Cenozoic bathyal and abyssal calcareous benthic foraminiferal zonation

W.A. Berggren and Kenneth G. Miller

1 Woods Hole Oceanographic Institution, Woods Hole, MA 02543
and Department of Geology, Brown University, Providence, RI 02912
2 Department of Geological Sciences, Rutgers University, New Brunswick, NJ 08903
and Lamont-Doherty Geological Observatory of Columbia University, Palisades, NY 10964

ABSTRACT: Deep-sea (bathyal-abyssal) benthic foraminifera provide a potential supplement to planktonic biostratigraphy. Benthic foraminifera are more resistant to dissolution and are often found in upper bathyal, lower abyssal, and higher latitude sediments which contain impoverished planktonic faunas. The biostratigraphic utility of benthic foraminifera was previously limited by poor understanding of their taxonomy and paleobathymetric distributions. During the past ten years, study of deep-sea benthic foraminifera from Deep Sea Drilling Project (DSDP) and Industry wells has provided an improved taxonomic base and empirical observations of age-depth distributions. Building on this data base, we establish 14 bathyal and 12 abyssal zones for the Cenozoic deep sea. Biostratigraphic resolution is higher in the abyssal realm during the Paleogene (9 abyssal versus 6 bathyal zones) and higher in the bathyal realm during the Neogene (3 abyssal versus 8 bathyal zones). During periods of accelerated taxonomic turnover (e.g., in the middle Miocene bathyal zone), deep-sea benthic foraminifera yield fairly refined zonations; in contrast, slow taxonomic turnover occurred during the Paleocene in the bathyal and abyssal realms and in the late Neogene in the abyssal realm, yielding few biostratigraphic subdivisions.

INTRODUCTION

Over the past 30 years, zonation of Cenozoic deep-water (bathyal to abyssal) sediments by means of calcareous plankton has resulted in a relatively precise biostratigraphic framework (for recent discussions of planktonic foraminiferal biostratigraphy, see Kennett and Srinivasan 1983; Toumarkine and Luterbacher 1985; Bolli and Saunders 1985; Berggren and Miller 1988). Similar applications using benthic foraminifera have been hampered by inadequate taxonomy, low abundances, high species dominance, and relatively long stratigraphic ranges. In addition, benthic foraminifera have changed their depth distribution patterns through time (e.g., Douglas and Woodruff 1981; Tjalsma and Lohmann 1983); therefore, deep-sea benthic foraminiferal stratigraphic ranges may partly reflect the migration of species across depth zones.

Over the past 15 years, there have been a large number of systematic studies of deep-sea benthic foraminifera, primarily on material recovered by the DSDP. In particular, major monographic treatments of deep-water benthic foraminifera have resulted in a better understanding of their taxonomy, biostratigraphy, and paleobathymetric distributions (Tjalsma and Lohmann 1983; Miller 1983; Tjalsma 1983; Thomas 1985; Woodruff 1985; Miller and Katz 1987a; Boersma 1986; van Morkhoven et al. 1986). The study of van Morkhoven et al. (1986) incorporated data from a large number of studies on the distribution of predominantly calcarceous benthic foraminiferal taxa from the bathyal and abyssal realms. We draw upon this data base to develop the zonations presented here; however, the synthesis of van Morkhoven et al. (1986) did not provide stratigraphic reference sections. We illustrate our zonal concepts by citing type levels for each zone using published studies of DSDP sections (Atlantic: Tjalsma and Lohmann 1983; Miller et al. 1985; Miller and Katz 1987a; Miller et al. 1987; Pacific: Boersma 1986), outcrop sections (Mexico: Nuttall 1930; Tunisia: Aubert and Berggren 1976; Spain: Berggren and Haq 1976), and other publicly available boreholes (Gulf of Mexico: Eureka boreholes E67-128, E68-151A, E66-73; van Morkhoven et al. 1986).

We recognize the following bathymetric divisions:

neritic <200m
bathyal 200-2000m:
upper bathyal 200-600m;
middle bathyal 600-1000m;
lower bathyal 1000-2000m;
abyssal >2000m:
upper abyssal 2000-3000m;
lower abyssal >3000m

Below the Calcite Compensation Depth (CCD; 3500-5000m during the Cenozoic: Van Andel 1975), calcareous forms are extremely rare to absent and agglutinated forms dominate.

Most previous depth zonations have not attempted to subdivide the abyssal zone (e.g., Berggren 1978). The advent of independently-derived paleodepth estimates (Berger and Winterer 1972) allowed reconstruction of age-paleodepth distributions of lower bathyal to abyssal taxa (e.g., Tjalsma and Lohmann 1983). Such reconstructions demonstrate that the bathyal/abyssal zonal (2000m) boundary is an important faunal dichotomy for the Paleogene and Neogene (Tjalsma and Lohmann 1983; Miller and Katz 1987a), and that the Cenozoic abyssal
zone may be subdivided into an upper and lower zone (e.g., Miller 1983; Miller et al. 1985; Miller and Katz 1987b).

Cenozoic deep-water benthic foraminifera generally exhibited wide bathymetric ranges. Still, as noted above, bathyal biofacies can be distinguished from abyssal biofacies based primarily upon abundances, although there are taxonomic differences (Tjalsma and Lohmann 1983; Miller et al. 1985; van Morkhoven et al. 1986; Miller and Katz 1987a). In fact, many taxa have different ranges in the bathyal and abyssal zones due to bathymetric migrations. Because of the different distributions of bathyal and abyssal taxa, we formulated zonations for each region using fundamentally different criteria. We based the bathyal zones upon the last occurrence (LO) of taxonomically distinct and stratigraphically useful taxa. Due to the lower rate of extinctions in the abyssal realm, first occurrences (FO) were used in addition to LO. We have tied our deep-water benthic foraminiferal zones to planktonic foraminiferal zonal schemes (Text-fig. 1) (Paleogene: Berggren and Miller 1988; Neogene: Blow 1969) and thence to a standard chronostratigraphy (Berggren et al. 1985).

