



Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale

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ABSTRACT

Planktonic foraminifera are widely utilized for the biostratigraphy of Cretaceous and Cenozoic marine sediments and are a fundamental component of Cenozoic chronostratigraphy. The recent enhancements in deep sea drilling recovery, multiple coring and high resolution sampling both offshore and onshore, has improved the planktonic foraminiferal calibrations to magnetostratigraphy and/or modified species ranges. This accumulated new information has allowed many of the planktonic foraminiferal bioevents of the Cenozoic to be revised and the planktonic foraminiferal calibrations to be reassessed. We incorporate these developments and amendments into the existing biostratigraphic zonal scheme.

In this paper we present an amended low-latitude (tropical and subtropical) Cenozoic planktonic foraminiferal zonation. We compile 187 revised calibrations of planktonic foraminiferal bioevents from multiple sources for the Cenozoic and have incorporated these recalibrations into a revised Cenozoic planktonic foraminiferal biochronology. We review and synthesize these calibrations to both the geomagnetic polarity time scale (GPTS) of the Cenozoic and astronomical time scale (ATS) of the Neogene and late Paleogene. On the whole, these recalibrations are consistent with the previous work; however, in some cases, they have led to major adjustments to the duration of biochrons. Recalibrations of the early–middle Eocene first appearance datums of *Globigerinatheka kugleri*, *Hantkenina singanoae*, *Guembeltrioides nuttalli* and *Turborotalia frontosa* have resulted in large changes in the durations of Biochrons E7, E8 and E9. We have introduced (upper Oligocene) Zone O7 utilizing the biostratigraphic utility of '*Paragloborotalia pseudokugleri*'. For the Neogene Period, major revisions are applied to the fohselliid lineage of the middle Miocene and we have modified the criteria for recognition of Zones M7, M8 and M9, with additional adjustments regarding the *Globigerinatella* lineage to Zones M2 and M3. The revised and recalibrated datums provide a major advance in biochronologic resolution and a template for future progress of the Cenozoic time scale.

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1. Introduction

1.1. Cenozoic planktonic foraminiferal biostratigraphy

Robust stratigraphic correlations are essential to decipher Earth history. Planktonic foraminifera have many characteristics considered ideal for biostratigraphic index fossils – morphologically distinct, diverse, rapidly-evolving, highly abundant, often globally distributed and high preservation potential. As such, they are extensively used for the biostratigraphy of Cretaceous and Cenozoic marine sediments and are a fundamental component of Cenozoic chronostratigraphy. Regional biostratigraphic schemes developed in parallel with taxonomic and stratigraphic research, beginning in the 1940s in the oil-producing parts of the USA (e.g. Cushman and Stainforth, 1945) and reaching high levels of sophistication by the mid-century for various key economic areas in the West (e.g. Bolli, 1957a,b) and Former Soviet Union (e.g. Subbotina, 1953). The process of generalizing these essentially local schemes was underway in the 1960s (e.g., Bandy, 1964; Banner and Blow, 1965) but was accelerated by the Deep Sea Drilling Project (DSDP), when it soon became clear that even in the deep Pacific Ocean there were “the same species assemblages and faunal succession as reported from other areas” (Krasheninnikov, 1971, p. 1055–1056). Hence integrated biostratigraphic schemes began to be regarded as global within broad latitudinal belts, although some

degree of provincialism was also recognized in different ocean basins, the Mediterranean Sea (e.g. Cita, 1973), and areas of high productivity.

The starting point for all biostratigraphy is the recognition of so-called biostratigraphic horizons (biohorizons) that can be thought of as levels that can be correlated between stratigraphic sections where the fossil content changes in some measurable way (see McGowran, 2005 for discussion). The biostratigraphic resolution is determined by morphospecies evolution (appearances and disappearances of species). Additional biohorizons include prominent changes in coiling direction. Since at least the mid-nineteenth century (Hedberg, 1976) it has been standard biostratigraphic practice to divide stratigraphic sections into zones and subzones, which are non-overlapping slices of stratigraphy that lie between prominent biohorizons and are characterized by a particular fossil content (see McGowran, 2005). The zones and subzones allow recognition of fairly broad and easily identifiable intervals of stratigraphy that can be widely correlated with confidence. The practice of naming and/or sequentially numbering biozones provides the biostratigrapher with a useful mnemonic and easy means of communication. The five types of biozones that can logically be based on stratigraphic lowest and highest occurrences (LO and HO) are shown in Fig. 1.

Throughout the Cenozoic the planktonic foraminifera have been most abundant and diverse in the tropics and subtropics, hence it is for these latitudes that the zonal schemes are most detailed and easy to

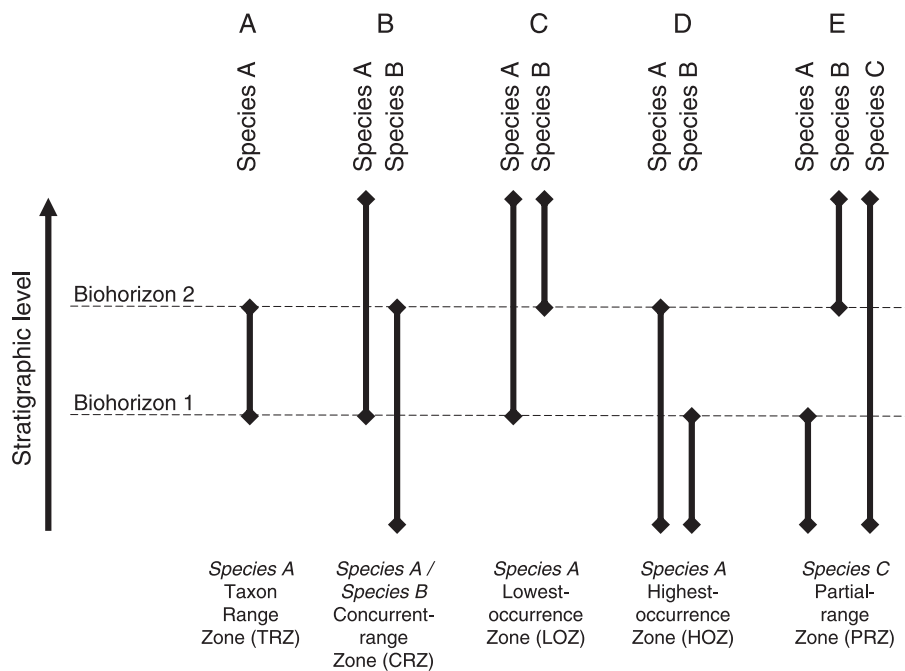


Fig. 1. Nomenclature of biostratigraphical zones modified from Hedberg (1976) and Pearson (1998) to illustrate the convention of Berggren and Pearson (2005) and this paper. Note that examples C, D and E are described as 'interval zones' by the International Stratigraphic Guide (Hedberg, 1976) and all five examples are described as 'interval zones' by the North American Commission on Stratigraphy. We prefer to refer to the five different logical possibilities by different names. Note that our naming convention demands that the named species occur within the zone, hence the necessity of species C in example E.

apply. Work in the temperate mid-latitudes and sub-polar oceans, especially in the Neogene when climatic gradients were more pronounced than in the Paleogene, either requires judicious use of secondary markers and the amalgamation of zones when key species are absent or the development of entirely separate zonal schemes (e.g. Jenkins, 1966, 1967, 1971; Kaneps, 1975; Poore and Berggren, 1975; Kennett and Srinivasan, 1983; Stott and Kennett, 1990). Nevertheless the tropical/subtropical schemes have always provided the central standard, and within that standard an increasing number of key datum levels have been accurately calibrated against magneto- and astro-chronological time scales.

The updated and revised tropical/subtropical zonation presented here is a much-modified and refined descendant of that originally developed by British Petroleum micropaleontologists in the Caribbean and Tanzania in the 1950s and 1960s (Bolli, 1957a,b, 1966; Blow, 1959; Blow and Banner, 1962; Bolli and Bermúdez, 1965). A significant innovation was made by Banner and Blow (1965) who partially described a set of zones using alphanumeric shorthand ('P' for Paleogene and 'N' for Neogene, with only the Neogene zones fully described, from N1 to N22). The remainder of this scheme was presented by Blow (1969) with extensive taxonomic and stratigraphic discussion; however note that one unfortunate consequence of this was that the Neogene began with Zone N4 due to uncertainty in the placement of the Oligocene/Miocene boundary. The Blow (1969) scheme was later revised and expanded upon by Blow (1979). A variant of this zonation was published by Berggren (1969) and originally attributed to "Blow and Berggren in Berggren (1969)"; see discussion in Berggren and Miller (1988). Numerous amendments to these zones have been suggested over the years, often for specific parts of the scheme that have failed to work optimally in certain areas. Comprehensive updates and correlations between alternative schemes were published by Stainforth et al. (1975), Kennett and Srinivasan (1983), Bolli and Saunders (1985), Berggren and Miller (1988), and Berggren et al. (1995b; referred to herein as BKSA95). This latter review introduced a new development to the alphanumeric notation for epoch-level intervals, namely the introduction of 'M' for Miocene, 'PL' for Pliocene and 'PT' for Pleistocene in place of the earlier 'N' for Neogene zones. Similarly, Berggren and Pearson (2005) produced a new revision for the Paleogene zones following extensive taxonomic work on the Paleocene and Eocene planktonic foraminifera (Olsson et al., 1999; Pearson et al., 2006), extending this practice to include 'P' for Paleocene, 'E' for Eocene and 'O' for Oligocene.

1.2. Recent developments and necessity for Cenozoic biostratigraphic review

In 2009 the research vessel the *JOIDES Resolution*, part of the Integrated Ocean Drilling Program (IODP) was refloated for a new campaign of ocean drilling, following a two year renovation. During IODP, as in DSDP and Ocean Drilling Program (ODP), planktonic foraminiferal biostratigraphy is extensively employed during Ship-board and post-cruise work to establish age–depth relationships.

The compilation of BKSA95 brought together the planktonic foraminifera and calcareous nannoplankton bioevents for the Cenozoic and has been frequently applied in regional and global biostratigraphy and correlations. Consistency of nomenclature is extremely sought after in biostratigraphy, and revision of zonal scheme(s) should not be embarked upon without due consideration. However, since 1995, a number of apparent deficiencies in the tropical planktonic foraminiferal zonal schemes have been discovered through detailed biostratigraphic investigations and taxonomic developments. The enhancements in deep sea drilling recovery, multiple coring, high resolution sampling both offshore and onshore, has improved the calibrations with the magnetostratigraphy and/or modified the species ranges and allowed many of the planktonic foraminiferal bioevents to be revised. For example, detailed biostratigraphic investigations from Ceara Rise (Chaisson and Pearson, 1997; Pearson and Chaisson, 1997; Turco et al., 2002), equatorial Pacific Ocean

(Wade et al., 2007), Indian Ocean (Hancock et al., 2002) and the Gorrondaxte and Agost sections in Spain (Payros et al., 2007, 2009; Larrasoña et al., 2008; Ortiz et al., 2008) have resulted in revision of the calibrations of numerous bioevents. Most of these changes are small and incremental in nature, but some (e.g., the revision of the lower–middle Eocene by Payros et al., 2007) are major developments. This accumulated new information presents the opportunity for a reassessment of the planktonic foraminiferal calibrations and to incorporate developments and amendments to the existing biostratigraphic zonal scheme.

Ocean Drilling Program Leg 154 (Ceara Rise, western tropical Atlantic Ocean) produced several new constraints on tropical planktonic foraminiferal biohorizons that are incorporated into the present study. The sedimentary succession on Ceara Rise is remarkably complete and continuous from the upper Paleocene to Recent (Curry et al., 1995). It is unfortunate that no magnetostratigraphy is available for the sites. Nevertheless a very complete series of foraminifera and nannofossil biohorizons was recorded (Backman and Raffi, 1997; Chaisson and Pearson, 1997; Pearson and Chaisson, 1997; Turco et al., 2002). Datums that are derived from Leg 154 sites are indirectly calibrated to the geomagnetic time scale by interpolation between other well calibrated events and through linear interpolation with the astro-chronology of Lourens et al. (2004). To ensure consistency we have also recalculated bioevents from Ceara Rise (Chaisson and Pearson, 1997; Pearson and Chaisson, 1997; Turco et al., 2002) and converted them to the magnetostratigraphy of Cande and Kent (1995) (Table 1, Fig. 2). A revised Cenozoic planktonic foraminiferal biochronology is a logical outcome of the improved age control, and the new campaign of ocean drilling by the *JOIDES Resolution* (e.g., Lyle et al., 2009; Pälike et al., 2009), as well as high resolution biostratigraphic studies since 1995 have acted as the catalyst to bring these new calibrations together.

1.3. A Cenozoic astronomical naming scheme

The ~405 kyr cycle of Earth's eccentricity is regarded as relatively stable over geological time (Laskar, 1999). Neogene geochronology has undergone major advances with integrated magneto-, astro-stratigraphies of continuous open marine and outcrop sedimentary successions (Hilgen et al., 2006 and references therein) and a well constrained astro-magneto-chronology for the entire Neogene (Lourens et al., 2004). An orbitally calibrated magnetostratigraphy for the Paleogene is still under development and is available to Chron C19n (Pälike et al., 2006). We propose here a naming scheme that relates astronomical (chronological) information with magnetostratigraphy. The naming scheme to define events by ~405 kyr eccentricity cycle follows the procedure used in Wade and Pälike (2004) and Pälike et al. (2006). The cycle count number is identified by the ~405 kyr eccentricity minima from Laskar et al. (2004), numerically coded, starting with number 1 for the most recent minimum and proceeding back in time (Table 2). As in Wade and Pälike (2004) we include a subscripted code for the geological epoch together with the magnetostratigraphy (excluding subchrons) closest to the ~405 kyr eccentricity minimum (Fig. 3).

1.4. Revision of Cenozoic tropical planktonic foraminiferal bio-, magneto-, astro-chronology

We have produced a revised and unified Cenozoic planktonic foraminiferal magnetobiochronology. We integrated planktonic foraminiferal data from multiple sources and incorporated these recalibrations into a revised Cenozoic planktonic foraminiferal biochronology and reviewed and synthesized these calibrations to both the geomagnetic polarity time scale (GPTS) and astronomical time scale (ATS). The biochronology has been derived from calibrations to the magnetostratigraphic polarity zones (chrons and subchrons) in deep sea and land sections where available. We have used linear interpolation to convert numerous bioevents to multiple time scales (Cande and Kent, 1995; Lourens et al., 2004; Luterbacher et al., 2004; Pälike et al., 2006) to

Table 1
Planktonic foraminiferal bioevents for the Cenozoic calibrated to the geomagnetic polarity time scale of **Cande and Kent (1995)**. Marker taxa are highlighted in bold. Previously published ages are on multiple time scales and refer to the data in each given reference.

| Zone (BKSA95 and BP05) (base) | Zone (this study) (base) | Datum | Notes | Age (Ma) This Study ^a | Published age (Ma) | Reference | Berggren et al. (1995a,b) | Berggren and Pearson (2005) |
|--------------------------------------|---------------------------|---|-------------------------------|----------------------------------|--------------------|-------------------------------|---------------------------|-----------------------------|
| | | T Globorotalia flexuosa | | 0.07 | 0.07 | Berggren et al. (1995a) | 0.07 | – |
| | | T Globigerinoides ruber (pink) | (Indo-Pacific only) | 0.12 | 0.12 | Thompson et al. (1979) | – | – |
| | | B Globigerinella calida | | 0.22 | 0.22 | Chaproniere et al., 1994 | 0.22 | – |
| | | B Globorotalia flexuosa | | 0.40 | 0.40 | Berggren et al. (1995a) | 0.40 | – |
| | | B Globorotalia hirsuta | | 0.45 | 0.45 | Pujol and Duprat (1983) | – | – |
| PT1b | PT1b | T Globorotalia tosaensis | | 0.61 | 0.61 | Mix et al. (1995) | 0.65 | – |
| | | B Globorotalia hessi | | 0.75 | 0.75 | Chaproniere et al. (1994) | 0.75 | – |
| | | X random to dextral in Pulleniatina | (Pacific) | 0.80 | 0.80 | Pearson (1995) | – | – |
| | | B Globorotalia excelsa | | 1.00 | 1.00 | Berggren et al. (1995a) | 1.00 | – |
| | | T Globoturborotalita obliquus | | 1.30 | 1.30 | Chaisson and Pearson (1997) | – | – |
| | | T Globoturborotalita apertura | | 1.63 | 1.64 | Chaisson and Pearson (1997) | – | – |
| <i>Pliocene/Pleistocene boundary</i> | | | | | 1.80 | Aguirre and Pasini (1985) | – | – |
| PT1a | PT1a | T Globigerinoides fistulosus | ^k | 1.88 | 1.88 | Chaisson and Pearson (1997) | 1.77 | – |
| | | B Globorotalia truncatulinoides | ^g | 1.93 | 1.92 | Chaisson and Pearson (1997) | 2.00 | – |
| | | T Globigerinoides extremus | | 1.99 | 1.98 | Chaisson and Pearson (1997) | 1.77 | – |
| | | B Pulleniatina finalis | | 2.05 | 2.04 | Chaisson and Pearson (1997) | – | – |
| | | T Globorotalia exilis | (Atlantic) | 2.10 | 2.09 | Chaisson and Pearson (1997) | 2.15 | – |
| | | Reappearance of Pulleniatina | (Atlantic) | 2.26 | 2.26 | Chaisson and Pearson (1997) | 2.30 | – |
| | | T Globoturborotalita woodi | | 2.30 | 2.33 | Chaisson and Pearson (1997) | – | – |
| | | T Globorotalia pertenuis | | 2.30 | 2.33 | Chaisson and Pearson (1997) | – | – |
| PL6 | PL6 (Indo-Pacific) | T Globorotalia pseudomiocenica | (Indo-Pacific) | 2.30 | 2.30 | Berggren et al. (1995a) | 2.30 | – |
| PL6 | PL6 (Atlantic) | T Globorotalia miocenica | (Atlantic) | 2.39 | 2.38 | Chaisson and Pearson (1997) | 2.30 | – |
| | | T Globorotalia limbata | | 2.39 | 2.38 | Chaisson and Pearson (1997) | – | – |
| | | T Globorotalia pertenuis | | 2.60 | 2.60 | Berggren et al. (1995a) | 2.60 | – |
| | | T Globoturborotalita decoraperta | | 2.75 | 2.75 | Chaisson and Pearson (1997) | – | – |
| | | T Globorotalia multicamerata | | 2.99 | 3.10 | Chaisson and Pearson (1997) | 3.09 | – |
| PL5 | PL5 (Atlantic) | T Dentoglobigerina altispira | (Atlantic)^h | 3.13 | 3.11 | Chaisson and Pearson (1997) | 3.09 | – |
| PL4 | PL4 | T Sphaeroidinellopsis seminulina | (Atlantic)^h | 3.16 | 3.14 | Chaisson and Pearson (1997) | 3.12 | – |
| | | B Globigerinoides fistulosus | | 3.33 | 3.33 | Berggren et al. (1995a) | 3.33 | – |
| | | B Globorotalia tosaensis | | 3.35 | 3.35 | Berggren et al. (1995a) | 3.35 | – |
| | | T Pulleniatina disappearance | (Atlantic) | 3.41 | 3.41 | Chaisson and Pearson (1997) | – | – |
| PL5 | PL5 (Indo-Pacific) | T Dentoglobigerina altispira | (Pacific) | 3.46 | 3.05 | Shackleton et al. (1995) | – | – |
| | | B Globorotalia pertenuis | | 3.51 | 3.52 | Chaisson and Pearson (1997) | 3.45 | – |
| PL4 | PL4 | T Sphaeroidinellopsis seminulina | (Pacific) | 3.57 | 3.20 | Shackleton et al. (1995) | – | – |
| | | T Pulleniatina primalis | | 3.65 | 3.65 | Berggren et al. (1995a) | 3.65 | – |
| | | B Globorotalia miocenica | (Atlantic) | 3.76 | 3.77 | Chaisson and Pearson (1997) | 3.55 | – |
| | | T Globorotalia plesiotumida | | 3.76 | 3.77 | Chaisson and Pearson (1997) | – | – |
| PL3 | PL3 | T Globorotalia margaritae | | 3.84 | 3.85 | Chaisson and Pearson (1997) | 3.58 | – |
| | | X Pulleniatina sinis.-dext. | | 4.07 | 4.08 | Chaisson and Pearson (1997) | 3.95 | – |
| | | T Pulleniatina spectabilis | (Pacific) | 4.20 | 4.20 | Berggren et al. (1995a) | 4.20 | – |
| | | B Globorotalia crassaformis | sensu lato | 4.30 | 4.31 | Chaisson and Pearson (1997) | 4.50 | – |
| PL2 | PL2 | T Globoturborotalita nepenthes | | 4.36 | 4.39 | Chaisson and Pearson (1997) | 4.20 | – |
| | | B Globorotalia exilis | | 4.44 | 4.45 | Chaisson and Pearson (1997) | – | – |
| | | T Sphaeroidinellopsis kochi | | 4.52 | 4.53 | Chaisson and Pearson (1997) | – | – |
| | | T Globorotalia cibaensis | | 4.60 | 4.60 | Berggren et al. (1995b) | 4.60 | – |
| <i>Miocene/Pliocene boundary</i> | | | | 5.33 | 5.33 | Van Couvering et al. (2000) | – | – |
| | | B Sphaeroidinella dehiscens | sensu lato | 5.48 | 5.54 | Chaisson and Pearson (1997) | 5.20 | – |
| PL1a | PL1 | B Globorotalia tumida | (Pacific) | 5.51 | 5.59 | Shackleton et al. (1995) | 5.60 | – |
| PL1a | PL1 | B Globorotalia tumida | (Atlantic) | 5.63 | 5.82 | Chaisson and Pearson (1997) | 5.60 | – |
| | | B Turborotalita humilis | | 5.71 | 5.84 | Chaisson and Pearson (1997) | – | – |
| | | T Globoquadrina dehiscens | | 5.80 | 5.80 | Berggren et al. (1995a) | 5.80 | – |
| | | B Globorotalia margaritae | | 5.95 | 6.09 | Chaisson and Pearson (1997) | 6.40 | – |
| M14 | M14 | T Globorotalia linguaensis | | 6.00 | 6.00 | Berggren et al. (1995) | 6.00 | – |
| | | B Globigerinoides conglobatus | | 6.08 | 6.20 | Chaisson and Pearson (1997) | – | – |
| | | X Neogloboquadrina acostaensis | Trans. sinis.-dext | 6.20 | 6.20 | Berggren et al. (1995b) | 6.20 | – |
| | | B Pulleniatina primalis | | 6.40 | 6.40 | Berggren et al. (1995b) | 6.40 | – |
| | | X Neogloboquadrina acostaensis | Trans. dext.-sinis | 6.60 | 6.60 | Berggren et al. (1995b) | 6.60 | – |
| | | X Neogloboquadrina atlantica | Trans. dext.-sinis | 6.80 | 6.80 | Berggren et al. (1995b) | 6.80 | – |
| | | B Neogloboquadrina humerosa | | 8.50 | 8.50 | Berggren et al. (1995b) | 8.50 | – |
| M13b | M13b | B Globorotalia plesiotumida | ^{c (1)} | 8.52 | 8.58 | Chaisson and Pearson (1997) | – | – |
| | | B Globigerinoides extremus | ^b | 8.86 | 8.94 | Turco et al. (2002) | – | – |
| | | B Globorotalia cibaensis | | 9.34 | 9.44 | Chaisson and Pearson (1997) | – | – |
| | | B Globorotalia juanai | | 9.62 | 9.76 | Chaisson and Pearson, 1997 | – | – |
| M13a | M13a | B Neogloboquadrina acostaensis | | 9.79 | 9.82 | Chaisson and Pearson (1997) | 10.90 | – |
| M12 | M12 | T Paragloborotalia mayeri | | 10.53 | 10.49 | Chaisson and Pearson (1997) | 11.40 | – |
| | | B Globorotalia limbata | | 10.66 | 10.57 | Chaisson and Pearson (1997) | – | – |
| | | T Cassigerinella chipolensis | ^b | 10.84 | 10.81 | Turco et al., 2002 | – | – |
| | | B Globoturborotalita apertura | | 11.12 | 11.19 | Chaisson and Pearson (1997) | – | – |
| | | T Globoturborotalita decoraperta | | 11.42 | 11.46 | Chaisson and Pearson (1997) | – | – |
| | | T Globigerinoides subquadratus | ^b | 11.46 | 11.55 | Turco et al. (2002) | – | – |
| M11 | M11 | B Globoturborotalita nepenthes | ^b | 11.55 | 11.64 | Turco et al. (2002) | 11.80 | – |
| M10 | M10 | T Fohsella fohsi | | 11.71 | 11.68 | Chaisson and Pearson (1997) | 11.90 | – |

Table 1 (continued)

Planktonic foraminiferal bioevents for the Cenozoic calibrated to the geomagnetic polarity time scale of **Cande and Kent (1995)**. Marker taxa are highlighted in bold. Previously published ages are on multiple time scales and refer to the data in each given reference.

