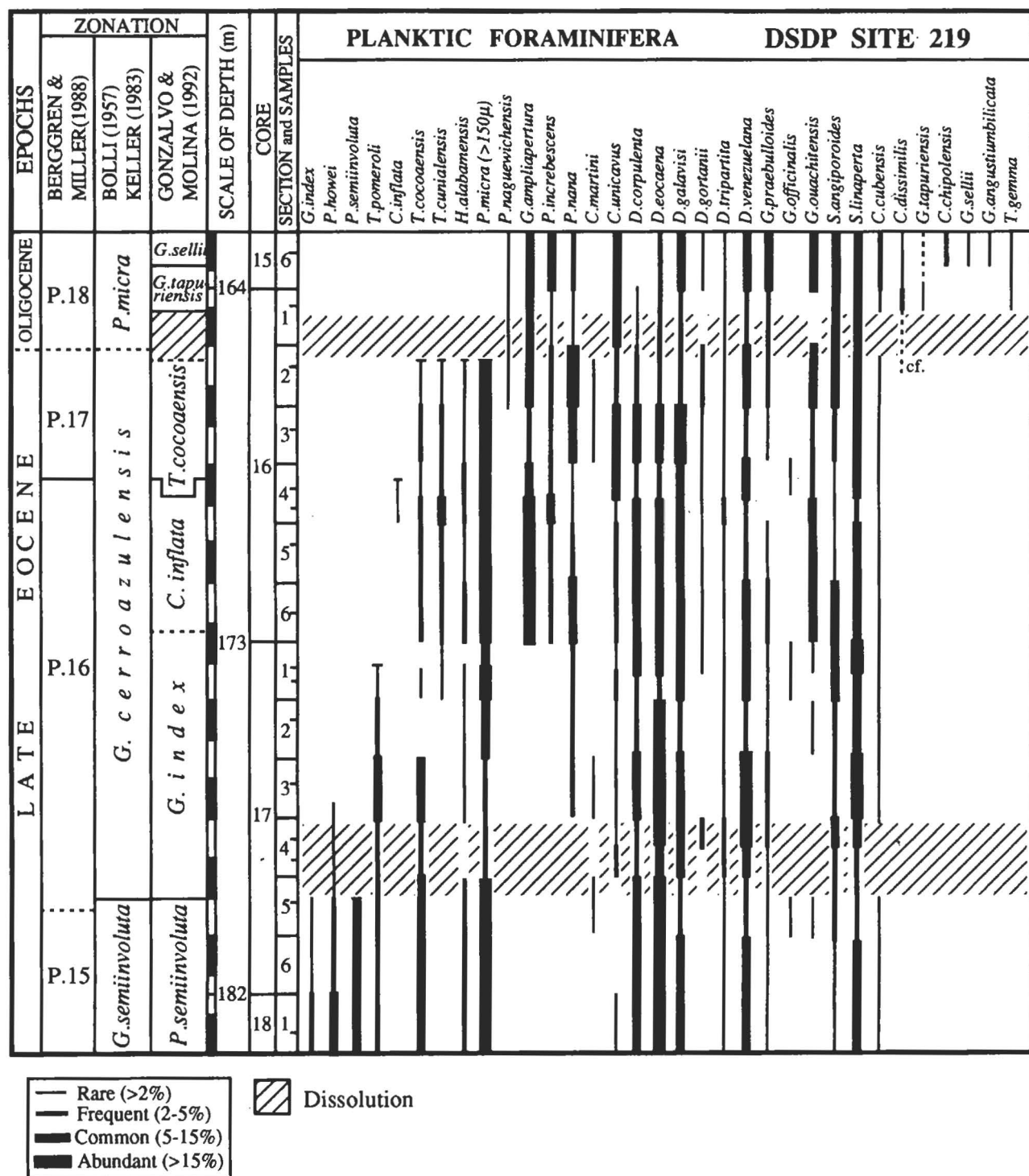Figure 7. Relative abundance of planktic foraminifera in Site 612 (Atlantic Ocean).