We present here two independent zonal schemes: one for the bathyal realm, the other for the abyssal realm (Text-fig. 1). The bathyal zonation was developed primarily at middle and upper bathyal locations from study of the Gulf of Mexico Eureka boreholes (van Morkhoven et al. 1986). The abyssal zonation was developed primarily from studies of abyssal DSDP sites, although the zonation appears applicable to lower bathyal sections (e.g., Site 516, Tjalsma 1982; Site 612, Miller and Katz 1987a) since the marker taxa are often present there (although in lower abundances). Paleodepth estimates for DSDP sites were independently determined using empirical age-depth relationships determined from “backtracking” (see Miller and Katz 1987b for discussion). Most of the stratigraphically-significant taxa have been discussed and illustrated by van Morkhoven et al. (1986).

Previous workers have established that there are a number of distinct deep-water benthic foraminiferal assemblages that may correlate from region to region. For example, Thomas (in press a,b) recognized 7 Cenozoic assemblages on the Maude Rise (Antarctica), while Mackensen (in Schlich, Wise et al., in press) noted similar assemblages (in number and composition) on the Kerguelen Plateau. These assemblages correspond with some of our zones, as do the faunal associations of Tjalsma (1983). However, since the boundaries of assemblage zonations are ill defined, and the concept of Oppel zones is debatable (cf. Hedberg 1976 and North American Commission on Stratigraphic Nomenclature 1983), we adopted an interval zone approach (sensu North American Stratigraphic Code 1983) in constructing our zonation. The required use of marker taxa in interval zonations may not be entirely appropriate for deep-sea benthic foraminifera since species are often rare or sporadic in their distributions. To counter this problem, we have supplied alternative boundary criteria where possible (i.e., more than one species as bounding criteria) and alternative indicators (those to be used in the local absence of bounding criteria). We caution against strict adherence to the definition using individual boundary criteria which may be locally rare or absent, and encourage the use of alternate indicators as supplements to the definitions. Despite these limitations, we believe that our zonations represent real and recognizable events in the paleontological record of deep-water benthic foraminifera and that development of formal zonations is warranted.

In establishing the benthic zonations, we recognize that the benthic foraminifera are inherently less reliable biostratigraphic markers than planktonic foraminifera. Benthic foraminifera are subject to local facies control, and often exhibit diachronous ranges. Nevertheless, certain species of benthic foraminifera typify strata of a given age and may be used in stratigraphic correlations. Comparison of benthic foraminiferal ranges shows that many species of deep-water benthic foraminifera have relatively short stratigraphic ranges which make them biostratigraphically useful (e.g., Cibicidoides subspiratus, C. truncatus, Bulimina callahani, among others). The first and last occurrences of many longer ranging benthic foraminiferal taxa may also be biostratigraphically useful, for they occur within one to two planktonic foraminiferal zones (for such comparisons see Miller and Katz 1987b).

We recognize that the stratigraphic uncertainties associated with our deep-water benthic foraminiferal zonations are one or more planktonic zones even in the best cases.

**BATHYAL BENTHIC FORAMINIFERAL Zonation**

**PALEOCENE**

*Zone BB1 Angulogavelinella avnimelechi-Anomalinoides rubiginosus Interval Zone*

**Definition:** The concurrent partial ranges of the nominate taxa between the LO of Bolivinoides draco (base) and the LO of A. avnimelechi and Neoflabellina Jarvisi (top).

**Planktonic Foraminiferal Zone Correlative:** approximately Zones P6 to P6 of Berggren and Miller (1988).

**Type Level:** Djebel Sidi Kalif section, southeast Tunisia, Sample 149, Zone P3 (Aubert and Berggren 1976).

**Associated Taxa:** Loxostomoides applanca, Tappaniina selmensis, Bulimina velascoensis, Bolivinoides delicatulus, Stensiolina beccariiformis, Cibicidoides dayi, C. hylphalus, Nuttalliodes truempyi, Nuttallinella florealis, Neoflabellina semireticulata, and Aragonia velascoensis.

**Comments:** Paleocene bathyal benthic foraminiferal assemblages contain components of the familiar “Velascotype” fauna (Berggren and Aubert 1975). Paleobathymetric ranges of some of these taxa were extensive (e.g., bathyal-abyssal: S. beccariiformis, N. truempyi) while others were more restricted (e.g., neritic-upper bathyal: L. applanca).

We have observed that the nominate taxa of Zone BB1 range as high as planktonic foraminiferal Zone P5 of Berggren and Miller (1988) in various outcrop sections (e.g., North Africa, the Caucasus Mountains, SW Europe). In the abyssal realm, a major faunal turnover occurred in
**TEXT-Figure 1**

Cenozoic bathyal and abyssal zonation with planktonic foraminiferal zones. Planktonic foraminiferal zones are drawn at equal duration.

![Diagram of Cenozoic Bathyal and Abyssal Zonation with Planktonic Foraminiferal Zones](image-url)
latest Zone P6a (see Zone AB2 and Discussion). A similar faunal turnover is associated with the end of Zone BB1 with the disappearance of the nominate and other taxa (Text-fig. 2). However, we have been unable to determine whether the faunal turnover in the bathyal locations is, in fact, correlative with the abyssal turnover and thus with latest Zone P6a. Thus, our placement of the top of Zone BB1 coinciding with the P6a/P6b boundary is an assumed equivalency.

Eocene

Zone BB2: Anomalinooides capitatus-Hanzawaia ammophila Partial Range Zone

Definition: The concomitant partial ranges of the nominate taxa between the LO of *A. avimelechi* and *Neoflabellina javisi* (base) and the FO of *Cibicidoides subspiratus* (top).

Planktonic Foraminiferal Zone Correlative: approximately Zones P6b to P8 of Berggren and Miller (1988).

Type Level: Eureka core E67-128, 5277' (1609m), Zone P7, Berggren and Miller (1988).

Associated Taxa: *Turrilina brevispira*, *Cibicidoides eocaenius*, *Bulimina callahani*, *B. trinitatensis*, *Nuttallides trueempi*, and *Rhezakina epigona*.