| Zone (BKSA95 and BP05) (base) | Zone (this study) (base) | Datum | Notes | Age (Ma) This Study ^a | Published age (Ma) | Reference | Berggren et al. (1995a,b) | Berggren and Pearson (2005) |
|-----------------------------------|--------------------------|---|---------------|----------------------------------|--------------------|-----------------------------|---------------------------|-----------------------------|
| | | T Globorotalia praescitula | | 11.90 | 11.90 | Berggren et al. (1995b) | 11.90 | – |
| | | B Globorotalia languaensis | b | 12.89 | 12.39 | Turco et al., 2002 | – | – |
| | | B Sphaeroidinellopsis subdehiscens | b | 13.00 | 13.03 | Turco et al. (2002) | – | – |
| M9b | M9b | B Fohsella robusta | | 13.09 | 13.18 | Chaisson and Pearson (1997) | 12.30 | – |
| M9a | | B Fohsella lobata | | – | 12.50 | Berggren et al. (1995b) | 12.50 | – |
| | | T Cassigerinella martinezpicoi | b | 13.22 | 13.28 | Turco et al. (2002) | – | – |
| M8 | M9a | B Fohsella fohsi | | 13.34 | 13.42 | Chaisson and Pearson (1997) | 12.70 | – |
| | M8 | B Fohsella "praefohsi" | | 13.74 | 14.00 | Pearson and Chaisson (1997) | – | – |
| | | T Fohsella peripheroronda | b | 13.77 | 13.87 | Turco et al. (2002) | 14.60 | – |
| | | T Clavatorella bermudezi | | 13.79 | 14.20 | Pearson and Chaisson (1997) | – | – |
| | | T Globorotalia archeomenardii | b | 13.84 | 13.87 | Turco et al. (2002) | – | – |
| M7 | M7 | B Fohsella peripheroacuta | b | 14.23 | 14.02 | Turco et al. (2002) | 14.80 | – |
| | | B Globorotalia praemenardii | | 14.39 | 14.90 | Pearson and Chaisson (1997) | – | – |
| | | T Praeorbulina sicana | | 14.56 | 14.40 | Shackleton et al. (1999) | 14.80 | – |
| | | T Globigerinatella insueta | | 14.69 | 15.00 | Pearson and Chaisson (1997) | – | – |
| M6 | M6 | B Orbulina suturalis | | 15.10 | 15.10 | Berggren et al. (1995b) | 15.10 | – |
| | | B Clavatorella bermudezi | f | 15.76 | 15.80 | Pearson and Chaisson (1997) | – | – |
| | | B Praeorbulina circularis | e | 16.00 | 16.00 | Berggren et al. (1995b) | 16.00 | – |
| | | B Globorotalia archeomenardii | | 16.29 | 16.20 | Pearson and Chaisson, 1997 | – | – |
| M5b | M5b | B Praeorbulina glomerosa | sensu stricto | 16.29 | 16.20 | Shackleton et al. (1999) | 16.10 | – |
| | | B Praeorbulina curva | | 16.30 | 16.30 | Berggren et al. (1995b) | 16.30 | – |
| M5a | M5a | B Praeorbulina sicana | | 16.40 | 16.40 | Berggren et al. (1995b) | 16.40 | – |
| M4b | M4b | B Fohsella birnageae | | 16.70 | 16.70 | Berggren et al. (1995b) | 16.70 | – |
| | | B Globorotalia zealandica | j | 17.30 | 17.30 | Berggren et al. (1995b) | 17.30 | – |
| M4a | M4a | T Catapsydrax dissimilis | | 17.62 | 17.50 | Shackleton et al. (1999) | 17.30 | – |
| M3 | | B Globigerinatella insueta | sensu stricto | 17.69 | 17.40 | Pearson and Chaisson (1997) | (18.8) | – |
| | | B Globorotalia praescitula | | 18.50 | 18.50 | Berggren et al. (1995b) | 18.50 | – |
| | | T Globoquadrina binaiensis | | 19.43 | 19.10 | Pearson and Chaisson (1997) | – | – |
| | M3 | B Globigerinatella sp. | | 19.66 | 20.20 | Pearson and Chaisson (1997) | – | – |
| | | B Globigerinoides altiaperturaus | | 20.50 | 20.50 | Berggren et al. (1995b) | 20.50 | – |
| | | T Tenuitella munda | | 21.40 | 21.40 | Berggren et al., 1995b | 21.40 | – |
| | | T Globigerina angulisuturalis | | 21.60 | 21.60 | Berggren et al. (1995b) | 21.60 | – |
| M2 | M2 | T 'Paragloborotalia' kugleri | | 21.81 | 21.00 | Shackleton et al. (1999) | 21.50 | – |
| | | T 'Paragloborotalia' pseudokugleri | | 22.04 | 21.10 | Shackleton et al. (1999) | 21.60 | – |
| M1b | M1b | B Globoquadrina dehiscens | | 23.20 | 23.20 | Berggren et al. (1995b) | 23.20 | – |
| | | B Globigerina ciperoensis | | 23.68 | 22.80 | Shackleton et al. (1999) | – | – |
| | | B Globigerinoides trilobus | sensu lato | 23.73 | 22.90 | Shackleton et al. (1999) | – | – |
| M1a | M1a | B 'Paragloborotalia' kugleri | | 23.73 | 22.90 | Shackleton et al. (1999) | 23.80 | – |
| <i>Oligocene/Miocene boundary</i> | | | | | 23.80 | Berggren et al. (1995b) | | |
| | | T Tenuitella gemma | | 24.3 | 24.3 | Berggren et al. (1995b) | 24.3 | – |
| | | LCO Globigerinoides primordius | | 24.3 | 24.3 | Berggren et al. (1995b) | 24.3 | – |
| | O7 | B 'Paragloborotalia' pseudokugleri | | 25.9 | 25.9 | Berggren et al. (1995b) | 25.9 | – |
| | | B Globigerinoides primordius | | 26.7 | 26.7 | Berggren et al. (1995b) | 26.7 | – |
| O6 | O6 | T Paragloborotalia opima | | 27.5 | 27.5 | Wade et al. (2007) | 27.1 | 27.1 |
| O5 | O5 | HCO Chiloguembelina cubensis | | 28.4 | 28.4 | Wade et al. (2007) | 28.5 | 28.5 |
| O4 | O4 | B Globigerina angulisuturalis | | 29.4 | 29.4 | Berggren et al. (1995b) | 29.4 | 29.4 |
| | | T Subbotina angiporoides | | 30.0 | 30.0 | Berggren et al. (1995b) | 30.0 | 30.0 |
| O3 | O3 | T Turborotalia ampliapertura | | 30.3 | 30.3 | Berggren et al. (1995b) | 30.3 | 30.3 |
| | | B Paragloborotalia opima | | 30.6 | 30.6 | Berggren et al. (1995b) | 30.6 | – |
| O2 | O2 | T Pseudohastigerina nagewichiensis | | 32.0 | 32.0 | Berggren et al. (1995b) | 32.0 | 32.0 |
| <i>Eocene/Oligocene boundary</i> | | | | | 33.7 | Berggren et al. (1995b) | | |
| O1 | O1 | T Hantkenina alabamensis | | 33.7 | 33.7 | Berggren and Pearson (2005) | 33.7 | 33.7 |
| | | HCO Pseudohastigerina micra | | 33.7 | 33.7 | Wade and Pearson (2008) | – | – |
| | | T Turborotalia cerroazulensis | | 33.8 | 33.8 | Berggren and Pearson (2005) | 33.8 | 33.8 |
| E16 | E16 | T Globigerinatheka index | | 34.3 | 34.3 | Berggren and Pearson (2005) | 34.3 | 34.3 |
| | | B Turborotalia cunialensis | | 35.3 | 35.3 | Berggren and Pearson (2005) | 35.2 | 35.3 |
| E15 | E15 | T Globigerinatheka semiinvoluta | | 35.8 | 35.8 | Berggren and Pearson (2005) | 35.3 | 35.8 |
| | | B Globigerinatheka semiinvoluta | | 38.0 | 38.0 | Wade (2004) | 38.4 | – |
| E14 | E14 | T Morozovelloides crassatus | | 38.0 | 38.0 | Wade (2004) | 38.1 | 38.0 |
| | | T Acarinina mcgowrani | | 38.0 | 38.0 | Wade (2004) | – | – |
| | | T Turborotalia frontosa | | 39.3 | 39.3 | Berggren et al. (1995b) | 39.3 | – |
| E13 | E13 | T Orbulinoides beckmanni | | 40.0 | 40.0 | Wade (2004) | 40.1 | 40.0 |
| E12 | E12 | B Orbulinoides beckmanni | | 40.5 | 40.5 | Berggren et al. (1995b) | 40.5 | 40.5 |
| | | T Acarinina bullbrookii | | 40.5 | 40.5 | Berggren et al. (1995b) | 40.5 | – |
| E11 | E11 | T Guembilitrioides nuttalli | | (42.3) | (42.3) | Berggren and Pearson (2005) | – | (42.3) |
| | | B Turborotalia pomeroli | | 42.4 | 42.4 | Berggren et al. (1995b) | 42.4 | – |
| | | B Globigerinatheka index | | 42.9 | 42.9 | Berggren et al. (1995b) | 42.9 | – |
| | | B Morozovelloides lehneri | | 43.5 | 43.5 | Berggren et al. (1995b) | 43.5 | – |
| E10 | E10 | T Morozovella aragonensis | | 43.6 | 43.6 | Berggren et al. (1995b) | 43.6 | 43.6 |
| E9 | E9 | B Globigerinatheka kugleri | | (44.4) | – | Pearson et al. (2004) | 45.8 | 45.8 |
| | | B Hantkenina singanoae | i | 44.5 | 43.5 | Payros et al. (2009) | 49.0 | – |

(continued on next page)

Table 1 (continued)

Planktonic foraminiferal bioevents for the Cenozoic calibrated to the geomagnetic polarity time scale of **Cande and Kent (1995)**. Marker taxa are highlighted in bold. Previously published ages are on multiple time scales and refer to the data in each given reference.

| Zone (BKSA95 and BP05) (base) | Zone (this study) (base) | Datum | Notes | Age (Ma) This Study ^a | Published age (Ma) | Reference | Berggren et al. (1995a,b) | Berggren and Pearson (2005) |
|-------------------------------|--------------------------|--|-------|----------------------------------|--------------------|-----------------------------|---------------------------|-----------------------------|
| E8 | E8 | B Guembilitrioides nuttalli | i | 46.4 | 45.5 | Payros et al. (2009) | – | 49.0 |
| | E7b | B Turborotalia frontosa | i | 49.0 | 48.6 | Payros et al. (2009) | – | – |
| E7 | E7a | B Acarinina cuneicamerata | | 50.4 | 50.4 | Hancock et al. (2002) | – | 50.4 |
| | | B Planorotalites palmerae | | 50.4 | 50.4 | Berggren et al. (1995b) | 50.4 | – |
| E6 | E6 | T Morozovella subbotinae | | 50.8 | 50.8 | Berggren and Pearson (2005) | – | 50.8 |
| E5 | E5 | B Morozovella aragonensis | | 52.3 | 52.3 | Berggren et al. (1995b) | 52.3 | 52.3 |
| | | T Morozovella marginodentata | | 52.5 | 52.5 | Berggren et al. (1995b) | 52.5 | – |
| | | T Morozovella lensiformis | | 52.7 | 52.7 | Berggren et al. (1995b) | 52.7 | – |
| | | T Morozovella aequa | | 53.6 | 53.6 | Berggren et al. (1995b) | 53.6 | – |
| E4 | E4 | B Morozovella formosa | | 54.0 | 54.0 | Berggren et al. (1995b) | 54.0 | 54.0 |
| | | B Morozovella lensiformis | | 54.0 | 54.0 | Berggren et al. (1995b) | 54.0 | – |
| E3 | E3 | T Morozovella velascoensis | | 54.5 | 54.5 | Berggren and Pearson (2005) | 54.7 | 54.5 |
| | | T Morozovella acuta | | 54.7 | 54.7 | Berggren et al. (1995b) | 54.7 | – |
| | | B Morozovella gracilis | | 54.7 | 54.7 | Berggren et al. (1995b) | 54.7 | – |
| | | B Igorina broedermanni | | 54.7 | 54.7 | Berggren et al. (1995b) | 54.7 | – |
| | | B Morozovella marginodentata | | 54.8 | 54.8 | Berggren et al. (1995b) | 54.8 | – |
| E2 | E2 | B Pseudohastigerina wilcoxensis | | 55.4 | 55.4 | Berggren and Pearson (2005) | – | 55.4 |
| | | B Globanomalina australiformis | | 55.5 | 55.5 | Berggren et al. (1995b) | 55.5 | – |
| E1 | E1 | B Acarinina sibaiaensis | | 55.5 | 55.5 | Berggren and Pearson (2005) | – | 55.5 |
| | | <i>Paleocene/Eocene boundary</i> | | | | Ouda and Aubry (2003) | | |
| P5 | P5 | T Globanomalina pseudomenardii | | 55.9 | 55.9 | Berggren et al. (1995b) | 55.9 | 55.9 |
| | | B Morozovella subbotinae | | 55.9 | 55.9 | Berggren et al. (1995b) | 55.9 | – |
| | | T Acarinina mckannai | | 56.3 | 56.3 | Berggren et al. (1995b) | 56.3 | – |
| | | T Acarinina acarinata | | 56.3 | 56.3 | Berggren et al. (1995b) | 56.3 | – |
| P4c | P4c | B Acarinina soldadoensis | d | 56.5 | 56.5 | Berggren et al. (1995b) | 56.5 | 56.5 |
| | | B Acarinina coalingensis | | 56.5 | 56.5 | Berggren et al. (1995b) | 56.5 | – |
| | | B Morozovella aequa | | 56.5 | 56.5 | Berggren et al. (1995b) | 56.5 | – |
| | | T Acarinina subsphaerica | | 57.1 | 57.1 | Berggren et al. (1995b) | 57.1 | 57.1 |
| | | B Acarinina mckannai | | 59.1 | 59.1 | Berggren et al. (1995b) | 59.1 | – |
| P4b | P4b | T Parasubbotina variospira | | 59.2 | 59.2 | Berggren et al. (1995b) | 59.2 | 59.2 |
| | | B Acarinina acarinata | | 59.2 | 59.2 | Berggren et al. (1995b) | 59.2 | – |
| | | B Acarinina subsphaerica | | 59.2 | 59.2 | Berggren et al. (1995b) | 59.2 | – |
| P4a | P4a | B Globanomalina pseudomenardii | | 59.4 | 59.4 | Berggren et al., 2000 | 59.2 | 59.4 |
| P3b | P3b | B Igorina albeari | | 60.0 | 60.0 | Berggren et al., 1995b | 60.0 | 60.0 |
| | | B Morozovella velascoensis | | 60.0 | 60.0 | Berggren et al., 1995b | 60.0 | – |
| | | B Morozovella conicotruncata | | 60.9 | 60.9 | Berggren et al., 1995b | 60.9 | – |
| P3a | P3a | B Morozovella angulata | | 61.0 | 61.0 | Berggren et al., 1995b | 61.0 | 61.0 |
| | | B Igorina pusilla | | 61.0 | 61.0 | Berggren et al., 1995b | 61.0 | – |
| | | B Morozovella praeangulata | | 61.2 | 61.2 | Berggren et al., 1995b | 61.2 | – |
| | | B Globanomalina imitata | | (61.3) | (61.3) | Berggren et al., 1995b | (61.3) | – |
| P2 | P2 | B Praemurica uncinata | | 61.4 | 61.4 | Berggren and Pearson, 2005 | 61.2 | 61.4 |
| P1c | P1c | B Globanomalina compressa | c (2) | 62.9 | 62.9 | Berggren and Pearson, 2005 | 63.0 | 62.9 |
| | | B Praemurica inconstans | | 62.9 | 62.9 | Berggren and Pearson, 2005 | 63.0 | 62.9 |
| | | B Parasubbotina varianta | | 63.0 | 63.0 | Berggren et al., 1995b | 63.0 | – |
| P1b | P1b | B Subbotina trilocolinoides | | 64.3 | 64.3 | Berggren et al., 1995b | 64.3 | 64.3 |
| P1a | P1a | T Parvularugoglobigerinaeugubina | | 64.8 | 64.8 | Berggren and Pearson, 2005 | 64.7 | 64.8 |
| | | B Parvularugoglobigerina extensa | | 64.9 | 64.9 | Olsson et al., 1999 | – | – |
| Pα | Pα | B Parvularugoglobigerina eugubina | | 64.97 | 64.97 | Berggren et al., 1995b | 64.97 | 64.97 |
| P0 | P0 | T Globotruncana | | 65.0 | 65.0 | Berggren et al., 1995b | 65.0 | 65.0 |

Notes: X, change in coiling direction. HCO Highest common occurrence. LCO Lowest common occurrence. (44.4) Estimated age.

^a Calibrated to **Cande and Kent (1995)**.

^b Calibration of **Turco et al. (2002)** on astronomical time scale of **Shackleton and Crowhurst (1997)**.

^c Replaces the and/or non zone of (1) **BKSA95**; (2) **Berggren and Pearson (2005)**.

^d Note mistake in **Berggren and Pearson (2005)**.

^e Note mistake in **Lourens et al. (2004)** table A2.3, where Bottom *Praeorbulina circularis* should read Top *Praeorbulina circularis*.

^f Note mistake in **Shackleton et al. (1999)** where 14.8 Ma should read 15.8 Ma. This mistake is also propagated in **Lourens et al. (2004)**.

^g Traditionally used as base N22, this datum is considered highly diachronous between ocean basins (see **Dowsett, 1988**).

^h Age adjusted to reflect the short stratigraphic duration between *D. altispira* and *S. seminulina* – see text for discussion.

ⁱ Calibrated to **Gradstein et al. (2004)**.

^j Note mistake in **BKSA95** (page 174) where LAD should read FAD.

^k Note mistake in **Berggren et al. (1995a, table 6)** where 1.6 Ma should read 1.77 Ma.

provide the reader with convenient “look up” tables and figures for age models and biostratigraphic control. The new and former calibration ages are given in **Tables 1, 3 and 4**.

Here, we present an amended low-latitude (tropical and subtropical) Cenozoic planktonic foraminiferal biochronology of 187 planktonic foraminiferal events for the Cenozoic (108 Neogene and 79 Paleogene) (**Figs. 2–4; Tables 1, 3 and 4**). Bioevents have been recalibrated to the GPTS of **Cande and Kent (1995)** and **Luterbacher et al. (2004)** and to the ATS of

Lourens et al. (2004) and **Pälike et al. (2006, from the Oligocene/Miocene boundary to Zone E11)** (**Tables 1, 3 and 4**). We recalibrate 61 primary and over 120 secondary bioevents for the Cenozoic. On the whole, these recalibrations are consistent with previous work. However, in some cases, they have led to major adjustments to the duration of biochrons (**Figs. 2–4**). Our revised and recalibrated datums provide a major advance in biochronologic resolution and a template for future progress to the Cenozoic time scale. The calibrations presented here represent the current status of

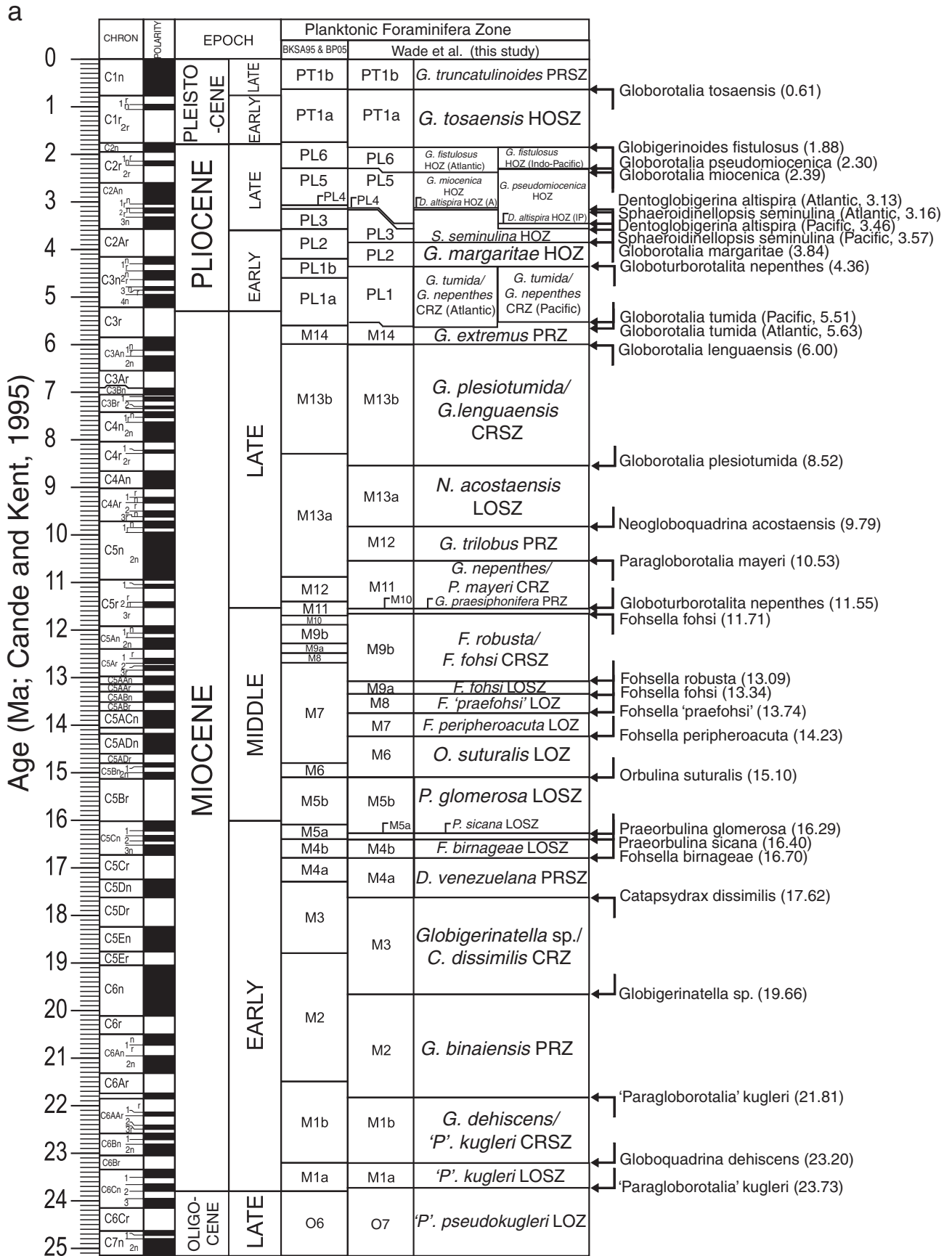


Fig. 2. Primary planktonic foraminiferal bioevents for the Cenozoic against the polarity time scale of Cande and Kent (1995). BKS95 = Berggren et al. (1995b); BP05 = Berggren and Pearson (2005). (a) 0–25 Ma; (b) 20–45 Ma; and (c) 40–65 Ma. A = Atlantic; IP = Indo-Pacific.

b

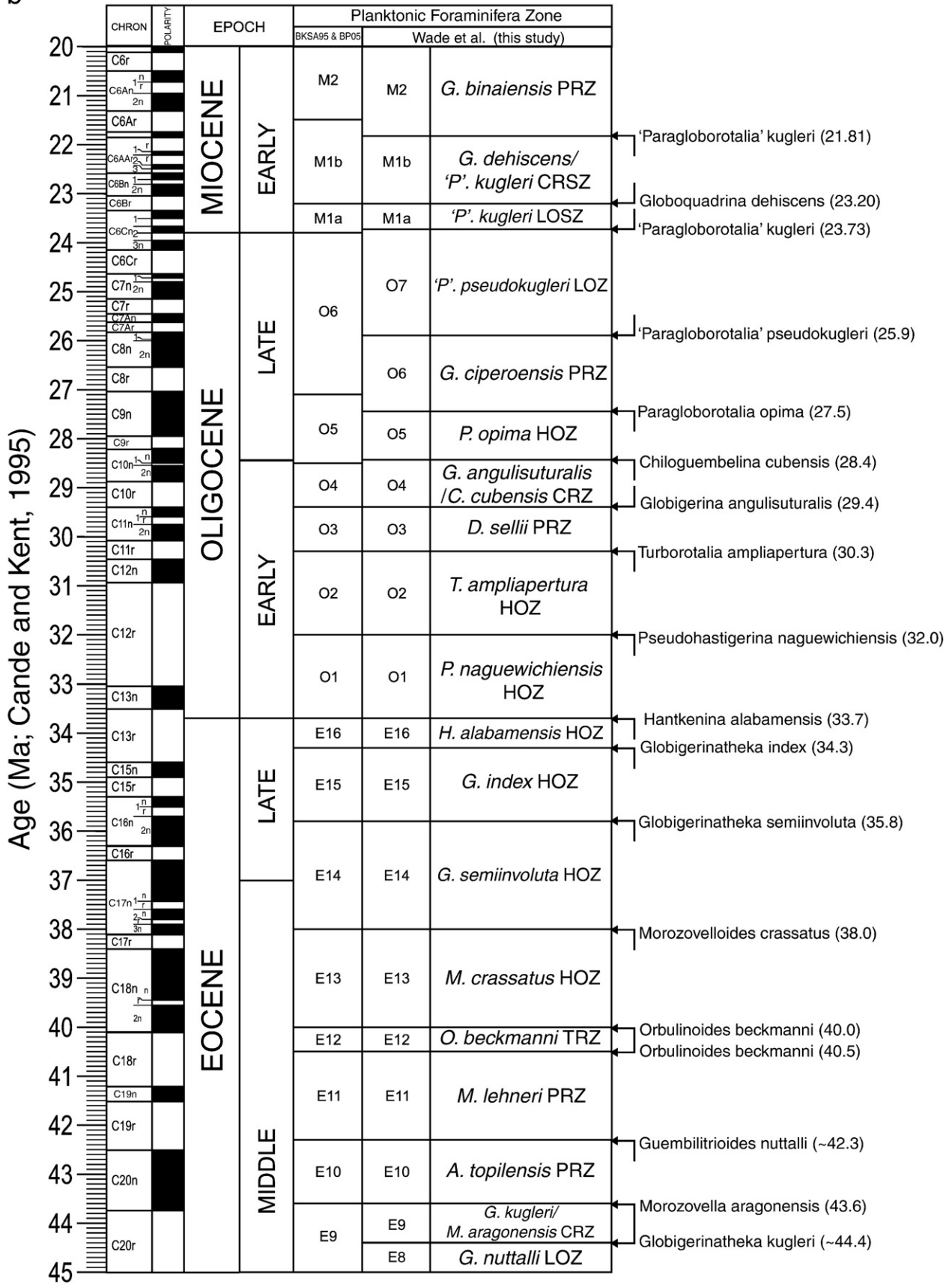


Fig. 2 (continued).