PLANKTIC FORAMINIFERA   DSDP SITE 219

Figure 8. Semiquantitative distribution of planktic foraminifera in Site 219 (Indian Ocean).

Key:
- Rare (>2%)
- Frequent (2-5%)
- Common (5-15%)
- Abundant (>15%)
- Dissolution

stratigraphy that places the Site 612 microtektite layer in the *C. bandyca* Zone and the Barbados microtektite layer in the *C. ornata* Zone (Saunders *et al.* 1984).

3.e. DSDP Site 219 (Indian Ocean)

Site 219 is located on the Chagos–Laccadive Ridge (9° 01.75′ S, 72° 52.67′ E) in the Indian Ocean at a water depth of 1764 m. Eocene–Oligocene sediments consist of 21 m of white oozes and chalks. Two carbonate

dissolution levels are recognized at the base of P16 and P18 (base Oligocene, Keller, 1983, 1986).

Figure 8 shows the species ranges and qualitative abundances at Site 219 (quantitative data were illustrated in Keller, 1986). All biozones have been recognized in this section except the short *C. lazzarii* and *P. increbescens* Zones that span the E/O boundary and is marked by dissolution at Site 219. *G. index* which defines the *G. index/C. inflata* Zone boundary disappears earlier in these low latitudes, at the same
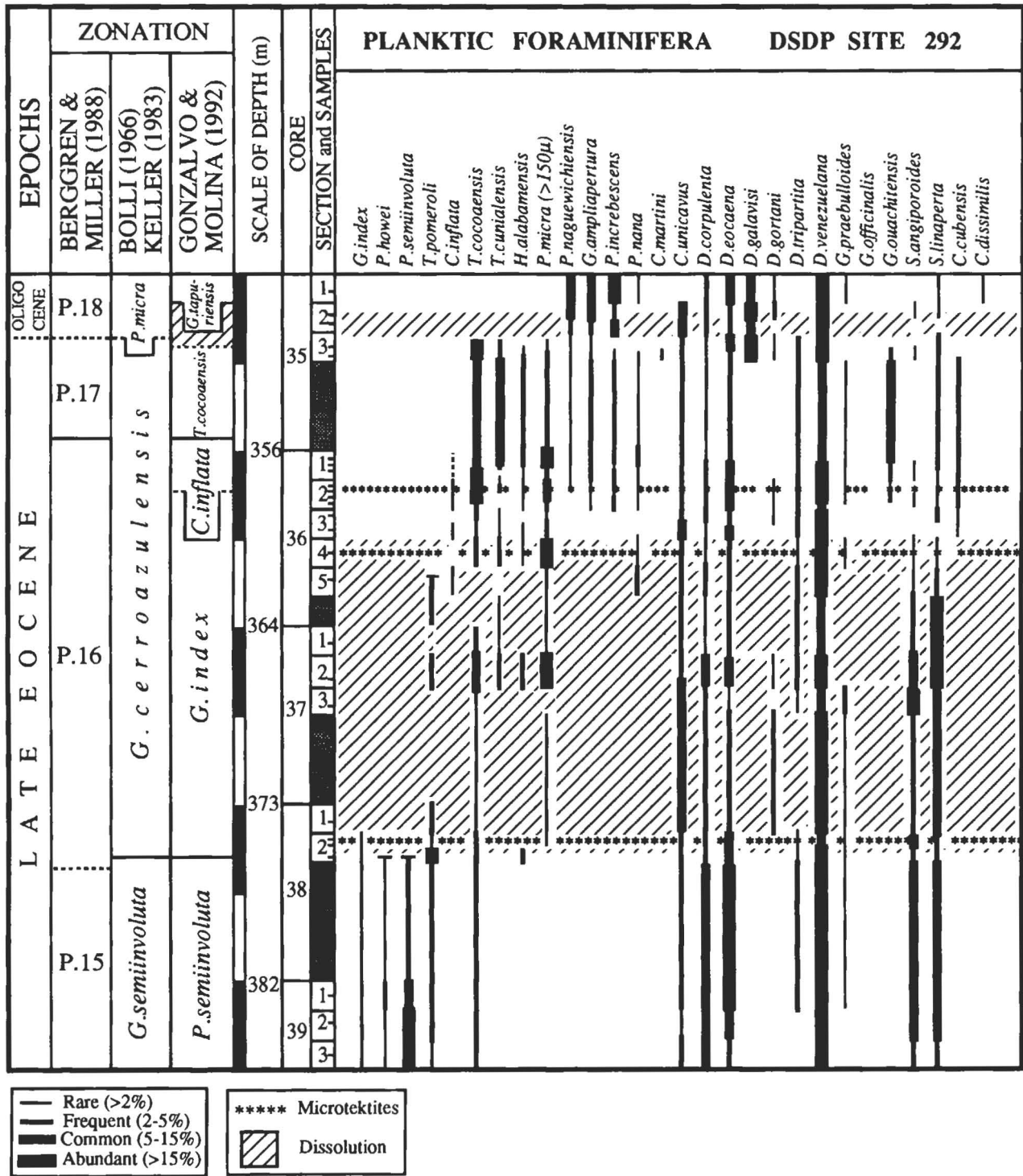
Figure 9. Semiquantitative distribution of planktic foraminifera in Site 292 (Pacific Ocean).