Comments: Both *A. capitatus* and *H. ammophila* first occur in Zone P6a and have distinctive morphologies which render them useful in lower Eocene bathyal biostratigraphy. In the bathyal and abyssal facies, the lower Eocene is characterized by renewal of benthic foraminiferal species following the turnover which occurred at or near the Paleocene/Eocene boundary recognized by the top of planktonic foraminiferal Zone P6a (Text-fig. 2). The benthic foraminiferal turnover and subsequent recolonization is less pronounced in neritic facies (North Africa and the Gulf Coastal Plain, Berggren, personal observation; Atlantic Coastal Plain, Olsom and Wise 1987).

Zone BB3: Cibicidoides subspiratus Total Range Zone

Definition: Total range of the nominate taxon.

Planktonic Foraminiferal Zone Correlative: approximately Zones P9 to P13 of Berggren and Miller (1988).

Type Level: South bank of Rio de la Punta, 100 yards west of La Antigua, Veracruz, Mexico; Plummer collection (Sample No. M-179) deposited in Paleontological Research Institute, Ithaca, N.Y. This is the type locality of the Aragon Formation and of the species *Cibicidoides subspiratus* Nuttall (1930); Zone P10 of Berggren and Miller (1988).

Associated Taxa: Most of the forms noted for Zone BB2 plus *Bulimina jacksonensis*, *Cibicidoides truncanus*, and *H. caribaeae*.

Comments: A supplementary marker for the base of this zone (and indeed for recognizing the extent of this zone) is the FO of *Hanzawaia caribaeae*, which has a stratigraphic range essentially identical to that of *C. subspiratus*, the nominate taxon. Thus, the FO and LO of *H. caribaeae* can serve as proxy indicators of the lower and upper boundaries, respectively, of Zone BB3.

This zone corresponds to most of the middle Eocene. During this interval, *Nuttallides trueempi* is a common component of bathyal assemblages. This taxon decreases sharply in abundance near the top of the middle Eocene, although it persists to the top of the Eocene in some sections.

An important benthic event is the migration of hispidocostate *uvigerinids* (*Uvigerina gardnerae-rippensis* group) into the bathyal realm near the planktonic foraminiferal Zone P9/P10 boundary (i.e., within the lower part of Zone BB3; see Text-figure 2).

Zone BB4: Cibicidoides truncanus Interval Zone

Definition: Partial range of the nominate taxon between the LO of *Cibicidoides subspiratus* (base) and the LO of the nominate taxon (top).

Planktonic Foraminiferal Zone Correlative: approximately Zones P14 to P17 of Berggren and Miller (1988).

Type Level: DSDP Hole 592, Sample 36-2, 119 cm; *Subbotina linaperta* Zone (Boersma 1986).

Associated Taxa: *Bulimina jacksonensis*, *Cibicidoides eocaenius*, *Bulimina tuxpanensis*, and *Hanzawaia ammophila* range beyond the top of this zone, *Nuttallides trueempi* ranges sporadically to the top of this zone, and *Bolivina byramensis*, *Planulina ambiguca*, *Uvigerina mexicana*, *Cibicidoides mexicanus*, *Siphonina tenacinarata*, *Cibicidina wallii*, and *Planulina aff. renzi* appear sequentially in the middle to upper part of this zone.

Comments: This zone corresponds essentially to the youngest part of the middle Eocene to the late Eocene. Important bathyal benthic foraminiferal events during this time include the migration of planulilids (*Planulina costata*, *P. aff. renzi*), *Melonis*, and siphonids (*Siphonina tenacinarata*) into the bathyal realm from the neritic realm (Text-fig. 2). There were a notable number of first appearances of predominantly bathyal taxa spanning the late Eocene (Zone BB4) and early Oligocene (Zone BB5; Text-fig. 2)(Tjalsma 1983; van Morkhoven et al. 1986).

Oligocene

Zone BB5: Turrilina aliasatica Interval Zone

Definition: The partial range of the nominate taxon between the LO of *Cibicidoides truncanus* (base) and the LO of *Plectofrondicularia paucicostata* and/or *Bulimina jacksonensis* (?*B. sculptilis*).

Planktonic Foraminiferal Zone Correlative: approximately Zones P18 to P20 of Berggren and Miller (1988).


Associated Taxa: *Cibicidoides micrus*, *C. praemundulus*, *C. mexicanus*, *C. dickersoni* (C. sp. 13 of van Morkhoven
TEXT-Figure 2
Cenozoic bathyal and abyssal faunal events. LO = last occurrence; LCO = last common occurrence. Last appearances are indicated with T; first occurrences are indicated with inverted T.

Comments: This zone corresponds essentially to the lower Oligocene. See comments under Zone BB6. The lower Oligocene (Rupelian) is characterized in many areas (northwest Europe, Mediterranean, northwest Atlantic (Labrador margin), Gulf Coast, Caribbean, Kerguelen Plateau; among others) by the presence of Rotalinina bulimoides and Turritilina alisatica (Reeves 1987). Planulina mexicana, P. costata, and P. renzi are characteristic elements of lower Oligocene neritic, upper, and middle bathyal to abyssal depths, respectively.

Zone BB6: Cibicidoides mexicanus-Uvigerina mexicana Interval Zone

Definition: Partial range of nominate taxa between the LO of Cibicidoides eocaenus (= C. tuxpamensis) and the LO of Uvigerina mexicana and/or Rectuvigerina stonei.


Associated Taxa: Essentially the same as those listed for Zone BB5 (above).