C

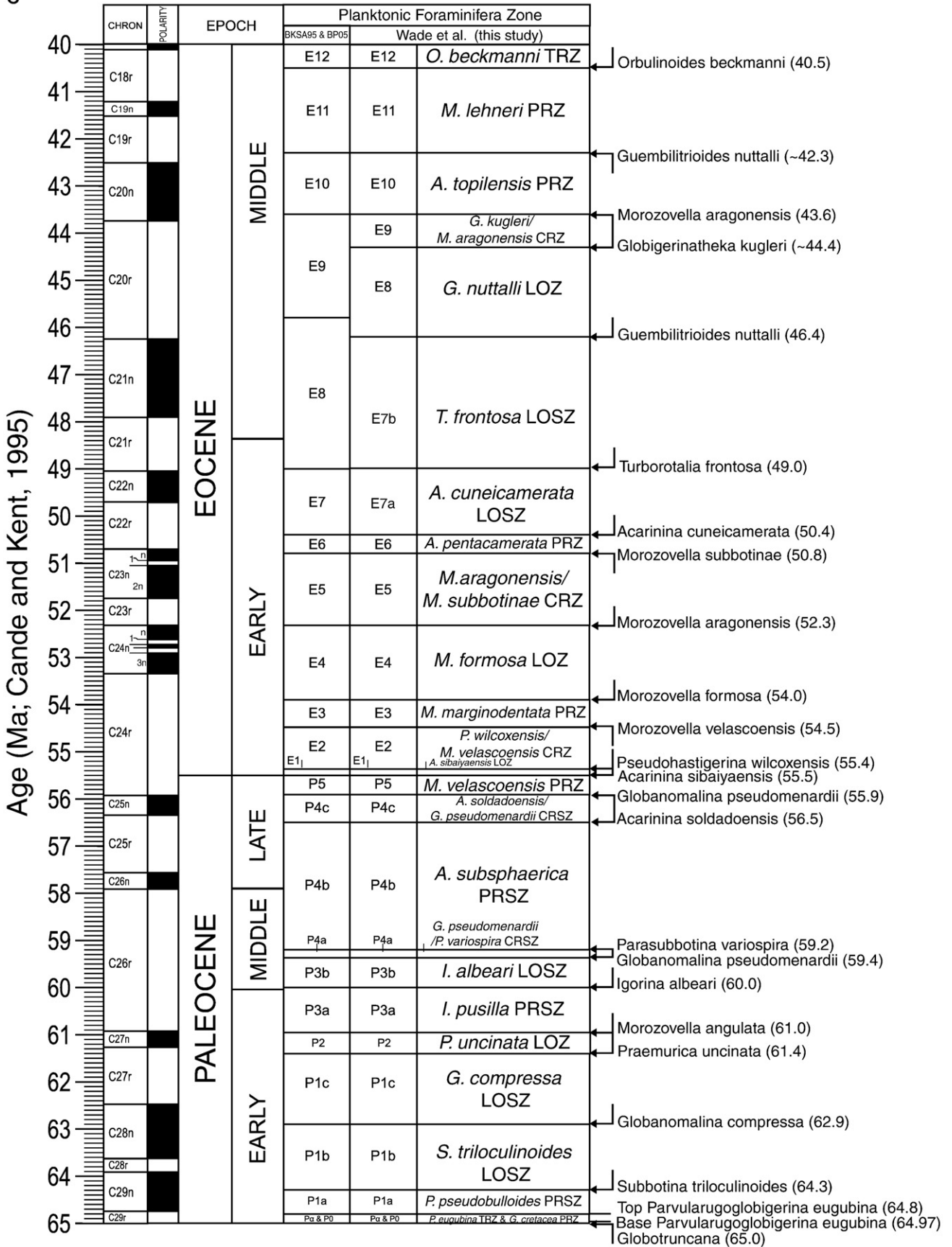


Fig. 2 (continued).

Table 2

Earth's ~405 kyr eccentricity cycle duration and ages for the Cenozoic with code names for the present to 41.5 Ma (base of Chron 19n).

| ~405 kyr cycle Cycle code/Chron | Younger end of cycle (Ma) | Older end of cycle (Ma) | Duration | Notes |
|------------------------------------|------------------------------|----------------------------|----------|--------------|
| 1 | −0.121 | 0.297 | 0.418 | ^a |
| 2 Pt-C1n | 0.297 | 0.702 | 0.405 | |
| 3 Pt-C1n | 0.702 | 1.106 | 0.405 | |
| 4 Pt-C1r | 1.106 | 1.516 | 0.410 | |
| 5 Pt-C1r | 1.516 | 1.922 | 0.406 | |
| 6 Pl-C2n | 1.922 | 2.329 | 0.408 | |
| 7 Pl-C2r | 2.329 | 2.736 | 0.407 | |
| 8 Pl-C2An | 2.736 | 3.144 | 0.408 | |
| 9 Pl-C2An | 3.144 | 3.543 | 0.399 | |
| 10 Pl-C2An | 3.543 | 3.944 | 0.401 | |
| 11 Pl-C2Ar | 3.944 | 4.341 | 0.397 | |
| 12 Pl-C3n | 4.341 | 4.742 | 0.402 | |
| 13 Pl-C3n | 4.742 | 5.155 | 0.413 | |
| 14 Pl-C3n | 5.155 | 5.559 | 0.404 | |
| 15 Mi-C3r | 5.559 | 5.968 | 0.409 | |
| 16 Mi-C3r | 5.968 | 6.374 | 0.407 | |
| 17 Mi-C3An | 6.374 | 6.765 | 0.391 | |
| 18 Mi-C3Ar | 6.765 | 7.172 | 0.406 | |
| 19 Mi-C3Bn | 7.172 | 7.574 | 0.403 | |
| 20 Mi-C4n | 7.574 | 7.983 | 0.409 | |
| 21 Mi-C4n | 7.983 | 8.395 | 0.412 | |
| 22 Mi-C4r | 8.395 | 8.797 | 0.402 | |
| 23 Mi-C4An | 8.797 | 9.205 | 0.409 | |
| 24 Mi-C4Ar | 9.205 | 9.602 | 0.397 | |
| 25 Mi-C4Ar | 9.602 | 10.008 | 0.406 | |
| 26 Mi-C5n | 10.008 | 10.423 | 0.415 | |
| 27 Mi-C5n | 10.423 | 10.834 | 0.412 | |
| 28 Mi-C5n | 10.834 | 11.240 | 0.406 | |
| 29 Mi-C5r | 11.240 | 11.644 | 0.405 | |
| 30 Mi-C5r | 11.644 | 12.059 | 0.414 | |
| 31 Mi-C5An | 12.059 | 12.461 | 0.403 | |
| 32 Mi-C5Ar | 12.461 | 12.870 | 0.409 | |
| 33 Mi-C5Ar | 12.870 | 13.273 | 0.403 | |
| 34 Mi-C5AAr | 13.273 | 13.678 | 0.405 | |
| 35 Mi-C5ABr | 13.678 | 14.078 | 0.400 | |
| 36 Mi-C5ACn | 14.078 | 14.479 | 0.401 | |
| 37 Mi-C5ADn | 14.479 | 14.895 | 0.416 | |
| 38 Mi-C5Bn | 14.895 | 15.297 | 0.403 | |
| 39 Mi-C5Br | 15.297 | 15.701 | 0.403 | |
| 40 Mi-C5Br | 15.701 | 16.099 | 0.399 | |
| 41 Mi-C5Cn | 16.099 | 16.493 | 0.393 | |
| 42 Mi-C5Cn | 16.493 | 16.904 | 0.411 | |
| 43 Mi-C5Cr | 16.904 | 17.308 | 0.404 | |
| 44 Mi-C5Dn | 17.308 | 17.718 | 0.410 | |
| 45 Mi-C5Dr | 17.718 | 18.134 | 0.416 | |
| 46 Mi-C5En | 18.134 | 18.528 | 0.393 | |
| 47 Mi-C5Er | 18.528 | 18.930 | 0.402 | |
| 48 Mi-C6n | 18.930 | 19.328 | 0.399 | |
| 49 Mi-C6n | 19.328 | 19.736 | 0.408 | |
| 50 Mi-C6r | 19.736 | 20.150 | 0.414 | |
| 51 Mi-C6An | 20.150 | 20.559 | 0.409 | |
| 52 Mi-C6An | 20.559 | 20.965 | 0.406 | |
| 53 Mi-C6Ar | 20.965 | 21.366 | 0.401 | |
| 54 Mi-C6AAr | 21.366 | 21.778 | 0.412 | |
| 55 Mi-C6Bn | 21.778 | 22.183 | 0.405 | |
| 56 Mi-C6Bn | 22.183 | 22.595 | 0.412 | |
| 57 Mi-C6Cn | 22.595 | 22.996 | 0.401 | |
| 58 Ol-C6Cn | 22.996 | 23.401 | 0.406 | |
| 59 Ol-C6Cn | 23.401 | 23.809 | 0.407 | |
| 60 Ol-C6Cr | 23.809 | 24.210 | 0.401 | |
| 61 Ol-C7n | 24.210 | 24.623 | 0.414 | |
| 62 Ol-C7r | 24.623 | 25.031 | 0.408 | |
| 63 Ol-C7Ar | 25.031 | 25.435 | 0.404 | |
| 64 Ol-C8n | 25.435 | 25.824 | 0.389 | |
| 65 Ol-C8n | 25.824 | 26.221 | 0.397 | |
| 66 Ol-C8r | 26.221 | 26.633 | 0.412 | |
| 67 Ol-C9n | 26.633 | 27.041 | 0.408 | |
| 68 Ol-C9n | 27.041 | 27.452 | 0.411 | |
| 69 Ol-C9r | 27.452 | 27.856 | 0.405 | |
| 70 Ol-C10n | 27.856 | 28.257 | 0.400 | |
| 71 Ol-C10r | 28.257 | 28.657 | 0.400 | |
| 72 Ol-C10r | 28.657 | 29.048 | 0.392 | |
| 73 Ol-C10r | 29.048 | 29.454 | 0.405 | |

Table 2 (continued)

| ~405 kyr cycle Cycle code/Chron | Younger end of cycle (Ma) | Older end of cycle (Ma) | Duration | Notes |
|------------------------------------|------------------------------|----------------------------|----------|--------------|
| 74 Ol-C11n | 29.454 | 29.861 | 0.407 | |
| 75 Ol-C11n | 29.861 | 30.274 | 0.413 | |
| 76 Ol-C11r | 30.274 | 30.681 | 0.407 | |
| 77 Ol-C12n | 30.681 | 31.081 | 0.400 | |
| 78 Ol-C12r | 31.081 | 31.488 | 0.407 | |
| 79 Ol-C12r | 31.488 | 31.892 | 0.404 | |
| 80 Ol-C12r | 31.892 | 32.303 | 0.411 | |
| 81 Ol-C12r | 32.303 | 32.708 | 0.404 | |
| 82 Ol-C12r | 32.708 | 33.120 | 0.413 | |
| 83 Ol-C12r | 33.120 | 33.523 | 0.403 | |
| 84 Ol-C13n | 33.523 | 33.921 | 0.398 | |
| 85 Eo-C13r | 33.921 | 34.322 | 0.401 | |
| 86 Eo-C13r | 34.322 | 34.734 | 0.412 | |
| 87 Eo-C13r | 34.734 | 35.151 | 0.417 | |
| 88 Eo-C15n | 35.151 | 35.548 | 0.398 | |
| 89 Eo-C16n | 35.548 | 35.956 | 0.407 | |
| 90 Eo-C16n | 35.956 | 36.351 | 0.395 | |
| 91 Eo-C16n | 36.351 | 36.751 | 0.401 | |
| 92 Eo-C17n | 36.751 | 37.158 | 0.406 | |
| 93 Eo-C17n | 37.158 | 37.557 | 0.399 | |
| 94 Eo-C17n | 37.557 | 37.971 | 0.414 | |
| 95 Eo-C17n | 37.971 | 38.369 | 0.398 | |
| 96 Eo-C17r | 38.369 | 38.768 | 0.399 | |
| 97 Eo-C18n | 38.768 | 39.179 | 0.410 | |
| 98 Eo-C18n | 39.179 | 39.576 | 0.397 | |
| 99 Eo-C18n | 39.576 | 39.979 | 0.403 | |
| 100 Eo-C18r | 39.979 | 40.374 | 0.395 | |
| 101 Eo-C18r | 40.374 | 40.781 | 0.407 | |
| 102 Eo-C18r | 40.781 | 41.193 | 0.412 | |
| 103 Eo-C18r | 41.193 | 41.601 | 0.408 | |
| 104 | 41.601 | 42.008 | 0.407 | |
| 105 | 42.008 | 42.407 | 0.400 | ^b |
| 106 | 42.407 | 42.814 | 0.407 | |
| 107 | 42.814 | 43.213 | 0.399 | |
| 108 | 43.213 | 43.625 | 0.413 | |
| 109 | 43.625 | 44.034 | 0.409 | |
| 110 | 44.034 | 44.442 | 0.408 | |
| 111 | 44.442 | 44.841 | 0.399 | |
| 112 | 44.841 | 45.238 | 0.396 | |
| 113 | 45.238 | 45.648 | 0.410 | |
| 114 | 45.648 | 46.063 | 0.415 | |
| 115 | 46.063 | 46.477 | 0.415 | |
| 116 | 46.477 | 46.875 | 0.398 | |
| 117 | 46.875 | 47.278 | 0.403 | |
| 118 | 47.278 | 47.675 | 0.397 | |
| 119 | 47.675 | 48.077 | 0.402 | |
| 120 | 48.077 | 48.485 | 0.409 | |
| 121 | 48.485 | 48.886 | 0.401 | |
| 122 | 48.886 | 49.297 | 0.411 | |
| 123 | 49.297 | 49.695 | 0.398 | |
| 124 | 49.695 | 50.100 | 0.405 | |
| 125 | 50.100 | 50.508 | 0.408 | |
| 126 | 50.508 | 50.899 | 0.391 | |
| 127 | 50.899 | 51.303 | 0.404 | |
| 128 | 51.303 | 51.704 | 0.401 | |
| 129 | 51.704 | 52.113 | 0.409 | |
| 130 | 52.113 | 52.532 | 0.419 | |
| 131 | 52.532 | 52.930 | 0.398 | |
| 132 | 52.930 | 53.331 | 0.401 | |
| 133 | 53.331 | 53.724 | 0.394 | |
| 134 | 53.724 | 54.129 | 0.405 | |
| 135 | 54.129 | 54.541 | 0.412 | |
| 136 | 54.541 | 54.953 | 0.412 | |
| 137 | 54.953 | 55.364 | 0.412 | |
| 138 | 55.364 | 55.763 | 0.399 | |
| 139 | 55.763 | 56.166 | 0.402 | |
| 140 | 56.166 | 56.568 | 0.402 | |
| 141 | 56.568 | 56.982 | 0.414 | |
| 142 | 56.982 | 57.388 | 0.406 | |
| 143 | 57.388 | 57.792 | 0.404 | |
| 144 | 57.792 | 58.202 | 0.410 | |
| 145 | 58.202 | 58.608 | 0.407 | |
| 146 | 58.608 | 59.020 | 0.412 | |
| 147 | 59.020 | 59.419 | 0.399 | |
| 148 | 59.419 | 59.824 | 0.404 | |
| 149 | 59.824 | 60.231 | 0.408 | |

Table 2 (continued)

| ~405 kyr cycle Cycle code/Chron | Younger end of cycle (Ma) | Older end of cycle (Ma) | Duration | Notes |
|------------------------------------|------------------------------|----------------------------|----------|-------|
| 150 | 60.231 | 60.639 | 0.407 | |
| 151 | 60.639 | 61.055 | 0.417 | |
| 152 | 61.055 | 61.462 | 0.407 | |
| 153 | 61.462 | 61.868 | 0.406 | |
| 154 | 61.868 | 62.261 | 0.392 | |
| 155 | 62.261 | 62.664 | 0.404 | |
| 156 | 62.664 | 63.072 | 0.407 | |
| 157 | 63.072 | 63.482 | 0.410 | |
| 158 | 63.482 | 63.896 | 0.413 | |
| 159 | 63.896 | 64.291 | 0.395 | |
| 160 | 64.291 | 64.693 | 0.401 | |
| 161 | 64.693 | 65.089 | 0.396 | |
| 162 | 65.089 | 65.494 | 0.405 | |
| 163 | 65.494 | 65.910 | 0.416 | |
| 164 | 65.910 | 66.313 | 0.403 | |
| 165 | 66.313 | 66.724 | 0.411 | |
| 166 | 66.724 | 67.121 | 0.397 | |
| 167 | 67.121 | 67.520 | 0.398 | |

^a This cycle ends in the future.

^b Cycles below Chron C19n are not named pending development on the Paleogene astronomical time scale.

Cenozoic tropical biostratigraphy and further updates and refinements are likely to follow with future IODP Expeditions. The enhanced recovery, multiple hole advanced piston coring of successions with high sedimentation rates and paleomagnetic control (e.g., Lyle et al., 2009; Pälike et al., 2009) will enable high resolution biostratigraphic studies and extension of the ATS beyond 40 Ma. We use the PT, PL, and M zonal scheme of BKSA95 and the O, E and P zonal scheme of Berggren and Pearson (2005). The 21 zones of the Neogene Period (BKSA95) and 29 zones of the Paleogene Period (Berggren and Pearson, 2005) are retained and amended to reflect updated chronostratigraphic calibration to the GPTS.

As with previous compilations (e.g., Berggren et al., 1985, 1995b), our magnetobiochronology is founded on first order calibrations between biostratigraphic events and the magnetostratigraphy in ocean drilling cores, as well as outcrop sections. These are supplemented with orbital compilations in instances where a magnetostratigraphy was absent (e.g., Ceara Rise). Here the current status of Cenozoic planktonic foraminiferal biostratigraphy is reviewed, refined and recalibrated, with modifications to the zonal criteria where necessary. All calibrated bioevents are listed in Tables 1, 3 and 4, primary events that define zonal boundaries are shown in bold and on Figs. 2–4.

Our revised zonation is primarily for application in open ocean settings of the Pacific, Indian and Atlantic oceans, and therefore we have not incorporated biostratigraphic information that is regionally restricted, such as to the Mediterranean, the high latitudes and other localized environments and when studies subsequent to BKSA95 have indicated them to be diachronous, unreliable or require further evaluation. Secondary bioevents that have not been used include: The last appearance datum (LAD) *Globoquadrina pseudofoliata* (Chaproniere et al., 1994), first appearance datum (FAD) *Globorotalia hirsuta* (Pujol and Duprat, 1983), FAD *Globoconella inflata* (Berggren et al., 1995a), FAD *Pulleniatina finalis* (Chaproniere et al., 1994), LAD *Neogloboquadrina atlantica* (Weaver and Clement, 1987), LAD *Globoconella puncticulata* (Atlantic) (Zijderveld et al., 1991), LAD *Globoquadrina baroemoenensis* (Curry et al., 1995), FAD *Globorotalia sphericomiozea* and *Globorotalia pliozea* (Srinivasan and Sinha, 1992), LAD *Globorotalia zealandica* (Li et al., 1992), FAD *Globigerinoides altiapertura* (Steininger et al., 1997), LAD *Globigerina labiacrassata* (BKSA95), FAD *Globigerinita boweni* (Li et al., 1992), LAD *Clavigerinella eocanica* (Pearson and Chaisson, 1997), LAD *Subbotina linaperta* (Wade, 2004), and LAD *Planorotalites capdevilensis* (Wade, 2004).

2. Neogene Period

The genus *Globorotalia* has been widely utilized in morphometric and biostratigraphic studies. Several subgenera exist in the literature

for keeled forms, that have been somewhat inconsistently applied by various workers. For example Cushman and Bermúdez (1949) named the subgenus *Globorotalia* (*Truncorotalia*) with *G. truncatulinoidea* as the type species. Bandy (1972) named several other subgenera (*Menardella*, *Fohsella*, *Hirsutella*) though these were not formally described and no type species was designated. Kennett and Srinivasan (1983) used these as subgenera and designated type species. As in the Paleocene (Olsson et al., 1999) and Eocene (Pearson et al., 2006) taxonomic atlases we have chosen not to use subgenera and refer to most of the above forms as *Globorotalia*, which are all part of a single clade descended from Miocene *G. praescitula* (Kennett and Srinivasan, 1983). The exception to this is the distinct taxonomic lineage of *Fohsella* which we use at the generic level because it is very likely polyphyletic with respect to the true *Globorotalia* and has a subtly different wall texture.

For the Neogene Period, the incorporation of revised bioevents from Ceara Rise (adopted by Lourens et al., 2004) has led to some major modifications to the planktonic foraminiferal stratigraphy and zonal scheme. Lourens et al. (2004) did not discuss the implications of their revised chronology to planktonic foraminiferal biostratigraphy. We have re-evaluated and assessed these events and compared them to previous magnetostratigraphic calibrations. In the majority of events discussed below the concept of the zone has remained the same, with the exception of Zones M9, M8, M7, M3, and M2.

Since the initiation of this work, The International Commission on Stratigraphy have proposed to lower the base of the Quaternary Period and the Pleistocene epoch to 2.58 Ma, at the same time capping the Neogene Period at that age (Gibbard et al., 2010). As this is not yet formally ratified in publication and has been met with widespread opposition (e.g., Van Couvering et al., 2009), we have used the former definition of the “real” Neogene (McGowran et al., 2009) as consisting of the Miocene, Pliocene, Pleistocene and Holocene/Recent, while awaiting a resolution of the controversy.

2.1. Amendment to the Pleistocene PT zones

Zone PT1. *Globigerinoides ruber* Partial-range Zone (herein renamed = Zone PT1 [*Globigerinoides fistulosus*–*Globorotalia truncatulinoidea* Interval Zone] of BKSA95).

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the HO of *Globigerinoides fistulosus* and the Recent.

Magnetostratigraphic calibration: Chron C2n–Chron C1n (present day).

Astronomical cycle calibration: 5_{Pt-C1r} – present day.

Estimated age: 1.88–0 Ma (as per Cande and Kent, 1995; Lourens et al., 2004); late Pliocene–Recent.

Remarks: The definition of the zone remains the same as in BKSA95, however, it has been renamed here according to the convention in Fig. 1 and of Berggren and Pearson (2005). Lourens et al. (2004) provided two astronomical ages for the LAD of *Globigerinoides fistulosus*, 1.77 Ma from Site 677 (Shipboard Scientific Party, 1988; Shackleton et al., 1990) and 1.88 Ma (Chaisson and Pearson, 1997). The calibration from Site 677 is poorly constrained between relatively widely spaced core catcher samples and requires further investigation, thus we use the LAD of *Globigerinoides fistulosus* from Ceara Rise of 1.88 Ma.

Subzone PT1b. *Globorotalia truncatulinoidea* Partial-range Subzone

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the HO of *Globorotalia tosaensis* and the Recent.

Magnetostratigraphic calibration: Chron C1n.

Astronomical cycle calibration: 2_{Pt-C1n} – present day.