time as *P. semiinvoluta* (P15/P16). For this reason, the *G. ampliapertura* and *P. increbescens* appearance data have been used tentatively to place this boundary. No microtektites have been found in this section although the nearby Site 216 has abundant microtektites coincident with the *P. semiinvoluta* extinction horizon (Keller, 1986; Keller *et al.* 1987*a*).

Relative species abundances and the faunal turnover in surface, intermediate and deep assemblages was illustrated and discussed in Keller, MacLeod & Barrera (1992). The patterns of faunal turnover are similar to Massignano and Torre Cardela with the successive disappearance of surface dwellers beginning at the top of the *P. semiinvoluta* Zone and increasing abundance of intermediate dwellers. By E/O boundary time all Eocene warm water surface dwellers disappeared and a new cooler temperature tolerant surface group consisting of small globigerinids evolved

(Keller, MacLeod & Barrera, 1992). Thus, although no impact horizons are present in Site 219, the faunal turnover patterns are the same as in the Atlantic and Tethys Oceans.

3.f. DSDP Site 292 (Pacific Ocean)

Site 292 is located on the Benham Rise in the northeastern Pacific (15° 49.11′ N, 124° 39.05′ E) at a water depth of 2943 m. During late Eocene time sediment deposition occurred near the equator at about 500 m depth with gradual subsidence to 1750 m depth by middle Oligocene time (Keller *et al.* 1987*b*). Late Eocene to Oligocene sediments consist of nannofossil chalk and ooze which overlie basement basalt.

Planktic foraminifera were studied by Ujiie (1975), who provided an initial biostratigraphic report, and more detailed quantitative biostratigraphic and palaeoclimatic studies were published by Keller (1982/83; 1986). Three microtektite horizons were identified, one near the top of the *G. semiinvoluta* Zone and two in the *G. cerroazulensis* Zone; an Ir anomaly is present at the middle microtektite horizon (Keller *et al.* 1987*a*). Our restudy of Site 292 places the oldest microtektite layer near the *G. index/G. semi-involuta* Zone boundary, and the other two layers in the uppermost part of the *G. index* Zone or the *G. cerroazulensis* Zone as earlier determined by Keller (1986; Keller *et al.* 1987*a*) (Fig. 9). As at Site 219, *G. index* disappears at nearly the same time as *P. semiinvoluta*, and the *G. ampliapertura* and *P. increbescens* first appearance tentatively marks the top of the *G. index* Zone. Our present data, based on the study of 22 sections from different latitudes, strongly indicate that the *G. index* extinction is a reliable marker horizon only in middle and high latitudes and that it disappears earlier in low latitude regions.

Faunal abundance changes in Site 292 are generally similar to Site 219 but relative abundances of taxa in the dissolution intervals are biased in favor of dissolution resistant species which are usually deeper dwelling forms (*D. venezuelana, S. linaperta, C. unicavus*, Fig. 9; Keller, 1986).