Comments: This zone essentially corresponds to the upper Oligocene. Differentiation between Zones BB5 and BB6 may be difficult if Plectrofrondicularia paucicostata and Balamina jacksonensis are absent or sporadic. Potentially, other taxa may be used to subdivide the Oligocene bathyal realm. Cibicidoides micus last appears in some sections in planktonic foraminiferal Zone P21 which spans the lower/upper Oligocene boundary (van Morkhoven et al. 1986; Miller and Katz 1987b). In some bathyal sections, the LO of this taxon is in Zone P20 (e.g., Site 516; Tjalsma 1983). Planulina costata, which first appears in low abundances in upper Eocene sections, occurs in high abundances in Oligocene bathyal sediments. In general, Planulina costata and P. ambigua are relatively more common in the lower part of the Oligocene (early Zone BB5: corresponding to Zones P18 and P19), whereas C. mexicanus is relatively more common in mid-Oligocene levels correlative with Zones P20 and P21. A common and morphologically distinct component of outer neritic to upper bathyal sections representing Zone BB5 is Bolivina aliformis, particularly in the Caribbean-Central American region. Anomalalinoides capitus has its LO in Zone P18 with doubtful occurrences having been recorded in lower Oligocene Zones P19 and P20 (van Morkhoven et al. 1986: 278). Uvigerina mexicana, U. havanensis, and Siphonina tenuicarinata are common components of Zones BB5 and BB6, but are relatively more abundant in the latter zone. Uvigerina adelinensis occurs commonly in Zone BB6 in some areas, for instance in the Caribbean. While Cibicidoides mexicanus ranges into the lower Miocene (van Morkhoven et al. 1986), this taxon apparently disap-

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Zone BB7: Cibicidoides barnetti Interval Zone

Definition: Partial range of the nominate taxon between the LO of Cibicidoides eocaenus (= C. tuxpamensis) and the LO of Uvigerina mexicana and/or Rectuvigerina stonei.

Planktonic Foraminiferal Zone Correlative: approximately Zones N4-N5.

Type Level: E68-151A, 4699', Zone N5.

Associated taxa: Most of the taxa listed above for Zones BB5-BB6 persist into Zone BB7. Several, such as Cibicidoides micus and C. sp. 14 of van Morkhoven et al. (1986) (LO in Zone P21) and C. dickersoni (LO in Zone P22) are no longer present. Several forms typical of (but not restricted to) the Oligocene have their LO at or near the top of Zone N5: Balamina impendens, Planulina ambigua, Cibicidoides mexicanus, Bolivina aliformis, Rectuvigerina stonei, Uvigerina mexicana, and Planulina costata.

Comments: A number of extinctions apparently occurred in the bathyal zone near the end of Zone N5 (van Morkhoven et al. 1986). It is not clear if this event was of similar significance to those observed near the Paleocene/Eocene boundary and in the middle Miocene (Text-fig. 2)(see Discussion). Uvigerina mexicana and U. spinulosa, while not restricted to Zone BB7, are relatively common and characteristic of this interval.

Zone BB8: Siphonina tenacinarina-Planulina subtennissima Interval Zone

Definition: Concurrent partial range of the nominate taxon between the LO of Cibicidoides mexicanus (base) and the LO of the nominate taxon (top).


Type level: E68-151A, 4511' (1375 m), Zone N7.

Comments: In addition to the nominate taxa, a number of taxa became extinct at the end of planktonic foraminiferal Zone N 9 (Anomalalinoides pseudogrosserogosus, Cibicidoides alaskanensis, Uvigerina basicordata, among others), N10 (C. havanensis, C. barnetti, C. sp. 11 of van Morkhoven et al. (1986), Bulimina jarvisi, Cibicidina walli, and Rectuvigerina seneti) and N11 (Rectuvigerina transversa, Hansawaia amnophila). This relatively rapid sequence of faunal extinctions constitutes one of the major benthic foraminiferal faunal events of the Cenozoic (Text-fig. 2).

Zone BB9: Rectuvigerina transversa Interval Zone

Definition: Partial range of the nominate taxon between the LO of Siphonina tenuicarinata and Planulina subtennissima (base) and the LO of the nominate taxon (top).

Type level: E66-73, 3560' (1113 m), Zone N11.


Zone BB10: Cibicidoides matanzasensis Interval Zone

Definition: Partial range of the nominate taxon between the LO of Rectuvigerina transversa (base) and the LO of Cibicidoides matanzasensis (top).


Type Level: E66-73, 3453' (1053 m), Zone N12.

Associated Taxa: Rectuvigerina mexicana, R. multicosata, Neeponides campester, Siphonina pozonensis, Cibicidoides guazumalenis, C. crebbsi, Plectofrondicularia vaughani, P. parri, Uvigerina carapitana, Planulina dohertyi, Cancris nuttalli, and Globocassidulina punctata, among others.

Zone BB11: Cibicidoides crebbsi Interval Zone

Definition: Partial range of the nominate taxon between the LO of Cibicidoides matanzasensis (base) and the LO of the nominate taxon (top).


Type Level: E66-73, 3242' (988 m), Zone N14.

Associated Taxa: See Zone BB10.

Zone BB12: Planulina ariminensis-Cibicidoides incrassatus Interval Zone

Definition: Concurrent partial ranges of the nominate taxa between the LO of Cibicidoides crebbsi (base) and the LO of Plectofrondicularia parri and/or P. vaughani.


Type Level: Sample No. C-6, ca. 203 m above base of Carmona-Dos Hermanos section, (a type section of Andalusian Stage), Guadalquivir Basin, SE Spain (see Berggren and Haq 1976 for sample locality data); Zone N17.

Associated Taxa: Rectuvigerina striata, R. multicostata, Hanzawaia matanzas, Cibicidoides incrassatus, Melonis pompolioides, Cibicidoides cicatricosis, C. incrassatus, C. mundulis, Pachyderma, C. praecinctus, Planulina ariminensis, Marginulina costata, M. hirsuta, Siphonina reticulata, S. planilconvexa, Melonis barleeanus, M. pompolioides, Bulimina costata, Uvigerina bononiensis group, P. renzi, and Uvigerina cardapiana. The latter two taxa disappear at the top of this zone along with P. parri and P. vaughani.

Comments: Upper Miocene bathyal benthic foraminiferal assemblages are characterized by relatively abundant lagenids, planulids, cibicidoids, and uvigerinids. Locally distinctive components of this zone include strigate Uvigerina carapitana, Cibicidoides grosseperforatus, and the angulotruncate Cibicorbis herricki (see van Morkhoven et al. 1986); however, we have not observed these taxa outside of the Caribbean-Gulf Coast area which precludes their usefulness as cosmopolitan zonal indices. The LO of Planulina renzi is a useful adjunct in delimiting the top of Zone BB12, although this form is often relatively rare in the terminal part of its range and it is restricted primarily to middle bathyal to abyssal depths.