Estimated age: 0.61–0 Ma (as per Cande and Kent, 1995; Lourens et al., 2004); late Pleistocene (including Holocene).

a

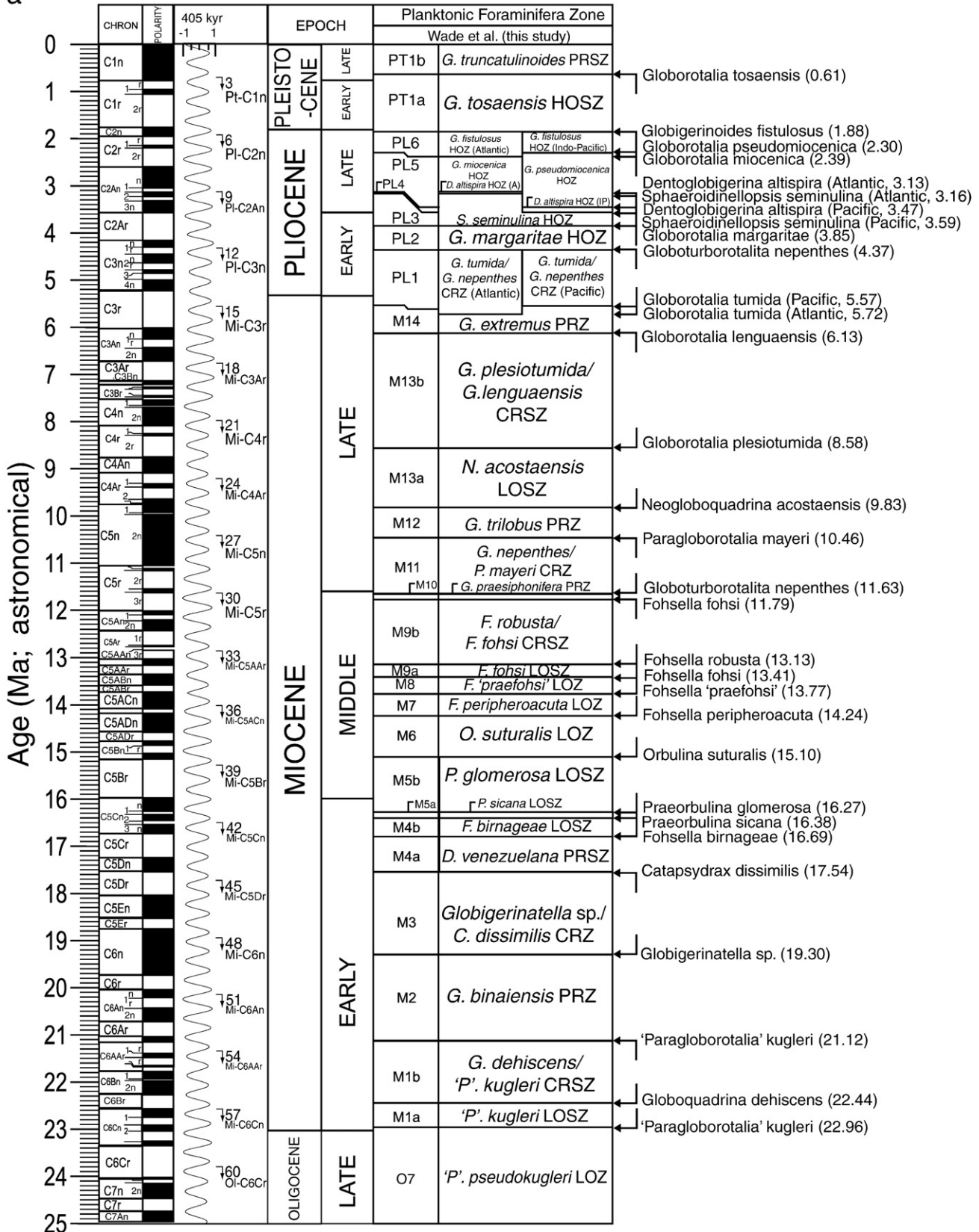


Fig. 3. Primary planktonic foraminiferal bioevents for the Neogene and late Paleogene against the astronomical time scale of Lourens et al. (2004, until base of Chron C6Cn.2n) and Pälike et al. (2006, from top Chron C6Cn.3n until base C19n). (a) 0–25 Ma and (b) 20–41.5 Ma. A = Atlantic; IP = Indo-Pacific. The ~405 kyr eccentricity cycle numbers are counted from the present.

b

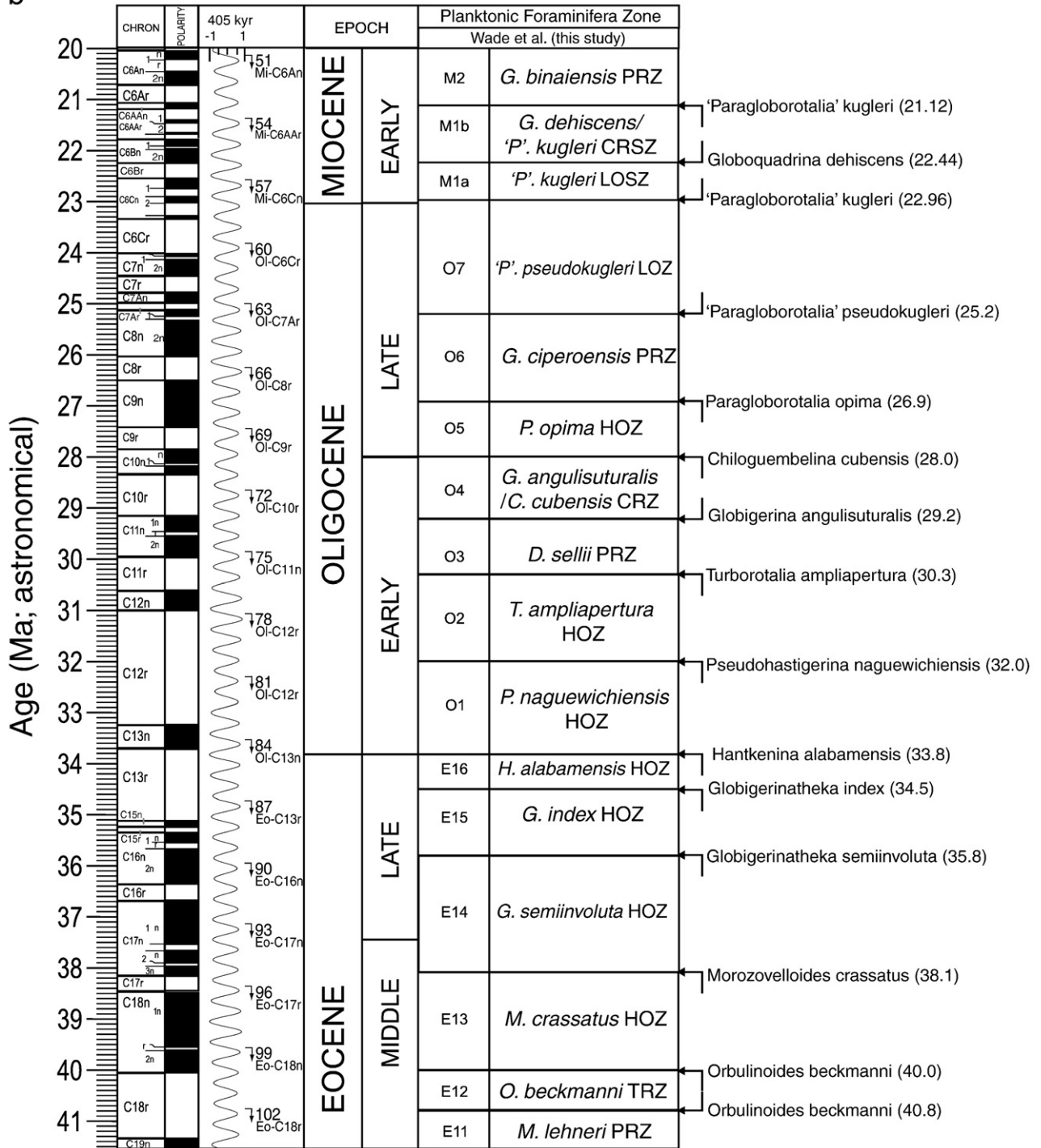


Fig. 3 (continued).

Remarks: The nomenclature and definition of this subzone remain the same as in Berggren et al. (1995a) and BKSA95.

Subzone PT1a. Globorotalia tosaensis Highest-occurrence Subzone (herein renamed = Subzone PT1a [Globigerinoides fistulosus–Globorotalia tosaensis Interval Sub-Zone] of Berggren et al., 1995a and BKSA95).

Definition: Biostratigraphic interval between the HO of Globigerinoides fistulosus and the HO of the nominate taxon, Globorotalia tosaensis.

Magnetostratigraphic calibration: Chron C2n–Chron C1n.

Astronomical cycle calibration: 5_{PT-C1r}–2_{PT-C1n}.

Estimated age: 1.88–0.61 Ma (as per Cande and Kent, 1995; Lourens et al., 2004); late Pliocene to late Pleistocene.

Remarks: This subzone is the same as Subzone PT1a of Berggren et al. (1995a) and renamed according to the convention of Berggren and Pearson (2005). See discussion for Zone PT1 regarding the LAD of Globigerinoides fistulosus.

2.2. Amendment to the Pliocene PL zones

Zone PL6 (Indo-Pacific). Globigerinoides fistulosus Highest-occurrence Zone (Indo-Pacific) (herein renamed = Zone PL6 [Globorotalia pseudomiocenic–Globigerinoides fistulosus Interval Zone] of Berggren et al., 1995a and BKSA95).

Table 3
Planktonic foraminiferal bioevents for the Neogene Period calibrated to the geomagnetic polarity time scale and astronomical time scale of **Lourens et al. (2004)**. Marker taxa are highlighted in bold.

| Zone (BKSA95 and BP05) (base) | Zone (this study) (base) | Datum | Notes | Astronomical age ^a | Reference | Published age (Ma) | Reference | Berggren et al. (1995a,b) |
|--------------------------------------|---------------------------|---|-----------------------|-------------------------------|-----------------------------|--------------------|-----------------------------|---------------------------|
| | | T Globorotalia flexuosa | | 0.07 | This study | 0.07 | Berggren et al., 1995a | 0.07 |
| | | T <i>Globigerinoides ruber</i> (pink) | (Indo-Pacific only) | 0.12 | This study | 0.12 | Thompson et al., 1979 | – |
| | | B Globigerinella calida | | 0.22 | This study | 0.22 | Chaproniere et al., 1994 | 0.22 |
| | | B Globorotalia flexuosa | | 0.40 | This study | 0.40 | Berggren et al., 1995a | 0.40 |
| | | B Globorotalia hirsuta | | 0.45 | This study | 0.45 | Pujol and Duprat, 1983 | 0.45 |
| PT1b | PT1b | T Globorotalia tosaensis | | 0.61 | Lourens et al., 2004 | 0.61 | Mix et al., 1995 | 0.65 |
| | | B Globorotalia hessi | | 0.75 | This study | 0.75 | Chaproniere et al., 1994 | 0.75 |
| | | X random to dextral in Pulleniatina | (Pacific) | 0.80 | This study | 0.80 | Pearson, 1995 | – |
| | | B Globorotalia excelsa | | 1.00 | This study | 1.00 | Berggren et al., 1995a | 1.00 |
| | | T Globoturborotalita obliquus | | 1.30 | Lourens et al., 2004 | 1.30 | Chaisson and Pearson, 1997 | – |
| | | T Globoturborotalita apertura | | 1.64 | Lourens et al., 2004 | 1.64 | Chaisson and Pearson, 1997 | – |
| <i>Pliocene/Pleistocene boundary</i> | | | | | | 1.81 | Aguirre and Pasini, 1985 | – |
| PT1a | PT1a | T Globigerinoides fistulosus | ^h | 1.88 | Lourens et al., 2004 | 1.88 | Chaisson and Pearson, 1997 | 1.77 |
| | | B Globorotalia truncatulinoides | ^f | 1.93 | Lourens et al., 2004 | 1.92 | Chaisson and Pearson, 1997 | 2.00 |
| | | T Globigerinoides extremus | | 1.98 | Lourens et al., 2004 | 1.98 | Chaisson and Pearson, 1997 | 1.77 |
| | | B Pulleniatina finalis | | 2.04 | Lourens et al., 2004 | 2.04 | Chaisson and Pearson, 1997 | – |
| | | T Globorotalia exilis | (Atlantic) | 2.09 | Lourens et al., 2004 | 2.09 | Chaisson and Pearson, 1997 | 2.15 |
| | | Reappearance of Pulleniatina | (Atlantic) | 2.26 | Lourens et al., 2004 | 2.26 | Chaisson and Pearson, 1997 | 2.30 |
| | | T Globoturborotalita woodi | | 2.30 | Lourens et al., 2004 | 2.33 | Chaisson and Pearson, 1997 | – |
| | | T Globorotalia pertenuis | | 2.30 | Lourens et al., 2004 | 2.33 | Chaisson and Pearson, 1997 | – |
| PL6 | PL6 (Indo-Pacific) | T Globorotalia pseudomiocenica | (Indo-Pacific) | 2.30 | This study | 2.30 | Berggren et al., 1995a | 2.30 |
| PL6 | PL6 (Atlantic) | T Globorotalia miocenica | (Atlantic) | 2.39 | Lourens et al., 2004 | 2.38 | Chaisson and Pearson, 1997 | 2.30 |
| | | T Globorotalia limbata | | 2.39 | Lourens et al., 2004 | 2.38 | Chaisson and Pearson, 1997 | – |
| | | T Globorotalia pertenuis | | 2.60 | This study | 2.60 | Berggren et al., 1995a | 2.60 |
| | | T Globoturborotalita decoraperta | | 2.75 | Lourens et al., 2004 | 2.75 | Chaisson and Pearson, 1997 | – |
| | | T Globorotalia multicamerata | | 2.98 | Lourens et al., 2004 | 3.10 | Chaisson and Pearson, 1997 | 3.09 |
| PL5 | PL5 (Atlantic) | T Dentoglobigerina altispira | (Atlantic) | 3.13 | Lourens et al., 2004 | 3.11 | Chaisson and Pearson, 1997 | 3.09 |
| PL4 | PL4 | T Sphaeroidinellopsis seminulina | (Atlantic) | 3.16 | Lourens et al., 2004 | 3.14 | Chaisson and Pearson, 1997 | 3.12 |
| | | B Globigerinoides fistulosus | | 3.33 | This study | 3.33 | Berggren et al., 1995a | 3.33 |
| | | B Globorotalia tosaensis | | 3.35 | This study | 3.35 | Berggren et al., 1995a | 3.35 |
| | | T Pulleniatina disappearance | (Atlantic) | 3.41 | Lourens et al., 2004 | 3.41 | Chaisson and Pearson, 1997 | – |
| PL5 (Ind) | PL5 (Indo-Pacific) | T Dentoglobigerina altispira | (Pacific) | 3.47 | Lourens et al., 2004 | 3.05 | Shackleton et al., 1995 | – |
| | | B Globorotalia pertenuis | | 3.52 | Lourens et al., 2004 | 3.52 | Chaisson and Pearson, 1997 | 3.45 |
| PL4 | PL4 | T Sphaeroidinellopsis seminulina | (Pacific) | 3.59 | Lourens et al., 2004 | 3.20 | Shackleton et al., 1995 | – |
| | | T Pulleniatina primalis | | 3.66 | This study | 3.65 | Berggren et al., 1995a | 3.65 |
| | | B Globorotalia miocenica | (Atlantic) | 3.77 | Lourens et al., 2004 | 3.77 | Chaisson and Pearson, 1997 | 3.55 |
| | | T Globorotalia plesiotumida | | 3.77 | Lourens et al., 2004 | 3.77 | Chaisson and Pearson, 1997 | – |
| PL3 | PL3 | T Globorotalia margaritae | | 3.85 | Lourens et al., 2004 | 3.85 | Chaisson and Pearson, 1997 | 3.58 |
| | | X Pulleniatina sinis.-dext. | | 4.08 | Lourens et al., 2004 | 4.08 | Chaisson and Pearson, 1997 | 3.95 |
| | | T Pulleniatina spectabilis | (Pacific) | 4.21 | This study | 4.20 | Berggren et al., 1995a | 4.20 |
| | | B Globorotalia crassaformis | sensu lato | 4.31 | Lourens et al., 2004 | 4.31 | Chaisson and Pearson, 1997 | 4.50 |
| PL2 | PL2 | T Globoturborotalita nepenthes | | 4.37 | Lourens et al., 2004 | 4.39 | Chaisson and Pearson, 1997 | 4.20 |
| | | B Globorotalia exilis | | 4.45 | Lourens et al., 2004 | 4.45 | Chaisson and Pearson, 1997 | – |
| | | T Sphaeroidinellopsis kochi | | 4.53 | Lourens et al., 2004 | 4.53 | Chaisson and Pearson, 1997 | – |
| PL1b | | T Globorotalia cibaoensis | | 4.61 | This study | 4.60 | Berggren et al., 1995b | 4.60 |
| <i>Miocene/Pliocene boundary</i> | | | | | | 5.33 | Van Couvering et al., 2000 | – |
| | | B Sphaeroidinella dehiscens | sensu lato | 5.53 | Lourens et al., 2004 | 5.54 | Chaisson and Pearson, 1997 | 5.20 |
| PL1a | PL1 | B Globorotalia tumida | (Pacific) | 5.57 | Lourens et al., 2004 | 5.59 | Shackleton et al., 1995 | 5.60 |
| PL1a | PL1 | B Globorotalia tumida | (Atlantic) | 5.72 | Lourens et al., 2004 | 5.82 | Chaisson and Pearson, 1997 | 5.60 |
| | | B Turborotalita humilis | | 5.81 | Lourens et al., 2004 | 5.84 | Chaisson and Pearson, 1997 | – |
| | | T Globoquadrina dehiscens | | 5.92 | This study | 5.80 | Berggren et al., 1995a | 5.80 |
| | | B Globorotalia margaritae | | 6.08 | Lourens et al., 2004 | 6.09 | Chaisson and Pearson, 1997 | 6.40 |
| M14 | M14 | T Globorotalia lenguaensis | | 6.13 | This study | 6.00 | Berggren et al. 1995 | 6.00 |
| | | B Globigerinoides conglobatus | | 6.20 | Lourens et al., 2004 | 6.20 | Chaisson and Pearson, 1997 | – |
| | | X Neogloboquadrina acostaensis | Trans. sinis.-dext. | 6.34 | This study | 6.20 | Berggren et al., 1995b | 6.20 |
| | | B Pulleniatina primalis | | 6.60 | This study | 6.40 | Berggren et al., 1995b | 6.40 |
| | | X Neogloboquadrina acostaensis | Trans. dext.-sinis. | 6.77 | This study | 6.60 | Berggren et al., 1995b | 6.60 |
| | | X Neogloboquadrina atlantica | Trans. dext.-sinis. | 6.99 | This study | 6.80 | Berggren et al., 1995b | 6.80 |
| | | B Neogloboquadrina humerosa | | 8.56 | This study | 8.50 | Berggren et al., 1995b | 8.50 |
| M13b | M13b | B Globorotalia plesiotumida | ^c | 8.58 | Lourens et al., 2004 | 8.58 | Chaisson and Pearson, 1997 | – |
| | | B Globigerinoides extremus | ^b | 8.93 | Lourens et al., 2004 | 8.94 | Turco et al., 2002 | – |
| | | B Globorotalia cibaoensis | | 9.44 | Lourens et al., 2004 | 9.44 | Chaisson and Pearson, 1997 | – |
| | | B Globorotalia juanai | | 9.69 | Lourens et al., 2004 | 9.76 | Chaisson and Pearson, 1997 | – |
| M13a | M13a | B Neogloboquadrina acostaensis | | 9.83 | Lourens et al., 2004 | 9.82 | Chaisson and Pearson, 1997 | 10.90 |
| M12 | M12 | T Paragloborotalia mayeri | | 10.46 | Lourens et al., 2004 | 10.49 | Chaisson and Pearson, 1997 | 11.40 |
| | | B Globorotalia limbata | | 10.64 | Lourens et al., 2004 | 10.57 | Chaisson and Pearson, 1997 | – |

Table 3 (continued)

Planktonic foraminiferal bioevents for the Neogene Period calibrated to the geomagnetic polarity time scale and astronomical time scale of Lourens et al. (2004). Marker taxa are highlighted in bold.

| Zone (BKSA95 and BP05) (base) | Zone (this study) (base) | Datum | Notes | Astronomical age ^a | Reference | Published age(Ma) | Reference | Berggren et al. (1995a,b) |
|-------------------------------|--------------------------|---------------------------------------|---------------|-------------------------------|----------------------|-------------------|----------------------------|---------------------------|
| | | T Cassigerinella chipolensis | ^b | 10.89 | Lourens et al., 2004 | 10.81 | Turco et al., 2002 | – |
| | | B Globoturborotalita apertura | | 11.18 | Lourens et al., 2004 | 11.19 | Chaisson and Pearson, 1997 | – |
| | | B Globoturborotalita decoraperta | | 11.49 | Lourens et al., 2004 | 11.46 | Chaisson and Pearson, 1997 | – |
| | | T Globigerinoides subquadratus | ^b | 11.54 | Lourens et al., 2004 | 11.55 | Turco et al., 2002 | – |
| M11 | M11 | B Globoturborotalita nepenthes | ^b | 11.63 | Lourens et al., 2004 | 11.64 | Turco et al., 2002 | 11.80 |
| M10 | M10 | T Fohsella fohsi | | 11.79 | Lourens et al., 2004 | 11.68 | Chaisson and Pearson, 1997 | 11.90 |
| | | T Globorotalia praescitula | | 13.73 | Lourens et al., 2004 | 11.90 | Berggren et al. 1995 | 11.90 |
| | | B Globorotalia languensis | ^b | 12.84 | Lourens et al., 2004 | 12.39 | Turco et al., 2002 | – |
| | | B Sphaeroidinellopsis subdehiscens | ^b | 13.02 | Lourens et al., 2004 | 13.03 | Turco et al., 2002 | – |
| M9b | M9b | B Fohsella robusta | | 13.13 | Lourens et al., 2004 | 13.18 | Chaisson and Pearson, 1997 | 12.30 |
| M9a | | B Fohsella lobata | | – | – | 12.50 | Berggren et al., 1995b | 12.50 |
| | | T Cassigerinella martinezpicoi | ^b | 13.27 | Lourens et al., 2004 | 13.28 | Turco et al., 2002 | – |
| M8 | M9a | B Fohsella fohsi | | 13.41 | Lourens et al., 2004 | 13.42 | Chaisson and Pearson, 1997 | 12.70 |
| | M8 | B Fohsella "praefohsi" | | 13.77 | Lourens et al., 2004 | 14.00 | Pearson and Chaisson, 1997 | – |
| | | T Fohsella peripheroronda | ^b | 13.80 | Lourens et al., 2004 | 13.87 | Turco et al., 2002 | 14.60 |
| | | T Clavatorella bermudezi | | 13.82 | Lourens et al., 2004 | 14.20 | Pearson and Chaisson, 1997 | – |
| | | T Globorotalia archeomenardii | ^b | 13.87 | Lourens et al., 2004 | 13.87 | Turco et al., 2002 | – |
| M7 | M7 | B Fohsella peripheroacuta | ^b | 14.24 | Lourens et al., 2004 | 14.02 | Turco et al., 2002 | 14.80 |
| | | B Globorotalia praemenardii | | 14.38 | Lourens et al., 2004 | 14.90 | Pearson and Chaisson, 1997 | – |
| | | T Praeorbulina sicana | | 14.53 | Lourens et al., 2004 | 14.40 | Shackleton et al., 1999 | 14.80 |
| | | T Globigerinatella insueta | | 14.66 | Lourens et al., 2004 | 15.00 | Pearson and Chaisson, 1997 | – |
| M6 | M6 | B Orbulina suturalis | | 15.10 | This study | 15.10 | Berggren et al., 1995b | 15.10 |
| | | B Clavatorella bermudezi | ^e | 15.73 | This study | 15.80 | Pearson and Chaisson, 1997 | – |
| | | B Praeorbulina circularis | ^d | 15.96 | This study | 16.00 | Berggren et al., 1995b | 16.00 |
| | | B Globorotalia archeomenardii | | 16.26 | Lourens et al., 2004 | 16.20 | Pearson and Chaisson, 1997 | – |
| M5b | M5b | B Praeorbulina glomerosa | sensu stricto | 16.27 | Lourens et al., 2004 | 16.20 | Shackleton et al., 1999 | 16.10 |
| | | B Praeorbulina curva | | 16.28 | This study | 16.30 | Berggren et al., 1995b | 16.30 |
| M5a | M5a | B Praeorbulina sicana | | 16.38 | This study | 16.40 | Berggren et al., 1995b | 16.40 |
| M4b | M4b | B Fohsella birnageae | | 16.69 | This study | 16.70 | Berggren et al., 1995b | 16.70 |
| | | B Globorotalia zealandica | ^g | 17.26 | This study | 17.30 | Berggren et al., 1995b | 16.30 |
| M4a | M4a | T Catapsydrax dissimilis | | 17.54 | Lourens et al., 2004 | 17.50 | Shackleton et al., 1999 | 17.30 |
| M3 | | B Globigerinatella insueta s. str. | | 17.59 | Lourens et al., 2004 | 17.40 | Pearson and Chaisson, 1997 | (18.8) |
| | | B Globorotalia praescitula | | 18.26 | This study | 18.50 | Berggren et al., 1995b | 18.50 |
| | | T Globoquadrina binaiensis | | 19.09 | Lourens et al., 2004 | 19.10 | Pearson and Chaisson, 1997 | – |
| | M3 | B Globigerinatella sp. | | 19.30 | Lourens et al., 2004 | 20.20 | Pearson and Chaisson, 1997 | – |
| | | B Globigerinoides altiapertura | | 20.03 | This study | 20.50 | Berggren et al., 1995b | 20.50 |
| | | T Tenuitella munda | | 20.78 | This study | 21.40 | Berggren et al. 1995 | 21.40 |
| | | T Globigerina angulisuturalis | | 20.94 | This study | 21.60 | Berggren et al., 1995b | 21.60 |
| M2 | M2 | T 'Paragloborotalia' kugleri | | 21.12 | Lourens et al., 2004 | 21.00 | Shackleton et al., 1999 | 21.50 |
| | | T 'Paragloborotalia' pseudokugleri | | 21.31 | Lourens et al., 2004 | 21.10 | Shackleton et al., 1999 | 21.60 |
| M1b | M1b | B Globoquadrina dehiscens | | 22.44 | This study | 23.20 | Berggren et al., 1995b | 23.20 |
| | | T Globigerina ciperoensis | | 22.90 | Lourens et al., 2004 | 22.80 | Shackleton et al., 1999 | – |
| | | B Globigerinoides trilobus | sensu lato | 22.96 | Lourens et al., 2004 | 22.90 | Shackleton et al., 1999 | – |
| M1a | M1a | B 'Paragloborotalia' kugleri | | 22.96 | Lourens et al., 2004 | 22.90 | Shackleton et al., 1999 | 23.80 |
| | | <i>Oligocene/Miocene boundary</i> | | 23.03 | Lourens et al., 2004 | 23.80 | Berggren et al., 1995b | |

Note: X, change in coiling direction.