4. How many Late Eocene impact horizons?

Microspherule horizons have been identified in late Eocene sediments in at least 19 localities including 16 deep-sea cores and outcrops on Barbados (Glass *et al.* 1985; Keller, D'Hondt & Vallier, 1983; Keller *et al.* 1987*a*). Some microspherule layers are accompanied by Ir anomalies, but other iridium anomalies are not associated with microspherules. Most sections contain evidence of only one microspherule layer, some contain two, and only one (Site 292) has been found that contains three stratigraphically distinct microspherule layers (Keller *et al.* 1987*a*). The actual number of late Eocene horizons with extraterrestrial

components (microspherules or Ir anomaly) is still in dispute. The debate surrounding the number of late Eocene impacts began between proponents of one impact (Glass & Crosbie, 1982) and proponents of multiple impacts (at least three) (Keller, D'Hondt & Vallier, 1983; Keller *et al.* 1987*a*). Later, Hazel (1989) using the graphic correlation technique concluded that there are not two or three different layers, but at least six and possibly more. Our data suggest that there are at least three and possibly four impact horizons as indicated by our refined biostratigraphic zonation of planktic foraminifera and recent advances in chronostratigraphy. The high number of layers proposed by Hazel (1989) is perhaps an artifact of the graphic correlation technique used, which was based on biostratigraphic data of many authors and several microfossil groups. It is well known that correlation of stratigraphic studies by different authors is inherently flawed by differing species concepts, different size fractions analysed, type of laboratory processing, sample spacing, preservation and even author bias. These effects all conspire against the high resolution necessary to identify and distinguish closely spaced microspherule and Ir horizons. For these reasons we believe that studies by single authors using the same stratigraphic concepts provide the most reliable correlation scheme.

In Figure 10 we illustrate our biostratigraphic correlation of 22 sections, nine of which have iridium anomalies or microtektite layers. In these sections there is evidence of three and possibly four impact horizons over a time period of about one million years. Biostratigraphically, these impact horizons occur in the *G. index* Zone (lower to middle part of *G. cerroazulensis* or P16 Zone) with one or possibly two layers near the base and two layers near the top of this zone (Fig. 10). The two layers near the top of the zone have long been recognised as separate but closely spaced impact events (Glass & Burns, 1987; Keller, D'Hondt & Vallier, 1983; Keller *et al.* 1987*a*). The microspherule layer near the base of *G. index* Zone has also been recognised from Sites 292, 216 and possibly Site 462A (Keller *et al.* 1987*a*). Site 216 may contain two closely spaced microspherule layers although the condensed interval, due to dissolution and possibly a short hiatus, does not allow positive stratigraphic separation. However, the microspherules show two populations with distinct geochemical aspects (Keller *et al.* 1987*a*; D'Hondt, Keller & Stallard, 1987). Thus, current evidence supports a maximum of four late Eocene impacts over a time span of about 1 Ma between about 34.7 and 35.7 Ma.

5. Causes of the extinctions

The biotic effects of these extraterrestrial bolide impacts were primarily studied by Keller, D'Hondt & Vallier (1983), Keller (1986), Keller *et al.* (1987*a*) and

Figure 10. Biostratigraphy and chronostratigraphy of the 22 selected sections restudied. Numbers in DSDP sites indicate core numbers and in land sections metres from the base.

MacLeod (1990), who concluded that there was no evidence for a mass extinction associated with these impact events. Moreover, late Eocene planktic foraminiferal species extinctions were observed to occur gradually with rarely more than two species extinct at the same horizon (Keller, 1986; Molina, 1986; Molina et al. 1986; Keller et al. 1987a; Molina, Keller & Madile, 1988). The present study confirms these earlier observations and finds a consistent absence of elevated species extinctions or faunal abundance changes associated with the impact horizons. The only species extinction that seems to coincide with an impact event is the G. index extinction in the Torre Cardela and Molino de Cobo sections. This species disappearance, however, is diachronous across latitudes and therefore the extinction is unlikely caused by a bolide impact. Based on the available biostratigraphic, faunal and stable isotopic data, we

conclude that none of the three to four late Eocene bolide impacts were of sufficient magnitude to affect measurably marine plankton communities.