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Zone BB13: Planulina rugosa-Uvigerina rutila Interval Zone

Definition: Concurrent partial ranges of the nominate taxa between the LO of Plectofrondicularia parri and/or P. vaughani and the LO of Rectuvigerina multicostata and/or R. striata.

Planktonic Foraminiferal Zone Correlative: Zones N18-N20.

Type Level: E68-151 A, 4416', Zone Pi2 (= N19)

Associated Taxa: Essentially same fauna as above (Zone BB13).

Comments: Lower Pliocene bathyal benthic foraminiferal assemblages are essentially the same as those seen in present-day environments. Typical faunal elements of the Mediterranean (Brolsma 1978; Jonkers 1984) and Gulf Coast-Mexican region (Kohl 1986) are seen to have widespread distribution. The two taxa chosen as nominate for Zones BB13 are relatively common and morphologically distinct in lower Pliocene bathyal sediments. In particular, Uvigerina rutila Cushman and Todd (= U. longistriata Perconig = U. longistriata Perconig of Jonkers 1984; non U. rutila Jonkers 1984) is a characteristic late Neogene faunal element (predominantly) in upper bathyal sediments of the Mediterranean and Caribbean regions (see also Boersma 1984). It is characterized by having thin, discontinuous, longitudinal costae and a triangular cross-section. On the basis of a comparative study of parasite material, Kohl (1986) included Trifarinholccki Dorman in the synonymy of U. rutila. The major numerical reduction in T. holccki (="Angulogerina B") in subsurface horizons of the Gulf of Mexico is used to denote the approximate position of the Pliocene/Pleistocene boundary in that region and coincides closely with the (local) FO of Hyalinea balthica. The last occurrence of U. rutila in the Mediterranean is associated with the Mammoth Event of the Gauss Chron at 3.16 Ma (Zachariasse et al. 1989).
PLIOCENE TO PLEISTOCENE

**Zone BB14: Cibicidoides pachyderma-Uvigerina peregrina Interval Zone**

Definition: Concurrent partial ranges of the nominate taxa between the LO of *Uvigerina multicostata* and/or *Uvigerina striata* (base) and the present time.


Type Level: E68-151A, 4366', Zone N22

Associated Taxa: *Bolivina alata*, *B. antiqua*, *B. dilatata*, *Bulimina aculeata*, *B. marginata*, *B. exilis*, *Planulina foveolata*, *Cibicidoides cicaticrus*, *C. mundulus*, *Melonis pompiloides*, *Signotruncus schlumbergeri*, *Uvigerina mediterranea*, among others.

Comments: Upper Pliocene-Pleistocene benthal benthic foraminiferal assemblages are generally characterized by distributional patterns reflecting glacial-interglacial fluctuations. We have chosen, accordingly, two of the more persistent and ubiquitous taxa as zonal indices for this, the youngest Neogene zone. Poag (1981) has delineated two distinct but intergrading ecophenotypes of *C. pachyderma* (identified as *C. floridanus*) as forma *bathyals* and forma *littoralis* which occur in the Gulf of Mexico and these have been identified in Pleistocene Eureka cores in the region as well (see also van Morkhoven et al. 1986: 20). Zone BB14 corresponds essentially to the total range of *Hyalina bathica*, but the enigmatic FO of this taxon and its sporadic distributional pattern precludes its use as a zonal marker. In the Mediterranean region, its FO coincides closely with the Pliocene/Pleistocene boundary (d'Onofrio 1981). In the Gulf of Mexico, it appears to be restricted to a relatively short lower Pleistocene interval following the last appearance of *Trifarina holeki* (= *U. rutila*) (Poag and Valentine 1976).

ABYSSAL BENTHIC FORAMINIFERAL ZONATION

PALEOCENE

**Zone AB1: Quadratobuliminella pyramidalis-Bulimina velascoensis Interval Zone**

Definition: The concurrent partial ranges of the nominate taxa between their FO (base) and the FO of *Bulimina bradburyi* (top).

Planktonic Foraminiferal Zone Correlative: approximately Zones Pa to P3a of Berggren and Miller (1988).

Type Level: DSDP Site 577, Sample 11-5, 47-54 cm, Zone P3a (Miller et al. 1987).

Associated Taxa: *Cibicidoides hyphalus*, *C. velascoensis*, *C. dayi*, *Anomalinoidea rubiginosa*, *Aragonina velascoensis*, *Neoflabellina semiriticulata*, *Stensioina beccariiformis*, *Nuttallinella florealis*, and *Nuttallides trumpeyi*.

Comments: Equivalent to the *Gavelinella beccariiformis* (= *Stensioina baccariformis*) Association of Tjalsma and Lohmann (1983). Paleocene abyssal benthic foraminiferal assemblages contain components of the familiar "Velasco type" fauna (Berggren and Aubert 1975), as do bathyal assemblages. Paleobathymetric ranges of many of the deep-water taxa were extensive (e.g., Tjalsma and Lohmann 1983).

*Bulimina bradburyi* first appears in Zone P3b at uppermost abyssal-lowermost bathyal (about 1800-2000 m paleodepth) Site 577 (Miller et al. 1987). Tjalsma and Lohmann noted the FO of this taxon within Zone P4. Again, this uncertainty of ±1 planktonic foraminiferal zone appears to be the limit of stratigraphic resolution of our zonation. *Abyssumina* spp. first appears near the top of Zone AB1 (within Zone P3, Tjalsma and Lohmann 1983; within Zone P4, van Morkhoven et al. 1986), providing a useful alternative criterion for the top of Zone AB1.

**Zone AB2: Bulimina bradburyi-Stensioina beccariiformis Concurrent Range Zone**

Definition: The concurrent ranges of the nominate taxa between the FO of *Bulimina bradburyi* (base) and the LO of *Stensioina beccariiformis* (top).

Planktonic Foraminiferal Zone Correlative: Approximately Zones P3b to P6a of Berggren and Miller (1988).