^a Calibrated to Lourens et al. (2004).

^b Calibration of Turco et al. (2002) on astronomical time scale of Shackleton and Crowhurst (1997).

^c Replaces the and/or non zone of (1) BKSA95.

^d Note mistake in Lourens et al. (2004) table A2.3, where Bottom Praeorbulina circularis should read Top Praeorbulina circularis.

^e Note mistake in Shackleton et al. (1999) where 14.8 Ma should read 15.8 Ma. This mistake is also propagated in Lourens et al. (2004).

^f Traditionally used as base N22, this datum is considered highly diachronous between ocean basins (see Dowsett, 1988).

^g Note mistake in BKSA95 (page 174) where LAD should read FAD.

^h Note mistake in Berggren et al. (1995a, table 6) where 1.6 Ma should read 1.77 Ma.

Definition: Biostratigraphic interval between the HO of *Globorotalia pseudomiocenica* and the HO of the nominate taxon *Globigerinoides fistulosus* in the Indo-Pacific province.

Magnetostratigraphic calibration: Subchron C2r.2r to Chron C2n.

Astronomical cycle calibration: $7_{\text{Pl-C2n}}-5_{\text{Pt-C1r}}$.

Estimated age: 2.30–1.88 Ma (as per Cande and Kent, 1995; Lourens et al., 2004); late Pliocene.

Remarks: This zone is the same as Zone PL6 (Indo-Pacific) of Berggren et al. (1995a) and BKSA95. This zone is specific to the Indo-Pacific realm because *Globorotalia pseudomiocenica* evolved into *G. miocenica* over the interval of Chron C2An.3n to Chron C2An.2n (~3.5–3.2 Ma) in the Atlantic realm (DSDP Site 502, Colombia Basin; Keigwin, 1982), whereas it persisted into younger biostratigraphic level in the Indo-Pacific realm (BKSA95: 166). It

is approximately equivalent in stratigraphic level to Zone PL6 (Atlantic). Renamed according to the convention of Berggren and Pearson (2005).

Zone PL6 (Atlantic). *Globigerinoides fistulosus* Highest-occurrence Zone (Atlantic) (herein renamed = Zone PL6 [*Globorotalia miocenica*-*Globigerinoides fistulosus* Interval Zone] of Berggren et al., 1995a and BKSA95).

Definition: Biostratigraphic interval between the HO of *Globorotalia miocenica* and the HO of the nominate taxon *Globigerinoides fistulosus* in the Atlantic province.

Magnetostratigraphic calibration: Subchron C2r.2r-Subchron C1r.2r.

Astronomical cycle calibration: $7_{\text{Pl-C2r}}-5_{\text{Pt-C1r}}$.

Estimated age: 2.39–1.88 Ma (as per Cande and Kent, 1995; Lourens et al., 2004); late Pliocene.

Table 4
Planktonic foraminiferal bioevents for the Paleogene Period calibrated to the geomagnetic polarity time scale of **Luterbacher et al. (2004)** and astronomical time scale of **Pälike et al. (2006)**. Marker taxa are highlighted in bold.

| Zone (BKSA95 and BP05) (base) | Zone (This study) (base) | Datum | Age (Ma) This study ^a | Astronomical age ^b | Published age (Ma) | Reference | BKSA95 | Berggren and Pearson (2005) |
|----------------------------------|--------------------------|---|----------------------------------|-------------------------------|--------------------|-------------------------------|-------------|-----------------------------|
| | | T Tenuitella gemma | 23.6 | 23.5 | 24.3 | Berggren et al., 1995b | 24.3 | – |
| | | LCO Globigerinoides primordius | 23.6 | 23.5 | 24.3 | Berggren et al., 1995b | 24.3 | – |
| | O7 | B 'Paragloborotalia' pseudokugleri | 25.4 | 25.2 | 25.9 | Berggren et al., 1995b | 25.9 | – |
| | | B Globigerinoides primordius | 26.3 | 26.1 | 26.7 | Berggren et al., 1995b | 26.7 | – |
| O6 | O6 | T Paragloborotalia opima | 27.3 | 26.9 | 27.5 | Wade et al., 2007 | 27.1 | 27.1 |
| O5 | O5 | HCO Chiliguembelina cubensis | 28.3 | 28.0 | 28.4 | Wade et al., 2007 | 28.5 | 28.5 |
| O4 | O4 | B Globigerina angulisurens | 29.5 | 29.2 | 29.4 | Berggren et al., 1995b | 29.4 | 29.4 |
| | | T Subbotina angiporoides | 30.1 | 29.8 | 30.0 | Berggren et al., 1995b | 30.0 | 30.0 |
| O3 | O3 | T Turborotalia ampliapertura | 30.4 | 30.3 | 30.3 | Berggren et al., 1995b | 30.3 | 30.3 |
| | | B Paragloborotalia opima | 30.8 | 30.8 | 30.6 | Berggren et al., 1995b | 30.6 | – |
| O2 | O2 | T Pseudohastigerina nagewichiensis | 32.2 | 32.0 | 32.0 | Berggren et al., 1995b | 32.0 | 32.0 |
| <i>Eocene/Oligocene boundary</i> | | | | | | | | |
| O1 | O1 | T Hantkenina alabamensis | 33.9 | 33.8 | 33.7 | Berggren and Pearson, 2005 | 33.7 | 33.7 |
| | | HCO Pseudohastigerina micra | 33.9 | 33.8 | 33.7 | Wade and Pearson, 2008 | – | – |
| | | T Turborotalia cerroazulensis | 34.0 | 33.9 | 33.8 | Berggren and Pearson, 2005 | 33.8 | 33.8 |
| E16 | E16 | T Globigerinatheka index | 34.5 | 34.5 | 34.3 | Berggren and Pearson, 2005 | 34.3 | 34.3 |
| | | B Turborotalia cunialensis | 35.4 | 35.4 | 35.3 | Berggren and Pearson, 2005 | 35.2 | 35.3 |
| E15 | E15 | T Globigerinatheka semiinvoluta | 35.8 | 35.8 | 35.8 | Berggren and Pearson, 2005 | 35.3 | 35.8 |
| | | B Globigerinatheka semiinvoluta | 37.7 | 38.0 | 38.0 | Wade, 2004 | 38.4 | – |
| E14 | E14 | T Morozovelloides crassatus | 37.7 | 38.1 | 38.0 | Wade, 2004 | 38.1 | 38.0 |
| | | T Acarinina mcgowrani | 37.7 | 38.1 | 38.0 | Wade, 2004 | – | – |
| | | T Turborotalia frontosa | 38.8 | 39.3 | 39.3 | Berggren et al., 1995b | 39.3 | – |
| E13 | E13 | T Orbulinoides beckmanni | 39.4 | 40.0 | 40.0 | Wade, 2004 | 40.1 | 40.0 |
| E12 | E12 | B Orbulinoides beckmanni | 39.8 | 40.8 | 40.5 | Berggren et al., 1995b | 40.5 | 40.5 |
| | | T Acarinina bullbrookii | 39.8 | 40.8 | 40.5 | Berggren et al., 1995b | 40.5 | – |
| E11 | E11 | T Guembilitrioides nuttalli | (41.4) | – | (42.3) | Berggren and Pearson, 2005 | – | (42.3) |
| | | B Turborotalia pomeroli | 41.5 | – | 42.4 | Berggren et al., 1995b | 42.4 | – |
| | | B Globigerinatheka index | 41.9 | – | 42.9 | Berggren et al., 1995b | 42.9 | – |
| | | B Morozovelloides lehneri | 42.5 | – | 43.5 | Berggren et al., 1995b | 43.5 | – |
| E10 | E10 | T Morozovella aragonensis | 42.6 | – | 43.6 | Berggren et al., 1995b | 43.6 | 43.6 |
| E9 | E9 | B Globigerinatheka kugleri | (43.4) | – | – | Pearson et al., 2004 | 45.8 | 45.8 |
| | | B Hantkenina singanoae | 43.5 | – | 43.5 | Payros et al., 2009 | 49.0 | – |
| E8 | E8 | B Guembilitrioides nuttalli | 45.5 | – | 45.5 | Payros et al., 2009 | – | 49.0 |
| | E7b | B Turborotalia frontosa | 48.6 | – | 48.6 | Payros et al., 2009 | – | – |
| E7 | E7a | B Acarinina cuneicamerata | 50.3 | – | 50.4 | Hancock et al., 2002 | – | 50.4 |
| | | B Planorotalites palmerae | 50.3 | – | 50.4 | Berggren et al., 1995b | 50.4 | – |
| E6 | E6 | T Morozovella subbotinae | 50.8 | – | 50.8 | Berggren and Pearson, 2005 | – | 50.8 |
| E5 | E5 | B Morozovella aragonensis | 52.3 | – | 52.3 | Berggren et al., 1995b | 52.3 | 52.3 |
| | | T Morozovella marginodentata | 52.8 | – | 52.5 | Berggren et al., 1995b | 52.5 | – |
| | | T Morozovella lensiformis | 53.1 | – | 52.7 | Berggren et al., 1995b | 52.7 | – |
| | | T Morozovella aequa | 54.0 | – | 53.6 | Berggren et al., 1995b | 53.6 | – |
| E4 | E4 | B Morozovella formosa | 54.4 | – | 54.0 | Berggren et al., 1995b | 54.0 | 54.0 |
| | | B Morozovella lensiformis | 54.4 | – | 54.0 | Berggren et al., 1995b | 54.0 | – |
| E3 | E3 | T Morozovella velascoensis | 54.9 | – | 54.5 | Berggren and Pearson, 2005 | 54.7 | 54.5 |
| | | T Morozovella acuta | 55.1 | – | 54.7 | Berggren et al., 1995b | 54.7 | – |
| | | B Morozovella gracilis | 55.1 | – | 54.7 | Berggren et al., 1995b | 54.7 | – |
| | | B Igorina broedermanni | 55.1 | – | 54.7 | Berggren et al., 1995b | 54.7 | – |
| | | B Morozovella marginodentata | 55.2 | – | 54.8 | Berggren et al., 1995b | 54.8 | – |
| E2 | E2 | B Pseudohastigerina wilcoxensis | 55.7 | – | 55.4 | Berggren and Pearson, 2005 | – | 55.4 |
| | | B Globanomalina australiformis | 55.8 | – | 55.5 | Berggren et al., 1995b | 55.5 | – |
| E1 | E1 | B Acarinina sibaiaensis | 55.8 | – | 55.5 | Berggren and Pearson, 2005 | – | 55.5 |
| <i>Paleocene/Eocene boundary</i> | | | | | | | | |
| P5 | P5 | T Globanomalina pseudomenardii | 56.7 | – | 55.9 | Berggren et al., 1995b | 55.9 | 55.9 |
| | | B Morozovella subbotinae | 56.7 | – | 55.9 | Berggren et al., 1995b | 55.9 | – |
| | | T Acarinina mckannai | 57.1 | – | 56.3 | Berggren et al., 1995b | 56.3 | – |
| | | T Acarinina acarinata | 57.1 | – | 56.3 | Berggren et al., 1995b | 56.3 | – |
| P4c | P4c | B Acarinina soldadoensis^d | 57.3 | – | 56.5 | Berggren et al., 1995b | 56.5 | 56.5 |
| | | B Acarinina coalingensis | 57.3 | – | 56.5 | Berggren et al., 1995b | 56.5 | – |
| | | B Morozovella aequa | 57.3 | – | 56.5 | Berggren et al., 1995b | 56.5 | – |
| | | T Acarinina subsphaerica | 57.9 | – | 57.1 | Berggren et al., 1995b | 57.1 | 57.1 |
| | | B Acarinina mckannai | 59.9 | – | 59.1 | Berggren et al., 1995b | 59.1 | – |
| P4b | P4b | T Parasubbotina variospira | 60.0 | – | 59.2 | Berggren et al., 1995b | 59.2 | 59.2 |
| | | B Acarinina acarinata | 60.0 | – | 59.2 | Berggren et al., 1995b | 59.2 | – |
| | | B Acarinina subsphaerica | 60.0 | – | 59.2 | Berggren et al., 1995b | 59.2 | – |
| P4a | P4a | B Globanomalina pseudomenardii | 60.2 | – | 59.4 | Berggren et al., 2000 | 59.2 | 59.4 |
| P3b | P3b | B Igorina albeari | 60.8 | – | 60.0 | Berggren et al., 1995b | 60.0 | 60.0 |
| | | B Morozovella velascoensis | 60.8 | – | 60.0 | Berggren et al., 1995b | 60.0 | – |
| | | B Morozovella conicotruncata | 61.7 | – | 60.9 | Berggren et al., 1995b | 60.9 | – |
| P3a | P3a | B Morozovella angulata | 61.7 | – | 61.0 | Berggren et al., 1995b | 61.0 | 61.0 |
| | | B Igorina pusilla | 61.7 | – | 61.0 | Berggren et al., 1995b | 61.0 | – |
| | | B Morozovella praeangulata | 61.9 | – | 61.2 | Berggren et al., 1995b | 61.2 | – |
| | | B Globanomalina imitata | (62.0) | – | (61.3) | Berggren et al., 1995b | (61.3) | – |

Table 4 (continued)

Planktonic foraminiferal bioevents for the Paleogene Period calibrated to the geomagnetic polarity time scale of Luterbacher et al. (2004) and astronomical time scale of Pälike et al. (2006). Marker taxa are highlighted in bold.

| Zone (BKSA95 and BP05) (base) | Zone (This study) (base) | Datum | Age (Ma) This study ^a | Astronomical age ^b | Published age (Ma) | Reference | BKSA95 | Berggren and Pearson (2005) |
|-------------------------------|-----------------------------|--|----------------------------------|-------------------------------|--------------------|----------------------------|--------------|-----------------------------|
| P2 | P2 | B Praemurica uncinata | 62.1 | – | 61.4 | Berggren and Pearson, 2005 | 61.2 | 61.4 |
| P1c | P1c | B Globanomalina compressa^c | 63.5 | – | 62.9 | Berggren and Pearson, 2005 | 63.0 | 62.9 |
| | | B Praemurica inconstans | 63.5 | – | 62.9 | Berggren and Pearson, 2005 | 63.0 | 62.9 |
| | | B Parasubbotina varianta | 63.6 | – | 63.0 | Berggren et al., 1995b | 63.0 | – |
| P1b | P1b | B Subbotina triloculinoides | 64.7 | – | 64.3 | Berggren et al., 1995b | 64.3 | 64.3 |
| P1a | P1a | T Parvularugoglobigerineuagubina | 65.2 | – | 64.8 | Berggren and Pearson, 2005 | 64.7 | 64.8 |
| | | B Parvularugoglobigerinaextensa | 65.4 | – | 64.9 | Olsson et al., 1999 | – | – |
| Pα | Pα | B Parvularugoglobigerinuagubina | 65.46 | – | 64.97 | Berggren et al., 1995b | 64.97 | 64.97 |
| P0 | P0 | T Globotruncana | 65.5 | – | 65.0 | Berggren et al., 1995b | 65.0 | 65.0 |

Notes: HCO Highest common occurrence. LCO Lowest common occurrence. (43.4) Estimated age.

^a Calibrated to Gradstein et al. (2004).

^b Calibrated to Pälike et al. (2006).

^c Replaces the and/or non zone of Berggren and Pearson (2005).

^d Note mistake in Berggren and Pearson (2005).

Remarks: This zone is the same as Zone PL6 (Atlantic) of Berggren et al. (1995a) and BKSA95. This zone is specific to the Atlantic Ocean (see remarks regarding Zone PL6 [Indo-Pacific]). It is approximately equivalent in stratigraphic level to Zone PL6 (Indo-Pacific). Renamed according to the convention of Berggren and Pearson (2005).

Zone PL5 (Indo-Pacific). Globorotalia pseudomiocenica Highest Occurrence Zone (herein renamed = Zone PL5 [Indo-Pacific] [Dentoglobigerina altispira–Globorotalia pseudomiocenica Interval Zone] of Berggren et al., 1995a and BKSA95).

Definition: Biostratigraphic interval between the HO of *D. altispira* and HO of the nominate taxon *Globorotalia pseudomiocenica* in the Indo-Pacific province.

Magnetostratigraphic calibration: Subchron C2An.3n–Subchron C2r.2r.

Astronomical cycle calibration: $9_{PI-C2An}-6_{PI-C2n}$.

Estimated age: 3.46–2.30 Ma (as per Cande and Kent, 1995); 3.47–2.30 Ma (as per Lourens et al., 2004); late Pliocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005).

Zone PL5 (Atlantic). Globorotalia miocenica Highest Occurrence Zone (herein renamed = Zone PL5 [Atlantic] [Dentoglobigerina altispira–Globorotalia miocenica Interval Zone] of Berggren et al., 1995a and BKSA95).

Definition: Biostratigraphic interval between the HO of *Dentoglobigerina altispira* and HO of the nominate taxon *Globorotalia miocenica* in the Atlantic province.

Magnetostratigraphic calibration: Subchron C2An.2n–Subchron C2r.2r.

Astronomical cycle calibration: $8_{PI-C2An}-7_{PI-C2r}$.

Estimated age: 3.13–2.30 Ma (as per Cande and Kent, 1995; Lourens et al., 2004); late Pliocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005).

Zone PL4. Dentoglobigerina altispira Highest Occurrence Zone (herein renamed = Zone PL4 [Sphaeroidinellopsis seminulina–*D. altispira* Interval Zone] of Berggren et al., 1995a and BKSA95).

Definition: Biostratigraphic interval between the HO of *Sphaeroidinellopsis seminulina* and HO of the nominate taxon *Dentoglobigerina altispira*.

Magnetostratigraphic calibration: Subchron C2An.2n (Atlantic); Subchron C2An.3n (Indo-Pacific).

Astronomical cycle calibration: $9_{PI-C2An}-8_{PI-C2An}$ (Atlantic); $10_{PI-C2An}-9_{PI-C2An}$ (Indo-Pacific).

Estimated age: Atlantic Ocean = 3.16–3.13 Ma (as per Cande and Kent, 1995; Lourens et al., 2004); Pacific Ocean = 3.57–3.46 Ma (as per Cande and Kent, 1995); 3.59–3.47 Ma (as per Lourens et al., 2004); late Pliocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005). A short biostratigraphic interval corresponding to

30 kyr between the LAD of *S. seminulina* and *D. altispira* was recognized by BKSA95. Chaisson and Pearson (1997) recorded these events at approximately the same stratigraphic level at Ceara Rise, but their sampling resolution suggested a short duration as in BKSA95, hence we estimate the timing of these events at 3.13 and 3.16 consistent with the stratigraphic record at Ceara Rise (Chaisson and Pearson, 1997) and the observations of BKSA95. The duration of Biochron PL4 is estimated to be 30 kyr in the Atlantic Ocean and 110 kyr in the Pacific Ocean.

Zone PL3. Sphaeroidinellopsis seminulina Highest Occurrence Zone (herein renamed = Zone PL3 [Globoquadrina altispira–Sphaeroidinellopsis subdehiscens Partial-range Zone] of Berggren, 1973, [Globorotalia margaritae–*S. seminulina* Interval Zone] of Berggren et al., 1995a and BKSA95).

Definition: Biostratigraphic interval between the HO of *Globorotalia margaritae* and HO of the nominate taxon *S. seminulina*.

Magnetostratigraphic calibration: Chron C2Ar–Subchron C2An.2n (Atlantic); Chron C2Ar–Subchron C2An.3n (Indo-Pacific).

Astronomical cycle calibration: $10_{PI-C2An}-9_{PI-C2An}$ (Atlantic); $10_{PI-C2An}-9_{PI-C2An}$ (Indo-Pacific).

Estimated age: Atlantic Ocean = 3.84–3.16 Ma (as per Cande and Kent, 1995); 3.85–3.16 Ma (as per Lourens et al., 2004); Pacific Ocean = 3.84–3.57 Ma (as per Cande and Kent, 1995); 3.85–3.59 Ma (as per Lourens et al., 2004); early–late Pliocene.

Remarks: The definition of this zone is the same as that of Berggren (1973). Renamed according to the convention of Berggren and Pearson (2005).

Zone PL2. Globorotalia margaritae Highest Occurrence Zone (herein renamed = Zone PL2 [Globorotalia margaritae–Sphaeroidinellopsis subdehiscens Partial-range Zone] of Berggren, 1973, [Globoturbotalita nepenthes–Globorotalia margaritae Interval Zone] of Berggren et al., 1995a and BKSA95).

Definition: Biostratigraphic interval between the HO of *Globoturbotalita nepenthes* and HO of the nominate taxon *Globorotalia margaritae*.

Magnetostratigraphic calibration: Subchron C3n.1r–Chron C2Ar.

Astronomical cycle calibration: $12_{PI-C3n}-10_{PI-C2An}$.

Estimated age: 4.36–3.84 Ma (as per Cande and Kent, 1995); 4.37–3.85 Ma (as per Lourens et al., 2004); early Pliocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005).

Zone PL1. Globorotalia tumida/Globoturbotalita nepenthes Concurrent-range Zone (herein renamed = Zone PL1 [Globigerina nepenthes - *Globorotalia tumida* Partial-range Zone] of Berggren, 1973, [Globorotalia tumida–Globoturbotalita nepenthes Interval Zone] of Berggren et al., 1995a and BKSA95).