The terminal Eocene event, the gradual extinction of Eocene species and the gradual decline in the relative abundances of dominant species, appears to be closely related to high latitude glaciation and climatic cooling. This is evident in both stable isotope analyses of deep-sea sections and the decrease in the relative abundance of surface dwellers toward the Eocene/Oligocene boundary and the correlative increase in intermediate and deep dwellers (Boersma, Premoli Silva & Shackleton, 1987; Barrera & Huber, 1991; Keller, MacLeod & Barrera, 1992, Figs, 3, 5). The succeeding Oligocene planktic foraminifera assemblages are dominated by globigerinid populations of simple morphology and low diversity. Their evolution is associated with the development of a

major ice sheet in Antarctica (Keigwin & Keller, 1984; Kennett, 1977; Barrera & Huber, 1991; Ehrmann & Mackensen, 1992). There is no evidence that the late Eocene climatic cooling was accelerated by the multiple impact events.

6. Hiatuses and sea level changes

The formation of deep-sea hiatuses can be shown to be generally related to climatic cooling, sea-level regression and the intensification of oceanic current circulation (Keller & Barron, 1983; Keller *et al.* 1987*b*; Miller & Hart, 1987). Moreover, increased carbonate dissolution in open ocean marine environments is frequently associated with sea-level transgressions when the locus of sedimentation shifts from the open ocean to continental shelf regions (MacLeod & Keller, 1991*a, b*). For these reasons, the most continuous sedimentation records can often be found in upper slope to outer continental shelf regions where surface productivity remains high during sea level changes.

Figure 10 shows the sea-level changes (Haq, Hardenbol & Vail, 1987) and the hiatuses present in 22 late Eocene/early Oligocene sections. Two intervals of strong carbonate dissolution and hiatuses are present in most sections near the E/O boundary and the late Eocene *G. index* Zone. At the E/O boundary a rising sea level coincides with a hiatus or carbonate dissolution in all but three deep-sea sections (Sites 277, 363, 366) and in these the E/O boundary is questionably present. Only in continental shelf to upper slope regions is a well-preserved continuous sediment record present (Massignano, and 3 sections in Spain). The dissolution and hiatus in the *G. index* Zone correlates with two short regressive phases in a generally transgressive sea. Similar to the E/O boundary interval, most deep-sea sections show dissolution and hiatuses at this time with the exception of sections deposited in outer shelf to upper slope environments. In two of these (Torre Cardela and Molino de Cobo) the dissolution interval is very short, coinciding with the transgressive maximum. This suggests that further studies of multiple impact events are most likely to succeed in currently onshore marine sequences similar to Massignano, Torre Cardela, Fuente Caldera and Molino de Cobo (Fig. 10).

7. Conclusions

Biostratigraphic data indicate the presence of three and possibly four impact horizons in the *G. index* Zone of the late Eocene. On the basis of these studies, we interpret the microtektite layer previously dated in the *G. semiinvoluta* Zone as belonging to the *G. index* Zone. Our data permits the positive identification of only three impact related horizons and weaker

evidence for a possible fourth horizon, spanning a period of about 1 Ma of the middle Priabonian between about 34.7 and 35.7 Ma.

No significant species extinctions or major species abundance changes occur within the interval of the four impact horizons (*G. index* Zone). However, there is a gradual and successive elimination of warm water surface dwellers throughout the middle of the late Eocene which culminates at the top of the *C. lazzarii* Zone. These gradual and selective warm surface water species extinctions are linked to the global climatic cooling that began in the middle Eocene and culminated in the early Oligocene. Current data does not provide any evidence for a direct link between the multiple late Eocene impact events and climate cooling or the gradual selective extinctions. The climatic cooling began well before the late Eocene impact events and was related to the isolation of Antarctica as Australia moved northward, the onset of a circum-Antarctic circulation and the subsequent growth of an Antarctic ice sheet. Extraterrestrial impact events during the late Eocene *G. index* Zone appear to have had no measurable effect on either the evolutionary progress of marine plankton or the ongoing climatic deterioration.

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