Type Level: DSDP Site 577, Sample 10-3, 63-70 cm, Zone P4 (Miller et al. 1987).

Associated Taxa: Essentially as for Zone AB1. In addition, *Globocassidulina subglobosa* and *Cibicidoides pseudoperlicidus* first appear near the base of this zone (Tjalsma and Lohmann 1983), although these FO are often locally delayed.

Comments: Equivalent to the *Cibicidoides* cf. *pseudoperculidus* Association of Tjalsma and Lohmann (1983). It is difficult to differentiate *Bulimina taxipamensis* from *B. bradburyi*, and we have lumped these taxa in some studies (e.g., Miller and Katz 1987a). However, the presence of the *B. bradburyi-taxipamensis* group in association with *Stensioina beccariiformis* is indicative of Zone AB2. There was a dramatic benthic foraminiferal taxonomic turnover near the end of the Paleocene (Text-fig. 2) (Schnitker 1979; Tjalsma and Lohmann 1983; Miller et al. 1987; Katz and Miller, in press; Thomas, in press a,b). Most of the characteristic "Velasco type" taxa became extinct, including *Stensioina beccariiformis*. Tjalsma and Lohmann (1983) noted that this turnover occurred near the end of Zone P5, although they lacked a good time series across this interval. Miller et al. (1987) noted the presence of the *S. beccariiformis* assemblage in one sample from Zone P6a at Site 577, suggesting that the turnover occurred in P6a or at the Paleocene/Eocene boundary. Thomas (in press a,b) established that the turnover occurred approximately 0.3 m.y. before the Paleocene/Eocene boundary of Berggren et al. (1985). This indicates that Zone AB2 spans most of the late Paleocene, and that the faunal turnover can be used to approximate the Paleocene/Eocene boundary on the basis of deep-water benthic foraminifera.
EOCENE

Zone AB3: Clinapertina-Alabamina dissonata Partial Range Zone

Definition: The concurrent partial ranges of the nominate taxa from the LO of Stensioina beccariiformis (base) to the FO of either Cibicidoides grimsdalei or Stilostomella aculeata.

Planktonic Foraminiferal Zone: Correlative with Zones P6b to P7 (partim) of Berggren and Miller (1988).

Type Level: DSDP Site 363, Sample 14-6 81-83 cm, Zone P6b (Tjalsma and Lohmann 1983).

Associated Taxa: Rhezakina epigona, Quadratobulimella pyramidalis, Nuttalides truempyi, Abyssammina poagi, Cibicidoides praemundulus, Alabamina dissonata, and Clinapertina spp.

Comments: Equivalent to the Clinapertina Association of Tjalsma and Lohmann (1983). Following the extinctions at the top of Zone AB2 (near the Paleocene/Eocene boundary), abyssal (and to a certain extent, benthal) faunas were reduced in diversity and numbers. A series of FO’s in the early Eocene repopulated the deep-sea (Text-fig. 2), including the widely-distributed Alabamina dissonata and Clinapertina spp., which both appeared in Zone P6b (Tjalsma and Lohmann 1983).

Zone AB4: Cibicidoides grimsdalei-Stilostomella aculeata Interval Zone

Definition: The concurrent partial ranges of the nominate taxa from the FO of either Cibicidoides grimsdalei or Stilostomella aculeata (base) to the FO Cibicidoides micrus (top).

Planktonic Foraminiferal Zone Correlative: approximately Zones P7 (partim) to P9 of Berggren and Miller (1988).

Type Level: DSDP Site 390 Sample 7-1, 90-95 cm, Zone P7 (Tjalsma and Lohmann 1983).

Associated Taxa: Essentially as in Zone AB3.

Comments: Cibicidoides subspiratus is a taxonomically distinct form which appeared in planktonic foraminiferal Zone P9 and may be used to recognize late Zone AB4. However, its abyssal distribution is sporadic, and therefore, this taxon is not suitable as the nominate form of this zone (Tjalsma and Lohmann 1983). Cibicidoides havanensis first appeared in this zone, and may be used to recognize the base of the zone.

Zone AB5: Cibicidoides micrus-Anomalinoidea capitatus Interval Zone

Definition: Concurrent partial ranges of the nominate taxa from the FO of Cibicidoides micrus (base) to the FO of Anomalinoidea semicribatus (top).


Type Level: Gays Coves, Barbados Sample GC4-74, Zone P11 (Tjalsma and Lohmann 1983).

Associated Taxa: Aragonia aragonensis, Hanzawaia ammophilus, Nuttalides truempyi, Abyssammina poagi, Alabamina dissonata, C. praemundulus, C. grimsdalei, C. havanensis, and Clinapertina spp. Bulimina callabahi became extinct within this zone, and Quadratobulimella pyramidalis became extinct at the top of this zone.

Comments: Tjalsma and Lohmann (1983) reported the FO of Cibicidoides micrus in Zone P10, while van Morkhoven et al. (1986) reported it near the beginning of the Eocene (Zone P6b). We have observed the FO of this taxon in Zone P10 in abyssal sites (e.g., Site 613), but it first occurs earlier at bathyal sites (e.g., Site 612, FO in Zone P7-P8; Miller and Katz 1987a). Thus, we believe that the FO of Cibicidoides micrus was diachronous with depth, but that the FO in the abyssal zone may be a useful means of recognizing the early/middle Eocene boundary and thus the base of Zone AB3.

Zone AB6: Anomalinoidea semicribatus-Aragonia aragonensis Concurrent Range Zone

Definition: Concurrent partial ranges of the nominate taxa from the FO of Anomalinoidea semicribatus (base) to the LO of Aragonia aragonensis (top).

Planktonic Foraminiferal Zone Correlative: Zones P12 to P14 of Berggren and Miller (1988).

Type Level: DSDP Site 360 Sample 47-2, 102-106 cm, Zone P12-13 (Tjalsma and Lohmann 1983).

Associated Taxa: Alabamina dissonata, Cibicidoides micrus, C. grimshalei, Aragonia aragonensis, Nuttalides truempyi, Abyssammina poagi, Bulimina semicostata, and (except for the upper part of the zone) C. subspiratus and Clinapertina spp.