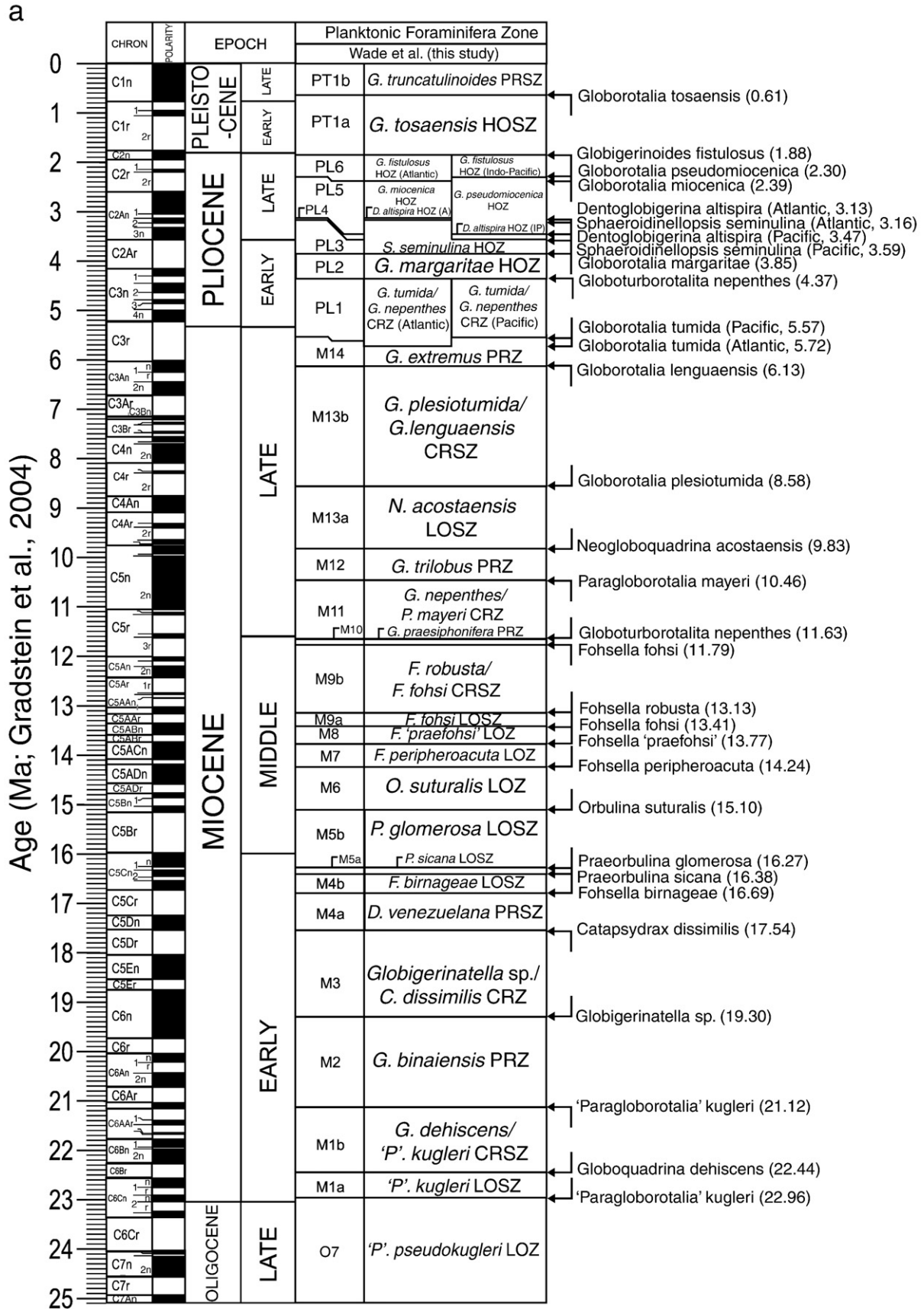


Fig. 4. Primary planktonic foraminiferal bioevents for the Cenozoic against the polarity time scale of Gradstein et al. (2004). (a) 0–25 Ma; (b) 20–45 Ma; and (c) 40–65 Ma. A = Atlantic; IP = Indo-Pacific.

b

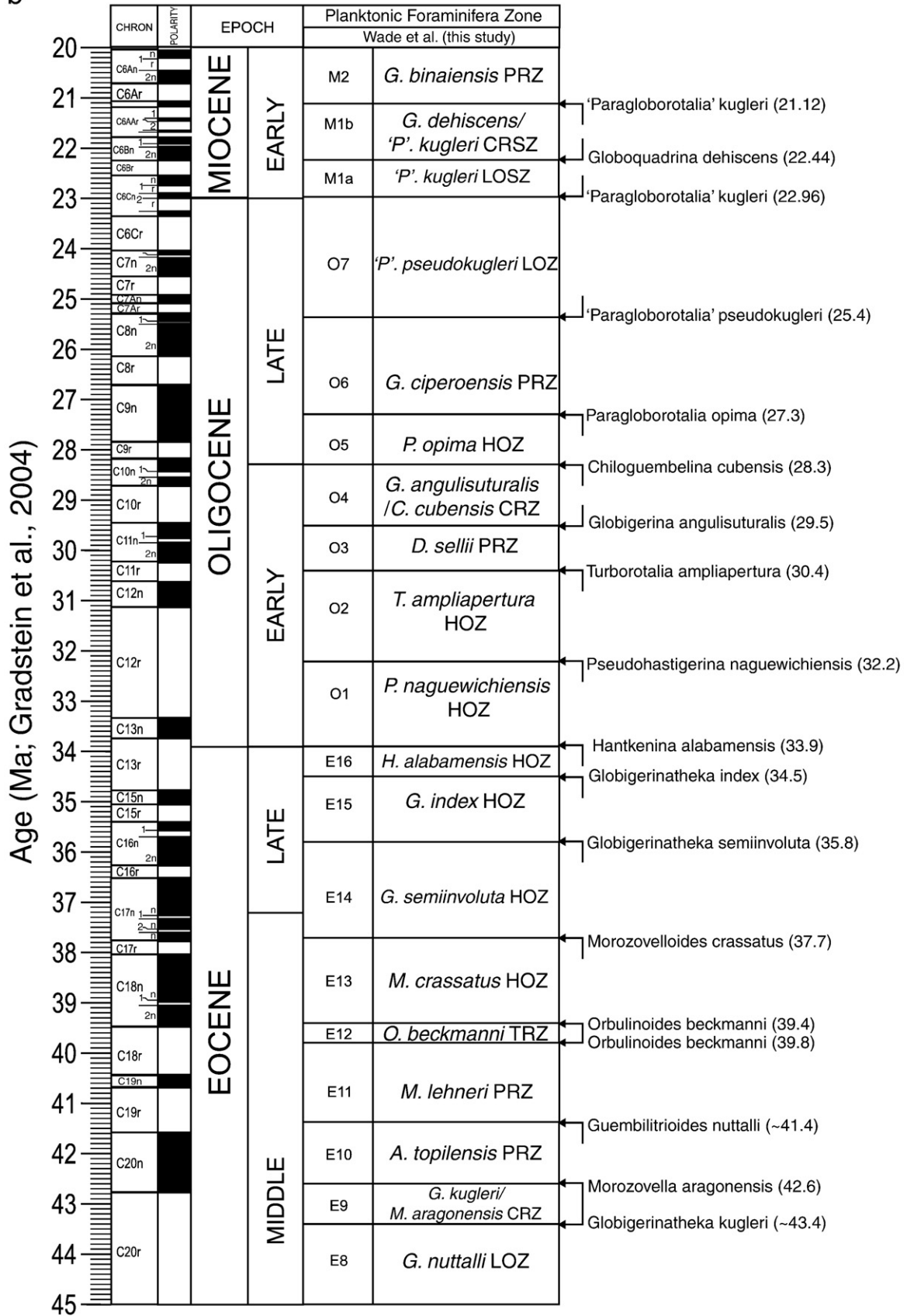


Fig. 4 (continued).

C

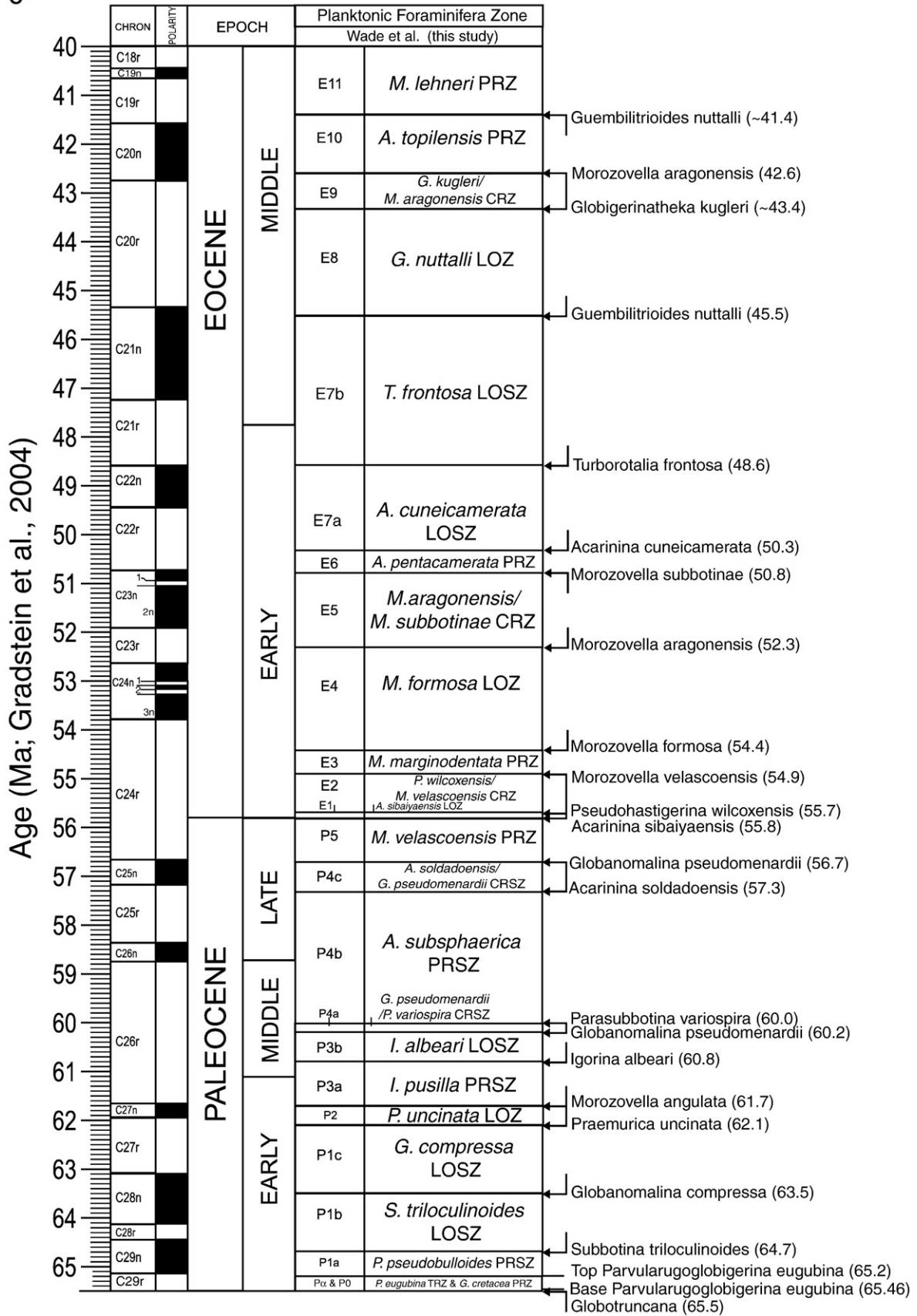


Fig. 4 (continued).

Definition: Concurrent range of the nominate taxa between the lowest occurrence (LO) of *Globorotalia tumida* and HO of *Globoturbotalita nepenthes*.

Magnetostratigraphic calibration: Chron C3r–Subchron C3n.1r.

Astronomical cycle calibration: 15_{Mi-C3r}–12_{Pl-C3n}.

Estimated age: Atlantic Ocean = 5.63–4.36 Ma (as per Cande and Kent, 1995); 5.72–4.37 Ma (as per Lourens et al., 2004); Pacific Ocean = 5.51–4.36 Ma (as per Cande and Kent, 1995); 5.57–4.37 Ma (as per Lourens et al., 2004); late Miocene–early Pliocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005). The extinction of *Globorotalia cibaoensis* was used to subdivide Zone PL1 and had a calibration of 4.6 Ma in BKS95. However, Chaisson and Pearson (1997) reported a much younger LAD for this species which was adopted by Lourens et al. (2004) to give an astronomical age on 3.23 Ma. As the much younger LAD at Ceara Rise is yet to be confirmed we use the 4.6 Ma calibration of BKS95. Due to this discrepancy, we have removed the subdivision of Zone PL1, pending further investigations.

Consistent with previous studies (e.g., Berggren, 1977; Srinivasan and Kennett, 1981b; Kennett and Srinivasan, 1983), there is a short stratigraphic interval (32 kyr) between the HO of *Globorotalia dehiscens* and the LO of *Sphaeroidinella dehiscens* (see Fig. 2a, Table 1). The LO of *G. tumida* occurs between these two distinctive events (Srinivasan and Chaturvedi, 1992). The FAD *G. tumida* has been revised to 5.63 and 5.51 Ma for the Atlantic and Pacific oceans respectively (Table 1). Thunell (1981), Srinivasan and Kennett (1981a) and Chaisson and Leckie (1993) record the FAD of *G. tumida* to be older than the LAD *G. dehiscens*. However, Hodell and Kennett (1986) have shown the LAD of *G. dehiscens* to be diachronous, and the extinction appears to occur earlier in higher latitudes in comparison to tropical sites (Srinivasan and Kennett, 1981b).

2.3. Amendment to the Miocene M zones

It is remarkable how few low-latitude open ocean sections exist with good recovery, high sedimentation rates, abundant planktonic foraminifera and a clearly defined magnetostratigraphy through the Miocene. This has significantly hindered direct correlations to the GPTS and the development of robust planktonic foraminifera magnetobiostratigraphy. Miller et al. (1985) produced a magnetostratigraphy DSDP Sites 563 and 558 (western North Atlantic Ocean), however even these records have unconformities. Many of the events through the Miocene have been calibrated from the Buff Bay Formation, Jamaica (BKS95) and not from deep sea cores. Following Lourens et al. (2004) we have recalibrated the ages from Ceara Rise, but note that these are not tied to a magnetostratigraphy, and the resulting ages are significantly younger than those recorded in BKS95. Our recalibrations have led to major changes to the age assignments and duration of Biochrons M10 to M13. We highlight some of the major changes below, but emphasize that this interval requires detailed study to confirm the ages of the events as defined from Ceara Rise (Chaisson and Pearson, 1997; Turco et al., 2002). The lower–middle Miocene interval is divided on the diagnostic index genus *Praeorbulina*. However, these taxa are rare at Ceara Rise (Pearson and Chaisson, 1997) and therefore were not included in the revised calibration, and we have retained the ages reported in BKS95 for FAD *Orbulina suturalis* (15.1 Ma), FAD *Praeorbulina circularis* (16.0 Ma), FAD *Praeorbulina curva* (16.3 Ma) and *Praeorbulina sicana* (16.4 Ma).

Zone M14. *Globigerinoides extremus* Partial-range Zone (herein renamed = Zone M14 [*Globorotalia linguaensis*–*G. tumida* Interval Zone] of BKS95).

Definition: Partial range of the nominate taxon between the HO of *Globorotalia linguaensis* and LO of *Globorotalia tumida*.

Magnetostratigraphic calibration: Subchron C3An.1n–Chron C3r.

Astronomical cycle calibration: 16_{Mi-C3r}–15_{Mi-C3r}.

Estimated age: Atlantic Ocean = 6.00–5.63 Ma (as per Cande and Kent, 1995); 6.13–5.72 Ma (as per Lourens et al., 2004); Pacific Ocean = 6.00–5.51 Ma (as per Cande and Kent, 1995); 6.13–5.57 Ma (as per Lourens et al., 2004); late Miocene.

Remarks: Following the detailed biostratigraphic investigations by Turco et al. (2002), Lourens et al. (2004) significantly revised the LAD of *G. linguaensis* to 8.97 Ma. The revised age is appreciably older than reported in BKS95 (derived from the Tonga Plateau; Chaproniere et al., 1994) and would place the event within the *Neogloboquadrina acostaensis* Lowest-occurrence Subzone (Subzone M13a), inconsistent with the established order of bioevents. However, it should be noted that Zhang et al. (1993) found the HO of *G. linguaensis* near the same horizon as the HO *G. plesiotumida* (8.52 Ma; Table 1), which is more consistent with the older age suggested by Turco et al. (2002). For stability we have retained the age established in BKS95, but this interval clearly requires further investigation. The zone is renamed according to the convention of Berggren and Pearson (2005).

Zone M13. *Neogloboquadrina acostaensis*/*Globorotalia linguaensis* Concurrent-range Zone

Definition: Concurrent range of the nominate taxa between the LO of *Neogloboquadrina acostaensis* and HO of *Globorotalia linguaensis*.

Magnetostratigraphic calibration: Subchron C5n.1n–Subchron C3An.1n.

Astronomical cycle calibration: 25_{Mi-C4Ar}–16_{Mi-C3r}.

Estimated age: 9.79–6.00 Ma (as per Cande and Kent, 1995); 9.83–6.13 Ma (as per Lourens et al., 2004); late Miocene.

Remarks: The nomenclature and definition of the zone remain the same as in BKS95.

Subzone M13b. *Globorotalia plesiotumida*/*Globorotalia linguaensis* Concurrent-range Subzone (herein amended and renamed, approximately equivalent to Subzone M13b [*Globigerinoides extremus*/*Globorotalia plesiotumida*–*G. linguaensis* Interval Subzone] of BKS95).

Definition: Concurrent range of the nominate taxa between the LO of *Globorotalia plesiotumida* and HO of *Globorotalia linguaensis*.

Magnetostratigraphic calibration: Subchron C4r.2r–Subchron C3An.1n.

Astronomical cycle calibration: 22_{Mi-C4r}–16_{Mi-C3r}.

Estimated age: 8.52–6.00 Ma (as per Cande and Kent, 1995); 8.58–6.13 Ma (as per Lourens et al., 2004); late Miocene.

Remarks: The definition used here removes the operational ambiguity inherent in the “and/or” designation in BKS95, in which the Subzone was defined as the biostratigraphic interval between the LO of *Globigerinoides extremus* and/or the LO of *Globorotalia plesiotumida* and the HO of *G. linguaensis*. Evidence since BKS95 indicates that the LOs of *Globigerinoides extremus* and *Globorotalia plesiotumida* may occur at different levels (compare Chaisson and Pearson, 1997 and Turco et al., 2002). The subzone is renamed here according to the convention of Berggren and Pearson (2005).

Subzone M13a. *Neogloboquadrina acostaensis* Lowest-occurrence Subzone (herein amended and renamed, approximately equivalent to Subzone M13a [*Neogloboquadrina acostaensis*–*Globigerinoides extremus*/*Globorotalia plesiotumida* Interval Subzone] of BKS95).

Definition: Biostratigraphic interval between the LO of the nominate taxon *Neogloboquadrina acostaensis* and LO of *Globorotalia plesiotumida*.

Magnetostratigraphic calibration: Subchron C5n.1n–Subchron C4r.2r.

Astronomical cycle calibration: 25_{Mi-C4Ar}–22_{Mi-C4r}.

Estimated age: 9.79–8.52 Ma (as per Cande and Kent, 1995); 9.83–8.58 Ma (as per Lourens et al., 2004); late Miocene.

Remarks: The definition used here removes the operational ambiguity inherent in the “and/or” designation in BKS95, in which the Subzone was defined as the biostratigraphic interval between the LO of *Neogloboquadrina acostaensis* and the LO of *Globigerinoides extremus* and/or the LO of *Globorotalia plesiotumida*. See remarks for Subzone M13b regarding the LADs of *Globigerinoides extremus* and *Globorotalia plesiotumida*. The subzone is renamed here according to the convention of Berggren and Pearson (2005).

There is a significant reduction in the duration of Sub-biochron M13a. The cyclostratigraphic age of the LO of *Neogloboquadrina acostaensis* (9.83 Ma) is derived from Ceara Rise (Chaisson and Pearson, 1997). This calibration was adopted by Lourens et al. (2004) and is significantly younger (1.07 myr) than in BKSA95 (10.90 Ma) and would move this event from early Subchron C5n.2n to Subchron C5n.1n. In BKSA95 the duration of this sub-biochron is 2.6 myr, from 10.9 to 8.3 Ma. Following Chaisson and Pearson (1997) this sub-biochron is recalibrated to 9.79 to 8.52 Ma and results in a change in the duration of Sub-biochron M13a to 1.27 myr, a reduction of 1.3 myr. Turco et al. (2002) noted the diachrony of the LO of *Neogloboquadrina acostaensis* between low latitudes and the Mediterranean. The age used in BKSA95 is calibrated to the magnetostratigraphy at Site 563 (Miller et al., 1985) and the discrepancy in calibrated ages may be due to further diachrony between the tropical and subtropical Atlantic Ocean, however, we note that the order of bioevents is consistent between Ceara Rise and Site 563.

Zone M12. *Globigerinoides trilobus* Partial-range Zone (herein renamed = Zone M12 [*Neogloboquadrina mayeri*-*Neogloboquadrina acostaensis* Interval Zone] of BKSA95).

Definition: Partial range of the nominate taxon between the HO of *Paragloborotalia mayeri* and LO of *Neogloboquadrina acostaensis*.

Magnetostratigraphic calibration: Subchron C5n.2n–Subchron C5n.1n.

Astronomical cycle calibration: 27_{Mi–C5n}–25_{Mi–C4a}.

Estimated age: 10.53–9.79 Ma (as per Cande and Kent, 1995); 10.46–9.83 Ma (as per Lourens et al., 2004); late Miocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005). As for *Neogloboquadrina acostaensis* (discussed above), there is a large difference between the age established in BKSA95 and that at Ceara Rise for the LAD of *Paragloborotalia mayeri* (10.53 Ma, this study; 11.40 Ma, BKSA95). The extinction of *Paragloborotalia mayeri* has been recalibrated to 10.53 Ma as per Chaisson and Pearson (1997) (given as *siakensis* in Turco et al., 2002). This is significantly younger (870 kyr) than the previous reported age of 11.40 Ma in BKSA95. The interpolated age would place this event mid C5n.2n rather than C5r.2r. The age used in BKSA95 is calibrated to the magnetostratigraphy at Site 563 (Miller et al., 1985) and this discrepancy may be due to diachrony between the tropical and subtropical Atlantic Ocean. Hilgen et al. (2000) noted the diachrony in the extinction of *P. mayeri* between the tropical Atlantic Ocean and the Mediterranean and diachrony with higher latitudes was suggested by Miller et al. (1991).

The extinction of *Paragloborotalia mayeri/siakensis* and the LO of *Neogloboquadrina acostaensis* and *Fohsella peripheroronda*, have been shown to be diachronous between the Mediterranean and equatorial Atlantic Ocean (Turco et al., 2002). We suggest that the younger calibrations through this interval may be due to further diachronism of extinction events in the Jamaican sections. Clearly, further work is required to constrain the bioevents through this interval.

Zone M11. *Globoturborotalita nepenthes/Paragloborotalia mayeri* Concurrent-range Zone (herein renamed = Zone M11 [*Globoturborotalita nepenthes/Neogloboquadrina mayeri* Concurrent-range Zone] of BKSA95).

Definition: Concurrent range of the nominate taxa between the LO of *Globoturborotalita nepenthes* and the HO of *Paragloborotalia mayeri*.

Magnetostratigraphic calibration: Subchron C5r.3r–Subchron C5n.2n.

Astronomical cycle calibration: 29_{Mi–C5r}–27_{Mi–C5n}.

Estimated age: 11.55–10.53 Ma (as per Cande and Kent, 1995); 11.63–10.46 Ma (as per Lourens et al., 2004); middle–late Miocene.

Remarks: Renamed to reflect inclusion of the species *mayeri* in the genus *Paragloborotalia*. In Table 1, we have incorporated the age established for the LAD of *Cassigerinella chipolensis* by Turco et al. (2002). This is younger than the suggested age of this event as in Chaisson and Leckie (1993) but appears to be a useful secondary event

within the *Globoturborotalita nepenthes/Paragloborotalia mayeri* Concurrent-range Zone (Zone M11). The HO of *Globigerinoides subquadratus* is found to be near-synchronous between Site 926 (equatorial Atlantic Ocean, Turco et al., 2002) and the Mediterranean (Hilgen et al., 2000).

Zone M10. *Globigerinella praesiphonifera* Partial-range Zone (herein amended and renamed = Zone M10 [*Globorotalia robusta-Globoturborotalita nepenthes* Interval Zone] of BKSA95).

Definition: Partial range of the nominate taxon between the HO of *Fohsella fohsi* and LO of *Globoturborotalita nepenthes*.

Magnetostratigraphic calibration: Subchron C5r.3r.

Astronomical cycle calibration: 30_{Mi–C5r}–29_{Mi–C5r}.

Estimated age: 11.71–11.55 Ma (as per Cande and Kent, 1995); 11.79–11.63 Ma (as per Lourens et al., 2004); middle Miocene.

Remarks: Amended to reflect the use of the LO of *F. fohsi* rather than the LO of *F. lobata* and *F. robusta* as in BKSA95. Renamed according to the convention of Berggren and Pearson (2005).

Following Turco et al. (2002), Lourens et al. (2004) revised the LAD *Globorotalia praescitula* from 11.9 (BKSA95) to 13.73 Ma. This placed the extinction of *G. praescitula* between the LOs of *F. 'praefohsi'* and *F. fohsi* (s.l.) and thus moved the extinction of *G. praescitula* from Zone M10 to M7. Initial investigations from Site U1337 (Expedition 320/321 Scientists, 2010) suggest that the biostratigraphic events are consistent with BKSA95 and therefore we have retained the calibration of 11.9 Ma here pending further investigations.