Comments: This zone is applicable at lower bathyal depths such as at DSDP Site 612 Sample 28-6, 146-150 cm (Miller and Katz 1987a). The abyssal benthic foraminiferan biostratigraphic subdivision of the later middle Eocene to late Eocene is often unclear since Aragonia was often rare to absent during this interval (Tjalsma and Lohmann 1983). Although Nuttalides truempyi and Abyssammina poagi ranged to the end of the Eocene (Tjalsma and Lohmann 1983; van Morkhoven et al. 1986), they were rare in the late Eocene (Tjalsma and Lohmann 1983). Therefore, high abundances of Abyssammina poagi or Nuttalides truempyi together with the presence of A. semicribatus are useful indicators of Zone AB6. Care must be taken to differentiate A. semicribatus from forms which have been noted in Zones P4-P11 that are transitional between A. rugibinosus or A. capitatus and A. semicribatus (van Morkhoven et al. 1986, p. 148).

Zone AB7: Nuttalides truempyi-Spiroplectammina specabilis Interval Zone

Definition: The partial range of the nominate taxa after the LO of Aragonia spp.

Planktonic Foraminiferal Zone Correlative: with Zones P15 to P17 of Berggren and Miller (1988).

Type Level: DSDP Hole 549A, Sample 35-1, 26-28 cm, approximately P15 (Miller et al. 1985).
Associated Taxa: Essentially the same as in Zone AB6. *Cibicidoides truncanus* and *Alabamina dissonata* disappear at the top of this zone.

Comments: In general, this zone corresponds in whole or in part to the upper Eocene. *Nuttallides truempyi* is often rare or absent from this zone in many sections and care must be taken to recognize this zone. The LO of *Spiroplectammina spectabilis* provides a diagnostic alternative marker for this zone, although this taxon is also rare in carbonate deep-sea sections. *Bolivina antegressa* often has its initial occurrence in this zone (e.g., Site 549, Miller et al. 1983; lower bathyal Site 612, Miller and Katz 1987a), although in some sections it does not appear until the Oligocene (e.g., Barbados, Wood et al. 1985; lower bathyal Site 516, Tjalsma 1983).

**OLIGOCENE**

**Zone AB8: Cibicidoides micrus-Cibicidoides grimsdalei Interval Zone**

Definition: Concurrent partial ranges of the nominate taxa from the LO of *Nuttallides truempyi* or *Spiroplectammina spectabilis* (base) to the LO of *Cibicidoides micrus* (top).

Planktonic Foraminiferal Zone Correlative: approximately Zones P18 to P21 of Berggren and Miller (1988).

Type Level: DSDP Site 563, Sample 22-3, 6-11 cm, Zone P18 (Miller and Katz 1987b).

Associated Taxa: *Anomalinoidea semicribratus*, *Bulimina glamor challengeri*, *B. jarvisi*, *Cibicidoides praemundulus*, *C. eocaenus (= C. tuxpanensis)*, *C. grimsdalei*, *C. havanensis*, *C. lauriae*, and *C. mexicanus*. *C. mundulus* evolved from *C. praemundulus* late in this zone; *Laticarinina paupera* first appears in this zone, although its distribution was sporadic until the middle Miocene (Miller and Katz 1987a).

Comments: *Cibicidoides grimsdalei* is often common in this zone, although it is not restricted to it. In general, this zone corresponds to the lower Oligocene. *Nuttallides truempyi* is rare and often disappears locally within the late Eocene. Therefore, based upon *Nuttallides truempyi* alone, this zone potentially may encompass part of the late Eocene. We chose to include the LO of the diagnostic taxon *Spiroplectammina spectabilis* in the definition of the base of Zone AB8. The absence of other distinct Eocene taxa such as *Abyssaminina* spp. and *Alabamina dissonata* is diagnostic of this zone. The presence of several other taxa which appeared near the end of the Eocene may also provide useful supplementary markers: *Astronion pusillum*, *Eggerella bradyi*, and *Epistominella exigua* (e.g., Miller et al. 1985). The FO of *Sphaeroidina bulloides* in planktonic foraminiferal Zone P19 (of Berggren and Miller 1988) may be useful in subdividing Zone AB8, although this taxon is rare in Oligocene abyssal sediments.

**Zone AB9: Cibicidoides eocaenus Interval Zone**

Definition: The partial range of the nominate taxon from the LO of *Cibicidoides micrus* (base) to the LO of *C. eocaenus (= C. tuxpanensis)* (top).

Planktonic Foraminiferal Zone Correlative: approximately Zone P22 (possibly all or part of Zone N4) of Berggren and Miller (1988).

Type Level: DSDP Site 563, Sample 16-3, 110-116 cm, Zone P22 (Miller and Katz 1987b).

Associated Taxa: Essentially the same as Zone AB8. *Cibicidoides praemundulus* last occurs in this zone.

Comments: *C. micrus* often last occurs in the lower Oligocene, while *C. eocaenus (= C. tuxpanensis)* may range into Zone N4 (e.g., Site 563, Miller and Katz 1987b), and therefore this zone may encompass all or part of Zone N4.

**NEOGENE**

**Zone AB10: Cassidulina havanensis Interval Zone**

Definition: Partial range of the nominate taxon from the LO of *C. eocaenus (= C. tuxpanensis)* (base) to the LO of *Cassidulina havanensis* (top).

Planktonic Foraminiferal Zone Correlative: Zones N4-N9.

Type Level: DSDP Site 563, Sample 10-1, 114-119 cm, Zone N8 (Miller and Katz 1987b).

Associated Taxa: *Cibicidoides bradyi*, *C. mundulus*, *Anomalinoidea semicribratus*, and *Sphaeroidina bulloides*. *Cibicidoides grimsdalei* became extinct at the base of this zone, but it cannot be used reliably in abyssal biostratigraphy as its last occurrence appears to be depth diachronous (Miller and Katz 1987b).