2.3.1. Revision of Zones M7–M9 (*Fohsella* lineage)

One of the key lineages used in the biostratigraphic subdivision of the middle Miocene is the fohsellid lineage (usually referred to in the earlier literature as *Globorotalia fohsi* and its various subspecies). All previous work agrees that early representatives of the lineage tend to be small forms with rounded peripheries, and that there is a gradual trend through time towards larger size and more acute peripheries which eventually results in keeled forms. After this more lobate morphotypes appear, as do more robust, biconvex forms. Taxonomic subdivision of this gradual chronocline into species and subspecies is inevitably subjective, and contrasting approaches were taken by Bolli (1957b), Blow (1957), Blow and Banner (1966), Olsson (1972), Stainforth et al. (1975), Kennett and Srinivasan (1983), Bolli and Saunders (1985) and Berggren (1993). These various taxonomic schemes are necessarily mirrored in different approaches to the biostratigraphic subdivision of the middle Miocene based upon the taxa.

The biostratigraphic scheme used here (in slightly modified form; see the discussion below) is that first suggested by Banner and Blow (1965), Blow and Banner (1966) and reflected in the N zonal concepts of Blow (1969). This scheme capitalizes on the biostratigraphic utility of this evolutionary lineage and uses the successive first occurrences of *F. peripheroacuta* (a morphotype that has a distinctly pinched or acute periphery), *F. 'praefohsi'* (which has an incipient keel on the final one or two chambers), and *F. fohsi* (which has a well-developed keel on the final chamber and an incipient keel throughout the last whorl), and finally the extinction of the group as successive zonal boundaries. These biohorizons originally delimited Zones N10–N12 (see also Kennett and Srinivasan, 1983) and in our scheme they delimit Zones M7–M9 (Fig. 5). We have found this scheme to provide excellent biostratigraphic control in the tropical Pacific and Atlantic Oceans (Pearson, 1995; Pearson and Chaisson, 1997).

There is, however, a taxonomic problem, as highlighted by Bolli and Saunders (1985), in that the morphology of the holotype of *Globorotalia (Fohsella) praefohsi* Blow and Banner does not seem to accord well with the concept of the taxon as originally suggested by Blow and Banner (1966). We agree with Bolli and Saunders that the *praefohsi* holotype can be regarded as a subjective synonym of *Globorotalia lobata* Bermúdez (= *F. lobata*), which is a more 'advanced' member of the lineage. The paratype, however, is more in accord with the concept of *praefohsi* as originally articulated by Blow and Banner (1966). It is also pertinent that the holotype of *praefohsi* comes from a higher

| Stage | Blow (1969) | Berggren et al. (1995) | Wade et al. (this study) | Datum Events |
|----------------|-------------|------------------------|--------------------------|--------------|
| middle Miocene | N14 | M11 | M11 | |
| | N13 | M10 | M10 | |
| | N12 | M9b | M9b | |
| | | | | |
| | N11 | M7 | M8 | |
| | N10 | | M7 | |
| | N9 | M6 | M6 | |
| N8 | M5 | M5 | | |

Fig. 5. Revision of mid Miocene “M” zones and comparison to previous zonations.

stratigraphic level than the paratype (Bolli and Saunders, 1985). Pearson (1995) and Pearson and Chaisson (1997) acknowledged this problem by referring to the N11 Zone fossil informally as *Fohsella 'praefohsi'*, as we have done, thereby retaining the concept of Blow and Banner (1966) as widely used subsequently (e.g. Kennett and Srinivasan, 1983) and deferring resolution of the taxonomic problem for future work. In contrast, BKSA95 placed *praefohsi* in synonymy with *lobata* and effectively eliminated the old biostratigraphic subdivision between Zones N11 and N12. At the same time BKSA95 introduced the first alphanumeric M-zone scheme for the Miocene and used the first occurrence of the most ‘advanced’ of all the fohsellids, *F. robusta* as a subzone marker for the first time (delimiting their Subzones M9a and M9b).

The problem with the solution of BKSA95 is that it eliminates a proven highly useful zone fossil (*F. 'praefohsi'*) along with the biostratigraphic resolution that it provides. It is clear that detailed taxonomic revision of *praefohsi* is required, based on new SEM micrographs of the relevant types and detailed descriptions. If the holotype does indeed prove to be a synonym of *lobata*, as the illustration suggests, then it may be desirable to name a new species that accords better with the intended concept of *praefohsi*, which could then be the zone fossil for Zone M8. It may be that Blow and Banner's paratype could be used to typify such a new species, or alternatively a holotype could be taken from well-preserved and well-dated assemblages from elsewhere. Pending such a resolution, we retain the informal taxon *F. 'praefohsi'* as the zone fossil for Zone M8 basing our concept not on the holotype illustration but on Blow and Banner's original description as well as subsequent illustrated specimens that accord with that concept such as those shown by Kennett and Srinivasan (1983).

Zone M9. *Fohsella fohsi* Taxon-range Zone (herein defined, approximately equivalent to Zone N12 [*Globorotalia (G.) fohsi* Partial-range Zone] of Blow, 1969; combined Zone M9 [*Globorotalia fohsi lobata*–*Globorotalia fohsi robusta* Interval Zone] and Zone M8 [*Globorotalia fohsi sensu stricto* Lineage Zone] of BKSA95).

Definition: Biostratigraphic interval characterized by the total range of the nominate taxon between its LO and HO.

Magnetostratigraphic calibration: Chron C5ABn–Subchron C5r.3r.

Astronomical cycle calibration: 34_{Mi–C5AAr}–30_{Mi–C5r}.

Estimated age: 13.34–11.71 Ma (as per Cande and Kent, 1995); 13.41–11.79 Ma (as per Lourens et al., 2004); middle Miocene.

Remarks: The new concept of Zone M9 follows from our modification of middle Miocene zonation discussed above. The HO of *Fohsella robusta* and *F. fohsi* are estimated to be at the same stratigraphic level. However, in the astronomical calibrations based on Ceara Rise, Turco et al. (2002) did not differentiate species within the fohsellid group and Chaisson and Pearson (1997) did not

comment on the HO of *F. robusta*. Therefore we use HO of *F. fohsi* to define the top of Zone M9.

Subzone M9b. *Fohsella robusta*/*Fohsella fohsi* Concurrent-range Subzone (herein amended and renamed = Subzone M9b [*Globorotalia fohsi robusta* Total Range Zone] of BKSA95; [*Globorotalia fohsi robusta* Total Range Zone] of Bolli, 1957b).

Definition: Concurrent range of the nominate taxa between the LO of *Fohsella robusta* and the HO of *F. fohsi*.

Magnetostratigraphic calibration: Chron C5AAn–Subchron C5r.3r.

Astronomical cycle calibration: 33_{Mi–C5Ar}–30_{Mi–C5r}.

Estimated age: 13.09–11.71 Ma (as per Cande and Kent, 1995); 13.13–11.79 Ma (as per Lourens et al., 2004); middle Miocene.

Remarks: The concept of Subzone M9b follows from our modification of middle Miocene zonation discussed above.

Subzone M9a. *Fohsella fohsi* Lowest-occurrence Subzone (herein defined, equivalent to Zone M8 [*Globorotalia fohsi sensu stricto* Lineage Zone] and Subzone M9a [*Globorotalia fohsi lobata* Lineage Zone] of BKSA95).

Definition: Biostratigraphic interval between the LO of *Fohsella fohsi* and the LO of *Fohsella robusta*.

Magnetostratigraphic calibration: Chron C5ABn–Chron C5AAn.

Astronomical cycle calibration: 34_{Mi–C5AAr}–33_{Mi–C5Ar}.

Estimated age: 13.34–13.09 Ma (as per Cande and Kent, 1995); 13.41–13.13 Ma (as per Lourens et al., 2004); middle Miocene.

Remarks: The new concept of Subzone M9a follows from our modification of middle Miocene zonation discussed earlier. The subzone differs from the concept of Subzone M9a (*Globorotalia fohsi lobata* Lineage Zone) as per BKSA95, which was defined as the biostratigraphic interval between LO of *Fohsella lobata* and LO of *F. robusta*. We have been unable to utilize the LO of *F. lobata* as Chaisson and Pearson (1997) and Turco et al. (2002) did not provide stratigraphic constraints on this taxon from Ceara Rise and therefore there is presently no astronomical calibration (Lourens et al., 2004). This is unfortunate as *F. lobata* is distinctive and the LO of this taxon appears isochronous in low latitudes (Srinivasan and Chaturvedi, 1992).

Turco et al. (2002) provided a refined calibration for the LAD of *Cassignella martinezpicoi* at Ceara Rise, which is consistent with studies elsewhere (Chaisson and Leckie, 1993). We have incorporated the revised age for the LAD of *Cassignella martinezpicoi* in Tables 1 and 3.

Zone M8. *Fohsella 'praefohsi'* Lowest-occurrence Zone (herein defined = Zone N11 [*Globorotalia (G.) praefohsi* Consecutive-range Zone] of Blow, 1969; and the upper part of Zone M7 [*Globorotalia peripheroacuta* Lineage Zone] of BKSA95).

Definition: Biostratigraphic interval between the LO of the nominate taxon *Fohsella 'praefohsi'* and the LO of *Fohsella fohsi*.

Magnetostratigraphic calibration: Chron C5ACn–Chron C5ABn.

Astronomical cycle calibration: 35_{Mi–C5ABr}–34_{Mi–C5AAr}.

Estimated age: 13.74–13.34 Ma (as per Cande and Kent, 1995); 13.77–13.41 Ma (as per Lourens et al., 2004); middle Miocene.

Remarks: The new concept of Zone M8 follows from our modification of middle Miocene zonation discussed above.

Zone M7. *Fohsella peripheroacuta* Lowest-occurrence Zone (herein defined = Zone N10 [*Globorotalia* (*Turborotalia*) *peripheroacuta* Consecutive-range Zone] of Blow, 1969; and the lower part of Zone M7 [*Globorotalia peripheroacuta* Lineage Zone] of BKSA95).

Definition: Biostratigraphic interval between the LO of the nominate taxon *Fohsella peripheroacuta* and the LO of *Fohsella 'praefohsi'*.

Magnetostratigraphic calibration: Chron C5ADn–Chron C5ACn.

Astronomical cycle calibration: 36_{Mi–C5ACn}–35_{Mi–C5ABr}.

Estimated age: 14.23–13.74 Ma (as per Cande and Kent, 1995); 14.24–13.77 Ma (as per Lourens et al., 2004); middle Miocene.

Remarks: The new concept of Zone M7 follows from our modification of middle Miocene zonation discussed above. Turco et al. (2002) provided a refined calibration for the LAD *Globorotalia archeomenardii* at Ceara Rise, which is consistent with studies elsewhere (Chaisson and Leckie, 1993). We have incorporated the refined calibration for the LAD *Globorotalia archeomenardii* in Tables 1 and 3.

Zone M6. *Orbulina suturalis* Lowest-occurrence Zone (herein renamed = Zone M6 [*Globorotalia peripheroronda* Partial-range Zone] of BKSA95).

Definition: Biostratigraphic interval between the LO of *Orbulina suturalis* and the LO of *Fohsella peripheroacuta*.

Magnetostratigraphic calibration: Subchron C5Bn.2n–Chron C5ADn.

Astronomical cycle calibration: 38_{Mi–C5Bn}–36_{Mi–C5ACn}.

Estimated age: 15.10–14.23 Ma (as per Cande and Kent, 1995); 15.10–14.24 Ma (as per Lourens et al., 2004); middle Miocene.

Remarks: Because of the rarity of *Orbulina* at the beginning of its range at Ceara Rise (Pearson and Chaisson, 1997) we have retained the age estimate from BKSA95. The Zone is renamed according to the convention of Berggren and Pearson (2005).

Zone M5. *Praeorbulina sicana* Lowest-occurrence Zone (herein renamed = Zone M5 [*Praeorbulina sicana*–*Orbulina suturalis* Interval Zone] of BKSA95).

Definition: Biostratigraphic interval between the LO of *Praeorbulina sicana* and the LO of *Orbulina suturalis*.

Magnetostratigraphic calibration: Subchron C5Cn.2n–Subchron C5Bn.2n.

Astronomical cycle calibration: 41_{Mi–C5Cn}–38_{Mi–C5Bn}.

Estimated age: 16.40–15.10 Ma (as per Cande and Kent, 1995); 16.38–15.10 Ma (as per Lourens et al., 2004); early–middle Miocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005). We follow the criterion of Jenkins et al. (1981) for the identification of *Praeorbulina sicana*, see also discussion in Kennett and Srinivasan (1983) and Pearson (1995).

Subzone M5b. *Praeorbulina glomerata* Lowest-occurrence Subzone (herein renamed = Subzone M5b [*Praeorbulina glomerata sensu stricto*–*Orbulina suturalis* Interval Subzone] of BKSA95).

Definition: Biostratigraphic interval between the LO of *Praeorbulina glomerata* and the LO of *Orbulina suturalis*.

Magnetostratigraphic calibration: Subchron C5Cn.1r–Subchron C5Bn.2n.

Astronomical cycle calibration: 41_{Mi–C5Cn}–38_{Mi–C5Bn}.

Estimated age: 16.29–15.10 Ma (as per Cande and Kent, 1995); 16.27–15.10 Ma (as per Lourens et al., 2004); early–middle Miocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005).

Subzone M5a. *Praeorbulina sicana* Lowest-occurrence Subzone (herein renamed = Subzone M5a [*Praeorbulina sicana*–*Praeorbulina glomerata sensu stricto* Interval Subzone] of BKSA95).

Definition: Biostratigraphic interval between the LO of *Praeorbulina sicana* and the LO of *Praeorbulina glomerata*.

Magnetostratigraphic calibration: Subchron C5Cn.2n–Subchron C5Cn.1r.

Astronomical cycle calibration: 41_{Mi–C5Cn}.

Estimated age: 16.40–16.29 Ma (as per Cande and Kent, 1995); 16.38–16.27 Ma (as per Lourens et al., 2004); early Miocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005).

Zone M4. *Globigerinoides bisphericus* Partial-range Zone (herein renamed = Zone M4 [*Catapsydrax dissimilis*–*Praeorbulina sicana* Interval Subzone] of BKSA95).

Definition: Partial range of the nominate taxon between the HO of *Catapsydrax dissimilis* and the LO of *Praeorbulina sicana*.

Magnetostratigraphic calibration: Chron C5Dr–Subchron C5Cn.2n.

Astronomical cycle calibration: 44_{Mi–C5Dn}–41_{Mi–C5Cn}.

Estimated age: 17.62–16.40 Ma (as per Cande and Kent, 1995); 17.54–16.38 Ma (as per Lourens et al., 2004); early Miocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005).

Subzone M4b. *Fohsella birnageae* Lowest Occurrence Subzone (herein renamed = Subzone M4b [*Globigerinoides bisphericus* Partial-range Subzone] of BKSA95).

Definition: Biostratigraphic interval between the LO of *Fohsella birnageae* and the LO of *Praeorbulina sicana*.

Magnetostratigraphic calibration: Subchron C5Cn.3n–Subchron C5Cn.2n.

Astronomical cycle calibration: 42_{Mi–C5Cn}–41_{Mi–C5Cn}.

Estimated age: 16.70–16.40 Ma (as per Cande and Kent, 1995); 16.69–16.38 Ma (as per Lourens et al., 2004); early Miocene.

Remarks: Renamed according to the convention of Berggren and Pearson (2005).

Subzone M4a. *Dentoglobigerina venezuelana* Partial-range Subzone (herein renamed = Subzone M4a [*C. dissimilis*–*Globorotalia birnageae* Interval Subzone] of BKSA95).

Definition: Partial range of the nominate taxon between the HO of *Catapsydrax dissimilis* and the LO of *Fohsella birnageae*.

Magnetostratigraphic calibration: Chron C5Dr–Subchron C5Cn.3n.

Astronomical cycle calibration: 44_{Mi–C5Dn}–42_{Mi–C5Cn}.

Estimated age: 17.62–16.70 Ma (as per Cande and Kent, 1995); 17.54–16.69 Ma (as per Lourens et al., 2004); early Miocene.

Remarks: Srinivasan and Chaturvedi (1992) point out the usefulness of the HO of *C. dissimilis* as a dissolution resistant form recorded in sites from the tropics to the subtropical. The HO of *C. dissimilis* is interpolated to within Chron C5Dr. This is consistent with studies at Site 608 (Miller et al., 1991), but inconsistent with Sites 516 and 558 where the HO of this species is reported within C5Dn (Berggren et al., 1983). Further work is required to confirm the age derived from Ceara Rise (Shackleton et al., 1999). Renamed according to the convention of Berggren and Pearson (2005).

2.3.2. *Globigerinatella* sp. and *G. insueta*

Cushman and Stainforth (1945) initially described the genus *Globigerinatella* from the Cipero Formation of Trinidad, with *G. insueta* as its only species, and used its first occurrence as the marker for the base of their *Globigerinatella insueta* Zone. The first occurrence of *G. insueta* remained a key zonal boundary through a number of subsequent, more highly subdivided biostratigraphic schemes (e.g. Bolli, 1957b; Banner and Blow, 1965; Blow, 1969; Kennett and Srinivasan, 1984; Bolli and Saunders, 1985).

Chaisson and Leckie (1993) were the first to describe distinct evolutionary trends in *Globigerinatella* based on their observations at ODP Site 806 on the Ontong Java Plateau, western tropical Pacific Ocean. They observed that the number of areal apertures tends to increase up section and that in the more advanced forms the apertures tend to be localized in patches on the test. Similar observations were reported by Spezzaferri (1994). Pearson (1995) described and illustrated similar evolutionary trends in specimens from ODP Sites 871 and 873 in the Marshall Islands region of the western tropical Pacific Ocean. He also observed that the earliest representatives of

Globigerinatella all lack supplementary apertures, an observation that was confirmed by Pearson and Chaisson (1997) from ODP Sites 925 and 926 on the Ceara Rise, western tropical Atlantic Ocean.

Pearson (1995) suggested that evolutionary trends in *Globigerinatella* might be useful for the biostratigraphic subdivision of the lower Miocene, an interval which is otherwise problematic for planktonic foraminifer biostratigraphy. He suggested splitting *Globigerinatella* into two taxa based on the presence or absence of areal apertures. From observations made on Cushman and Stainforth's (1945) type material at the US National Museum, Pearson (1995) reported that the holotype and all paratypes of *G. insueta* possess areal apertures, even though they were not mentioned in the original description and are not visible on all the type illustrations. Hence forms with areal apertures were included by Pearson (1995) and subsequently by Pearson and Chaisson (1997) in *G. insueta sensu stricto* and forms without were included as *Globigerinatella* sp.

Pearson (1995) and Pearson and Chaisson (1997) suggested that the 'chambers' of *Globigerinatella* that possess areal and/or multiple sutural apertures are homologous with the bullae of *Globigerinita* spp., and that *Globigerinita* was the ancestral form (see also the ontogenetic studies of Brönnimann (1951), and comments in Bolli and Saunders, 1985). The wall texture of *Globigerinatella* shows a typical micro-perforate structure identical to that seen in *Globigerinita* and *Tenuitella* (Pearson, 1995; Pearson and Wade, 2009). The evolution of *Globigerinatella* involved the development of highly swollen bullae which, critically, themselves have bullae superimposed upon them, the process being potentially repeated several times during the ontogeny of a single individual. The early growth stage is essentially identical to *Globigerinita*, such that it is only in the adult form that the diagnostic characters become clear. This being the case, designation of an individual to the genus *Globigerinatella* requires the presence of at least one additional bulla superimposed on the bulla-like chamber that is typical of adult *Globigerinita* (see also Bolli and Saunders, 1985, p. 189).

The 'calibration' for the first occurrence of *Globigerinatella insueta* in BKS95 was given as 18.8 Ma, although this was "inferred inasmuch as there is no direct calibration for the FAD of *G. insueta* at present," nor were BKS95 aware of the gradual evolution described above.

Of the sites that have so far shown the full evolutionary lineage, the Atlantic Ocean site (Ceara Rise) provides the best opportunity for calibrating the successive first appearances of *Globigerinatella* sp. and *G. insueta sensu stricto*, although it is unfortunate that no magnetostratigraphy is available for them. Pearson and Chaisson (1997) calibrated the events at 20.2 Ma and 17.4 Ma respectively, based on interpolation between other foraminifera and nannofossil datums in the age models for ODP Sites 925 and 929. Of the two *Globigerinatella* FADs, the most useful for re-defining the M2/M3 Zone boundary (=N5/N6 Zone boundary in older schemes) is *Globigerinatella* sp., as there is only a short interval of time (~50 kyr) between the FAD of *G. insueta sensu stricto* and the LAD of *C. dissimilis* which marks the M3/M4 (=N6/N7) Zone boundary (see also Pearson, 1995). We therefore revise the zonal definition of Zone M3 to utilize the LO of *Globigerinatella* sp.

Zone M3. *Globigerinatella* sp./*Catapsydrax dissimilis* Concurrent-range Zone (herein defined, equivalent to Zone M3 [*Globigerinatella insueta*/*C. dissimilis* Concurrent-range Zone] and upper part of Zone M2 [*C. dissimilis* Partial-range Zone] of BKS95).

Definition: Concurrent range of the nominate taxa between the LO of *Globigerinatella* sp. and the HO of *Catapsydrax dissimilis*.

Magnetostratigraphic calibration: Chron C6n–Chron C5Dr.

Astronomical cycle calibration: 48_{Mi–C6n}–44_{Mi–C5Dn}.

Estimated age: 19.66–17.62 Ma (as per Cande and Kent, 1995); 19.30–17.54 Ma (as per Lourens et al., 2004); early Miocene.

Remarks: The new concept of Zone M3 follows from developments in the understanding of the *Globigerinatella* lineage (discussed above). Within the *Globigerinatella* sp./*C. dissimilis* Concurrent-range Zone (Zone M3) the LO of *Globigerinatella insueta* has been revised from

~18.8 Ma (BKS95) to 17.69 Ma (interpolated from Pearson and Chaisson, 1997). The younger age of the LO of *G. insueta* is supported by studies from Site 1148 (South China Sea, Li et al., 2004), though unfortunately there is no magnetostratigraphy through this interval.

Zone M2. *Globoquadrina binaiensis* Partial-range Zone (herein amended = lower part of Zone M2 [*C. dissimilis* Partial-range Zone] of BKS95).

Definition: Partial range of the nominate taxon between the HO of '*Paragloborotalia*' *kugleri* and the LO of *Globigerinatella* sp.

Magnetostratigraphic calibration: Chron C6AAn–Chron C6n.

Astronomical cycle calibration: 53_{Mi–C6Ar}–48_{Mi–C6n}.

Estimated age: 21.81–19.66 Ma (as per Cande and Kent, 1995); 21.12–19.30 Ma (as per Lourens et al., 2004); early Miocene.

Remarks: The new concept of Zone M2 follows from developments in the understanding of the *Globigerinatella* lineage (discussed above). We provisionally refer to *kugleri* and *pseudokugleri* as '*Paragloborotalia*' pending further investigations of these taxa (see Pearson and Wade, 2009 for discussion).

Zone M1. '*Paragloborotalia*' *kugleri* Taxon-range Zone (herein renamed = Zone M1 [*Globorotalia kugleri* Total Range Zone] of BKS95).

Definition: Total range of the nominate taxon.

Magnetostratigraphic calibration: Subchron C6Cn.2n–Chron C6AAn.

Astronomical cycle calibration: 57_{Mi–C6Cn}–53_{Mi–C6Ar}.

Estimated age: 23.73–21.81 Ma (as per Cande and Kent, 1995); 22.96–21.12 Ma (as per Lourens et al., 2004); early Miocene.

Remarks: Renamed to accord with assignment of the species *kugleri* to the temporary genus '*Paragloborotalia*'.

Subzone M1b. *Globoquadrina dehiscens*/*Paragloborotalia*' *kugleri* Concurrent-range Subzone (herein renamed = Subzone M1b [*Globorotalia kugleri*/*Globoquadrina dehiscens* Concurrent-range Subzone] of BKS95).

Definition: Concurrent range of the nominate taxa between the LO of *Globoquadrina dehiscens* and the HO of '*Paragloborotalia*' *kugleri*.

Magnetostratigraphic calibration: Chron C6Br–Chron C6AAn.

Astronomical cycle calibration: 56_{Mi–C6Bn}–53_{Mi–C6Ar}.

Estimated age: 23.20–21.81 Ma (as per Cande and Kent, 1995); 22.44–21.12 Ma (as per Lourens et al., 2004); early Miocene.

Remarks: Renamed to accord with assignment of the species *kugleri* to the temporary genus '*Paragloborotalia*'. We have presently retained the LO of *G. dehiscens* to define the base of Subzone M1b, however, it should be noted that this event has been reported as diachronous (see Spezzaferri, 1994).

Subzone M1a. '*Paragloborotalia*' *kugleri* Lowest-occurrence Subzone (herein renamed = Subzone M1a [*Globigerinoides primordius* Interval Subzone] of BKS95).

Definition: Biostratigraphic interval between the LO of '*Paragloborotalia*' *kugleri* and the LO of *Globoquadrina dehiscens*.

Magnetostratigraphic calibration: Subchron C6Cn.2n–Chron C6Br.

Astronomical cycle calibration: 57_{Mi–C6Cn}–56_{Mi–C6Bn}.