Comments: This zone encompasses the early Miocene to earliest middle Miocene. The LO of *Cibicidoides mexicanus* in Zone N5 may be useful in subdividing this zone, but its distribution is sporadic in the abyssal zone. *Planulina wuellerstorfi* appears near the top of this zone (generally in planktonic foraminiferal Zone N9, although it has been reported from Zone N8 (Thomas 1985)); the presence of this distinctive taxon is a useful biostratigraphic marker for middle Miocene and younger strata. As in the bathyal realm, a number of taxa had their last occurrences during planktonic foraminiferal Zones N8 to N11 (= latest Zone AB10 to early Zone AB11) (Text-fig. 2). The nominate taxon is a distinct form common in many abyssal sections; for illustration see Miller and Katz (1987b, pl. 3, fig. 3).

**Zone AB11: Buitimellina grazi Interval Zone**

Definition: Partial range of the nominate taxon from the LO of *Cassidulina havanensis* (base) to the LO of *Buitimellina grazi* (top).

Planktonic Foraminiferal Zone Correlative: with Zones N10-N11 and probably N12.

Type Level: DSDP Site 563, 8-2, 114-120 cm, Zone N11 (Miller and Katz 1987b).

Associated Taxa: *Planulina wuellerstorfi*, *Cibicidoides mundulus*, *C. robertsonianus*, *C. bradyi*, *Melonis pom-
pilioides forma sphaeroides, Pyrgo murrhina, and Hoeglundina elegans.

Comments: A third major taxonomic turnover of the Cenozoic abyssal realm occurred during late Zone AB10 to Zone AB11 (Text-fig. 2; see discussion). Many of the modern-day deep-water benthic foraminifera appeared at this time (e.g., Planulina wuellerstorfi, Pyrgo murrhina) and several relic “Paleogene” forms became extinct (e.g., Cibicidoides havanensis, Buliminina jorvisi, and Hansawaia amphipila).

Zone AB12: Planulina wuellerstorfi Interval Zone
Definition: Partial range of Planulina wuellerstorfi following the extinction of Buliminella grata to the present time.

Planktonic Foraminiferal Zone Correlative: with Zones N13-N23 (possibly all or part of Zone N12).

Type Level: DSDP Site 563 Sample 5-2, 130-136 cm, Zone N14/15 (Miller and Katz 1987b).

Associated Taxa: most of the present-day faunal elements.

Comments: This long zone (essentially the late Neogene of Berggren and Van Couvering 1974) spans the interval from the mid-part of the middle Miocene (Serravallian Stage) to the present day. It is difficult to subdivide this interval using abyssal benthic foraminifera on a global basis, although local subdivisions are possible (e.g., Thomas 1986a). The initial appearance of Anomalinaoides globulosus (in planktonic foraminiferal Zone N15; van Morkhoven et al. 1986) may be used to subdivide the zone into a late middle Miocene and a late Miocene to Pliocene (including “Recent”) zone, but distinguishing A. globulosus from its antecedents is difficult and its exact stratigraphic range remains debatable. For example, Miller and Katz (1987b) reported the initial appearance of A. globulosus in Zone N12.

DISCUSSION
Cenozoic bathyal and abyssal benthic foraminifera were marked by several periods of relative stability. Few first and last occurrences are recorded in the bathyal realm during the Paleocene planktonic Zones P1 to P5 (Text-fig. 2), limiting useful biostratigraphic subdivision with benthic foraminifera. Similarly, there were virtually no global first or last occurrences in the late Neogene (planktonic foraminiferal Zones N13-N23) abyssal realm; therefore, this 13 m.y. interval remains unzoned (Text-fig. 1).

There were at least three intervals of increased last occurrences in abyssal benthic foraminifera (Text-fig. 2):

1) latest Paleocene (Zone P6a) (Schnitker 1979; Tjalsma and Lohmann 1983; Miller et al. 1987, Katz and Miller, in press; Thomas, in press a,b);

2) late Eocene to earliest Oligocene between ca. 39.5 and 35 Ma in planktonic foraminiferal Zones P15 to early P18 (Schnitker 1979; Miller 1983; Tjalsma and Lohmann 1983; Corliss et al. 1984; Miller et al. 1985; Wood et al. 1985; Corliss and Keigwin 1986); and

3) early middle Miocene between 17 and 13 Ma in planktonic foraminiferal Zones N8 to N11 (Berggren 1972; Schnitker 1979; Woodruff 1985; Thomas 1985, 1986a, b; Schnitker 1986; Miller and Katz 1987b).

In the bathyal realm, the latest Paleocene and middle Miocene were also intervals of increased turnover (Text-fig. 2), as shown by the range chart of van Morkhoven et al. (1986). The late Eocene-earliest Oligocene turnover was less pronounced at bathyal depths. Nevertheless, Nuttalides truempyi generally disappeared from the bathyal realm in the earliest late Eocene. An influx of new taxa appeared in the bathyal realm in the late Eocene to Oligocene; consequently, late Eocene and Oligocene bathyal assemblages were distinct from middle Eocene assemblages (Tjalsma 1983). A period of extinctions apparently occurred in bathyal benthic foraminifera in the early Miocene (top of Zone N5; Text-fig. 2), as shown by the range chart of van Morkhoven et al. (1986). There appears to be no corresponding change in abyssal benthic foraminifera (Miller and Katz 1987b).

In developing these zonations, we have attempted to use readily recognizable taxa whose ranges are relatively well known (see Tjalsma and Lohmann 1983; Tjalsma 1983; Miller et al. 1985; van Morkhoven et al. 1986; Miller and Katz 1987b for detailed range data), minimizing problems of diachrony. Still, there are problems with locally-delayed first occurrences and premature last occurrences. For example, although N. truempyi ranges to the top of the Eocene in many abyssal sections, it is rare or absent in the uppermost Eocene (last 2 m.y.) in others. Because of such problems, the zonations given here have a minimum uncertainty of about 2 m.y., although uncertainties may be larger. Despite these limitations, the benthic foraminiferal zonations defined here should prove useful in biostratigraphically subdividing strata, both as a supplement to other standard biostratigraphies and in the absence of other age-diagnostic microfossils.

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