Estimated age: 23.73–23.20 Ma (as per Cande and Kent, 1995); 22.96–22.44 Ma (as per Lourens et al., 2004); early Miocene.

Remarks: Renamed to accord with provisional assignment of the species *kugleri* to the genus '*Paragloborotalia*'.

2.4. Oligocene/Miocene boundary

The closest planktonic foraminiferal biostratigraphic event to the Oligocene/Miocene Boundary is the LO of '*P.*' *kugleri*. Our recalibrated age from Ceara Rise (Pearson and Chaisson, 1997) of FAD '*P.*' *kugleri* is 23.73 Ma. This is 70 kyr younger than the previously published age in BKS95 but is very consistent with studies from the Global Stratotype Section and Point (GSSP) at the Lemme-Carrosio Section, where the LO of '*P.*' *kugleri* is within Subchron C6Cn.2n (Steininger et al., 1997). Thus the uppermost Oligocene Zone O7 (this study; Zone O6 as per Berggren and Pearson, 2005) extends into the Miocene and reflects

the short stratigraphic interval between the base of the Miocene as designated by the base of Subchron C6Cn.2n and the LO of 'P.' *kugleri*.

3. Paleogene Period

For the Paleogene Period all zonal concepts have remained consistent with Berggren and Pearson (2005), except Zone O6 which we have amended and added Zone O7. The adjustments to the Paleogene magnetobiochronology are minor and mainly exhibit revised magnetostratigraphic calibrations. We have updated the calibrated ages of *Paragloborotalia opima* and *Chiloguembelina cubensis* as per Wade et al. (2007) which have slightly modified the duration of Biochrons O5 and O6. In addition we provide datum events calibrated to the ATS of Pälike et al. (2006) to Zone E11. We have not attempted to incorporate tuned ages from Ceara Rise for the Oligocene (Pearson and Chaisson, 1997; Shackleton et al., 1999), because of the significant differences in the age estimates between Site 925 and 929 (Shackleton et al., 1999, p. 1926). Substantial revisions occur in the early–mid Eocene (see below).

3.1. Amendment to the Oligocene O zones

Zone O7. 'Paragloborotalia' pseudokugleri Lowest-occurrence Zone (herein defined = upper part of Zone O6 [*Globigerina ciproensis* Partial-range Zone] of Berggren and Pearson, 2005).

Definition: Biostratigraphic interval between the LO of the nominate taxon 'Paragloborotalia' *pseudokugleri* and the LO of 'Paragloborotalia' *kugleri*.

Magnetostratigraphic calibration: Subchron C8n.1n–Subchron C6Cn.2n.

Astronomical cycle calibration: 63_{O1-C7Ar}–57_{Mi-C6Cn}.

Estimated age: 25.9–23.73 Ma (as per Cande and Kent, 1995); 25.4–22.96 Ma (as per Gradstein et al., 2004); 25.2 (as per Pälike et al., 2006) –22.96 Ma (as per Lourens et al., 2004); late Oligocene–earliest Miocene.

Remarks: The recalibration of the LAD *P. opima* from 27.1 Ma (BKSA95) to 27.5 Ma (Wade et al., 2007) has resulted in an increase in the duration of Biochron O6 as per Berggren and Pearson (2005) from 3.3 to 3.7 myr. The FAD of 'P.' *pseudokugleri* allows greater resolution for this interval. We have subdivided the interval between HO *P. opima* and LO 'P.' *kugleri*, using the LO of 'P.' *pseudokugleri* resulting in a shorter duration of Biochron O6 and the introduction of Zone O7.

The age of the FAD of 'P.' *pseudokugleri* in BKSA95 is derived from Hole 803D and Hole 628A (Leckie et al., 1993), where this bioevent was recorded within Chron C8n and Chron C7n, respectively. Further support for the stratigraphic utility of 'P.' *pseudokugleri* comes from sites drilled during ODP Leg 115 (Premoli Silva and Spezzaferri, 1990), ODP Leg 208 (Shipboard Scientific Party, 2004) and Site 1148 (Li et al., 2004); unfortunately, these sites either do not have magnetostratigraphy through this interval or the magnetostratigraphy is ambiguous. Although this taxon is rare at Site 1218 (equatorial Pacific Ocean), the LO of 'P.' *pseudokugleri* at 121.56 ± 0.61 meters composite depth is within Subchron C8n.1n (Shipboard Scientific Party, 2002), consistent with the age estimate in BKSA95.

Zone O6. *Globigerina ciproensis* Partial-range Zone (herein amended = lower part of Zone O6 [*Globigerina ciproensis* Partial-range Zone] of Berggren and Pearson, 2005).

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon, between the HO of *Paragloborotalia opima* and the LO of 'Paragloborotalia' *pseudokugleri*.

Magnetostratigraphic calibration: Chron C9n–Subchron C8n.1n.

Astronomical cycle calibration: 67_{O1-C9n}–63_{O1-C7Ar}.

Estimated age: 27.5–25.9 Ma (as per Cande and Kent, 1995); 27.3–25.4 Ma (as per Luterbacher et al., 2004); 26.9–25.2 Ma (as per Pälike et al., 2006); late Oligocene.

Remarks: See above discussion.

Zone O5. *Paragloborotalia opima* Highest-occurrence Zone

Definition: Biostratigraphic interval between the highest common occurrence (HCO) of *Chiloguembelina cubensis* and the HO of the nominate taxon *Paragloborotalia opima*.

Magnetostratigraphic calibration: Subchron C10n.1n–Chron C9n.

Astronomical cycle calibration: 70_{O1-C10n}–67_{O1-C9n}.

Estimated Age: 28.4–27.5 Ma (as per Cande and Kent, 1995); 28.3–27.3 Ma (as per Luterbacher et al., 2004); 28.0–26.9 Ma (as per Pälike et al., 2006); late Oligocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005). Coccioni et al. (2008) have confirmed that the HCO of *C. cubensis* is a robust stratigraphic marker for the Oligocene. The age of the LAD of *P. opima* and LAD of *C. cubensis* have been revised as per Wade et al. (2007).

Zone O4. *Globigerina angulisuturalis*/*Chiloguembelina cubensis* Concurrent-range Zone

Definition: Concurrent range of the nominate taxa between the LO of *Globigerina angulisuturalis* and the HCO of *Chiloguembelina cubensis*.

Magnetostratigraphic calibration: Subchron C11n.1n–C10n.1n.

Astronomical cycle calibration: 73_{O1-C10r}–70_{O1-C10n}.

Estimated age: 29.4–28.4 Ma (as per Cande and Kent, 1995); 29.5–28.3 Ma (as per Luterbacher et al., 2004); 29.2–28.0 Ma (as per Pälike et al., 2006); early Oligocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005). The FAD of *G. angulisuturalis* has been recorded in Chron C11n.1n in DSDP Holes 516 F (Rio Grande Rise, South Atlantic Ocean; Berggren et al., 1985) and Site 558 (North Atlantic Ocean; Miller et al., 1985) and (somewhat equivocally) in C11n.1n in ODP Holes 628A (Little Bahama Bank, North Atlantic Ocean) and 803D (Ontong Java Plateau, western Pacific Ocean; Leckie et al., 1993; see also BKSA95; p. 173, table 10). More recently in the Contessa, Monte Cagnero and Pieve d'Accinelli sections in the Umbria-Marche Basin, Italy, Coccioni et al. (2008) have recorded the FAD of *G. angulisuturalis* approximately 400 kyr younger, within mid-Chron C10r. The discrepancy may lie in preservational bias or diachrony between the open ocean and Tethys. We retain the calibration of C11n.1n (BKSA95) in this work pending further investigations.

Zone O3. *Dentoglobigerina sellii* Partial-range Zone

Definition: Partial range of the nominate taxon between the HO of *Turborotalia ampliapertura* and the LO of *Globigerina angulisuturalis*.

Magnetostratigraphic calibration: Chron C11r–Subchron C11n.1n.

Astronomical cycle calibration: 76_{O1-C11r}–73_{O1-C10r}.

Estimated age: 30.3–29.4 Ma (as per Cande and Kent, 1995); 30.4–29.5 Ma (as per Luterbacher et al., 2004); 30.3–29.2 Ma (as per Pälike et al., 2006); early Oligocene.

Remarks: The nomenclature and definition of the zone remains the same as in BKSA95 and Berggren and Pearson (2005).

Zone O2. *Turborotalia ampliapertura* Highest-occurrence Zone

Definition: Biostratigraphic interval between the HO of *Pseudohastigerina naguwichiensis* and the HO of the nominate taxon *Turborotalia ampliapertura*.

Magnetostratigraphic calibration: Chron C12r–Chron C11r.

Astronomical cycle calibration: 80_{O1-C12r}–76_{O1-C11r}.

Estimated age: 32.0–30.3 Ma (as per Cande and Kent, 1995); 32.2–30.4 Ma (as per Luterbacher et al., 2004); 32.0–30.3 Ma (as per Pälike et al., 2006); early Oligocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005).

Zone O1. *Pseudohastigerina naguwichiensis* Highest-occurrence Zone

Definition: Biostratigraphic interval between HO of *Hantkenina alabawensis* and HO of the nominate taxon *Pseudohastigerina naguwichiensis* (Berggren and Pearson, 2005).

Magnetostratigraphic calibration: Chron C13r–Chron C12r.

Astronomical cycle calibration: 84_{O1-C13n}–80_{O1-C12r}.

Estimated age: 33.7–32.0 Ma (as per Cande and Kent, 1995); 33.9–32.2 Ma (as per Luterbacher et al., 2004); 33.8–32.0 Ma (as per Pälike et al., 2006); early Oligocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005).

3.2. Amendment to the Eocene E zones

Zone E16. *Hantkenina alabamensis* Highest-occurrence Zone

Definition: Partial range of the nominate taxon between the HO of *Globigerinatheka index* and the HO of *Hantkenina alabamensis*.

Magnetostratigraphic calibration: Chron C13r–Chron C12r.

Astronomical cycle calibration: $86_{Eo-C13r}$ – $84_{Ol-C13n}$.

Estimated age: 34.3–33.7 Ma (as per Cande and Kent, 1995); 34.5–33.9 Ma (as per Luterbacher et al., 2004); 34.5–33.8 Ma (as per Pälike et al., 2006); late Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005). We have added the HCO of *Pseudohastigerina micra* as a secondary marker for the Eocene/Oligocene boundary. *Pseudohastigerina micra* is common in upper Eocene sediments, and this form undergoes a significant size decrease coeval with the extinction of *Hantkenina* (Wade and Pearson, 2008; Wade and Olsson, 2009). This event appears to be coeval between the Indian Ocean (Wade and Pearson, 2008) and the Gulf of Mexico (Miller et al., 2008).

Zone E15. *Globigerinatheka index* Highest-occurrence Zone

Definition: Biostratigraphic interval between the HO of *Globigerinatheka semiinvoluta* and the HO of the nominate taxon *Globigerinatheka index*.

Magnetostratigraphic calibration: Subchron C16n.2n–Chron C13r.

Astronomical cycle calibration: $89_{Eo-C16n}$ – $86_{Eo-C13r}$.

Estimated age: 35.8–34.3 Ma (as per Cande and Kent, 1995); 35.8–34.5 Ma (as per Luterbacher et al., 2004); 35.8–34.5 Ma (as per Pälike et al., 2006); late Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005).

Zone E14. *Globigerinatheka semiinvoluta* Highest-occurrence Zone

Definition: Biostratigraphic interval between the HO of *Morozovelloides crassatus* and the HO of the nominate taxon, *Globigerinatheka semiinvoluta*.

Magnetostratigraphic calibration: Subchron C17n.3n–Subchron C16n.2n.

Astronomical cycle calibration: $95_{Eo-C17n}$ – $89_{Eo-C16n}$.

Estimated age: 38.0–35.8 Ma (as per Cande and Kent, 1995); 37.7–35.8 Ma (as per Luterbacher et al., 2004); 38.1–35.8 Ma (as per Pälike et al., 2006); middle–late Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005).

Zone E13. *Morozovelloides crassatus* Highest-occurrence Zone

Definition: Biostratigraphic interval between the HO of *Orbulinoides beckmanni* and the HO of the nominate taxon, *Morozovelloides crassatus*.

Magnetostratigraphic calibration: Subchron C18n.2n–Subchron C17n.3n.

Astronomical cycle calibration: $100_{Eo-C18r}$ – $95_{Eo-C17n}$.

Estimated age: 40.0–38.0 Ma (as per Cande and Kent, 1995); 39.4–37.7 Ma (as per Luterbacher et al., 2004); 40.0–38.1 Ma (as per Pälike et al., 2006); middle Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2006).

Zone E12. *Orbulinoides beckmanni* Taxon-range Zone

Definition: Total range of the nominate taxon between its LO and HO.

Magnetostratigraphic calibration: Chron C18r–Subchron C18n.2n.

Astronomical cycle calibration: $102_{Eo-C18r}$ – $100_{Eo-C18r}$.

Estimated age: 40.5–40.0 Ma (as per Cande and Kent, 1995); 39.8–39.4 Ma (as per Luterbacher et al., 2004); 40.8–40.0 Ma (as per Pälike et al., 2006); middle Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005). Note there are significant differences in the duration of this biochron depending upon which time scale is used. Recent studies have suggested that the LO of *Orbulinoides beckmanni* is diachronous (Edgar et al., 2010) and the HO in low latitudes is younger than previous calibrations (Luciani et al., 2010).

Zone E11. *Morozovelloides lehneri* Partial-range Zone

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the HO of *Guembeltrioides nuttalli* and the LO of *Orbulinoides beckmanni*.

Magnetostratigraphic calibration: Chron C19r–Chron C18r.

Estimated age: 42.3–40.5 Ma (as per Cande and Kent, 1995); 41.4–39.8 Ma (as per Luterbacher et al., 2004); middle Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2006). The age of the HO of *Guembeltrioides nuttalli* is not well constrained and requires further study.

Zone E10. *Acarinina topilensis* Partial-range Zone

Definition: Partial range of the nominate taxon between the HO of *Morozovella aragonensis* and the HO of *Guembeltrioides nuttalli*.

Magnetostratigraphic calibration: Chron C20n–Chron C19r.

Estimated age: 43.6–42.3 Ma (as per Cande and Kent, 1995); 42.6–41.4 Ma (as per Luterbacher et al., 2004); middle Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005).

3.2.1. Early–middle Eocene

Owing to the pervasive occurrence of chert in the early and middle Eocene (Muttoni and Kent, 2007), the interval corresponding to 50–44 Ma (late Ypresian–early Lutetian) and the lower/middle Eocene boundary has often proved difficult to recover in deep sea cores. This has significantly hampered the correlations of planktonic foraminiferal bioevents to the GPTS through this interval. The basal zone of the middle Eocene has traditionally been recognized in planktonic foraminiferal biostratigraphy by the lowest occurrence of *Hantkenina* (Bolli, 1957a,b, 1966; Berggren et al., 1985, BKSA95) which was calibrated by Lowrie et al. (1982) to the top of Chron C22n. Due to inconsistencies between the nannofossil and planktonic foraminiferal biostratigraphies, Pearson et al. (2004) suggested that the initial appearance of *Hantkenina* was diachronous. Therefore Berggren and Pearson (2005) used the LO of *Guembeltrioides nuttalli* as the base of Zone E8 corresponding to the lower/middle Eocene (Ypresian–Lutetian) boundary.

In a detailed magnetobiostratigraphic study of an expanded lower–middle Eocene succession from the western Pyrenees, Payros et al. (2007) examined the divergence of planktonic foraminiferal Zones P9 and P10 and the standard zonation (BKSA95). Unlike BKSA95 which places the boundary between planktonic foraminiferal Zones P9 and P10 within calcareous nannofossil Zone NP14 (Subzone CP12a) and magnetic polarity Chron C22n/C21r boundary, they found the boundary to occur within Zone NP15 (=Zone CP13) and Chron C20r. This is consistent with the biostratigraphic results of Pearson et al. (2004) from Tanzania. Rögl and Egger (2010) have recently corroborated this by recognizing the evolutionary transition of *Clavigerinella* to *Hantkenina* in the upper part of Zone NP15b. The P9/P10 zonal boundary is therefore a surprising 3.1 myr younger than in BKSA95. The significantly younger calibrations for the LO of *Hantkenina* and *Guembeltrioides nuttalli* are also confirmed by Ortiz et al. (2008) and Larrasoña et al. (2008) from the Agost Section in Spain. Payros et al. (2007) used the Luterbacher et al. (2004) time scale, here we recalibrate the FAD of *Globigerinatheka kugleri*, *Hantkenina singanoae*, *Guembeltrioides nuttalli* and *Turborotalia frontosa* to Cande and Kent (1995), resulting in FADs of 44.4, 44.5, 46.4 and 49 Ma, respectively (Figs. 2c, 6, Table 1). This has major implications for the durations of Biochrons E7, E8 and E9 (Fig. 2c).

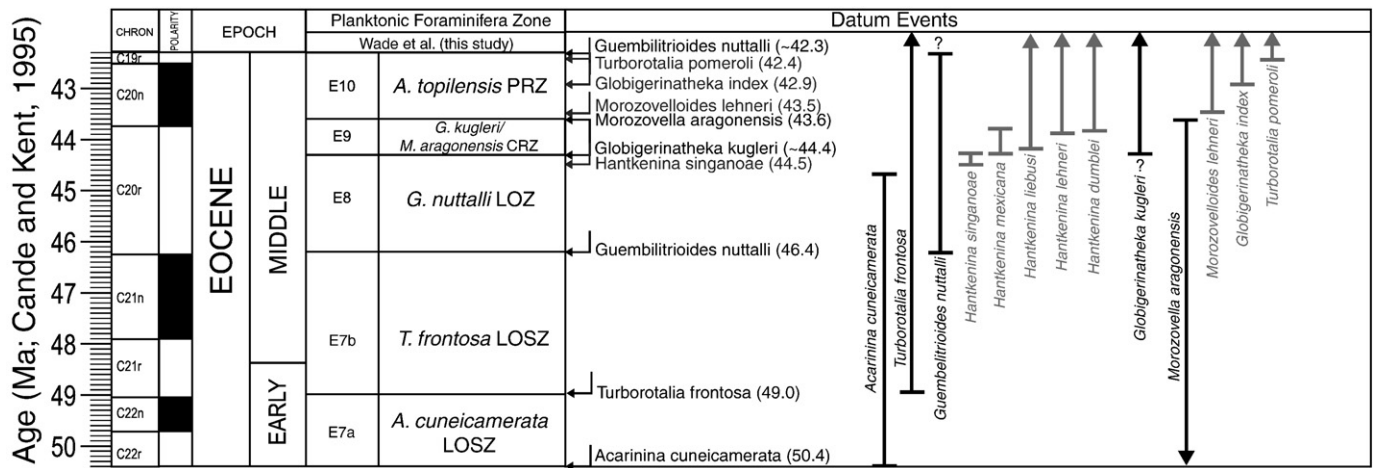


Fig. 6. Planktonic foraminiferal bioevents for the early–middle Eocene against the polarity time scale of Cande and Kent (1995). Primary marker taxa are in black, secondary markers and uncalibrated events to the magnetochronology are shown in grey. Planktonic foraminifera ranges are constrained from the Agost Section (Larrasoña et al., 2008; Ortiz et al., 2008) and Tanzania Drilling Project Site 2 (Pearson, unpublished data).

The revised FAD of *H. singanoae* (Payros et al., 2007) is younger than the previously accepted age of the FAD of *G. kugleri* (as per BKS95). However, in Tanzania Drilling Project Site 2 and 20 (Nicholas et al., 2006) a short interval exists between these events, equivalent to about 100 kyr (Fig. 6) and suggests a revised age of ~44.4 for the FAD of *G. kugleri*.

The changes in the biochronology through this interval has resulted in the duration of Biochron E7 changing from 1.4 to 4 myr. Payros et al. (2007, 2009) point out the stratigraphic utility of the LO of *T. frontosa*. Following the earlier zonation of Blow (1979), we have used this event to subdivide Zone E7 into Subzones E7a and E7b (Figs. 2c, 4c and 6). Note the E7a/E7b subzonal boundary (this study) is not the same criterion as the E7/E8 zonal boundary of Berggren and Pearson (2005), although on Cande and Kent (1995) magnetochronology, our age for the E7a/E7b subzonal boundary is similar to the value of the E7/E8 zonal boundary in Berggren and Pearson (2005).

There is at present a proposal to define/place the GSSP for the base of the Lutetian Stage (base middle Eocene) at a level equivalent the LO of *Blackites inflatus* (mid-Zone NP14 = CP12a/b boundary) within Chron C21r–47.76 Ma (as per Gradstein et al., 2004) at the Gorrondatxe Section, Biscaye Province, Spain (Molina et al., submitted for publication). This level is younger than the FAD of *T. frontosa* and within sub-biochron E7b.

Zone E9. *Globigerinatheka kugleri*/*Morozovella aragonensis* Concurrent-range Zone

Definition: Concurrent range of the nominate taxa between the LO of *Globigerinatheka kugleri* and the HO of *Morozovella aragonensis*.

Magnetochronologic calibration: Chron C20r (estimated)–Chron C20n. **Estimated age:** 44.4–43.6 Ma (as per Cande and Kent, 1995); 43.4–42.6 Ma (as per Luterbacher et al., 2004); middle Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005). The age of the LO of *Globigerinatheka kugleri* is not well constrained and there is a significant need for further study of this interval in continuous sections with magnetostratigraphy (see above discussion).

Zone E8. *Guembeltrioides nuttalli* Lowest-occurrence Zone

Definition: Biostratigraphic interval between the LO of the nominate taxon *Guembeltrioides nuttalli* and the LO of *Globigerinatheka kugleri*.

Magnetochronologic calibration: Chron C21n–Chron C20r (estimated).

Estimated age: 46.4–44.4 Ma (as per Cande and Kent, 1995); 45.5–43.4 Ma (as per Luterbacher et al., 2004); middle Eocene.

Remarks: While the nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005), the duration and boundary ages of the biochron have changed significantly (see above discussion). Payros et al. (2007) find the LO of *Guembeltrioides*

nuttalli in upper Chron C21n. However, a slightly younger level within Chron C20r was found by Larrasoña et al. (2008).

Zone E7. *Acarinina cuneicamerata* Lowest-occurrence Zone

Definition: Biostratigraphic interval between the LO of the nominate taxon *Acarinina cuneicamerata* and the LO of *Guembeltrioides nuttalli*.

Magnetochronologic calibration: Chron C22r (estimated) to Chron C21n.

Estimated age: 50.4–46.4 Ma (as per Cande and Kent, 1995); 50.3–45.5 Ma (as per Luterbacher et al., 2004); early–middle Eocene.

Remarks: The definition of this zone remains the same as in Berggren and Pearson (2005), however, the estimated duration of the biochron is much longer because of recalibration of the LO of *Guembeltrioides nuttalli* (Payros et al., 2007).

Subzone E7b. *Turborotalia frontosa* Lowest-occurrence Subzone

Definition: Biostratigraphic interval between the LO of the nominate taxon *Turborotalia frontosa* and the LO of *Guembeltrioides nuttalli*.

Magnetochronologic calibration: Chron C21r to Chron C21n.

Estimated age: 49.0–46.4 Ma (as per Cande and Kent, 1995); 48.6–45.5 Ma (as per Luterbacher et al., 2004); middle Eocene.

Remarks: Zone E7 has been subdivided based on the LO of *T. frontosa* (Payros et al., 2007). See discussion in Berggren and Miller (1988) regarding previous use of *T. frontosa* as a zonal marker.

Subzone E7a. *Acarinina cuneicamerata* Lowest-occurrence Subzone

Definition: Biostratigraphic interval between the LO of the nominate taxon *Acarinina cuneicamerata* and the LO *Turborotalia frontosa*.

Magnetochronologic calibration: Chron C22r–Chron C21r.

Estimated age: 50.4–49.0 Ma (as per Cande and Kent, 1995); 50.3–48.6 Ma (as per Luterbacher et al., 2004); early Eocene.

Remarks: Zone E7 has been subdivided based on the LO of *T. frontosa* (Payros et al., 2007).

Zone E6. *Acarinina pentacamerata* Partial-range Zone

Definition: Partial range of the nominate taxon between the HO of *Morozovella subbotinae* and the LO of *Acarinina cuneicamerata*.

Magnetochronologic calibration: Subchron C23n.1n–Chron C22r.

Estimated age: 50.8–50.4 Ma (as per Cande and Kent, 1995); 50.8–50.3 Ma (as per Luterbacher et al., 2004); early Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005).

Zone E5. *Morozovella aragonensis*/*Morozovella subbotinae* Concurrent-range Zone

Definition: Concurrent range of the nominate taxa between the LO of *Morozovella aragonensis* and the HO of *Morozovella subbotinae*.

Magnetostratigraphic calibration: Chron C23r–Subchron C23n.1n.
Estimated age: 52.3–50.8 Ma (as per [Cande and Kent, 1995](#) and [Luterbacher et al., 2004](#)); early Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Zone E4. *Morozovella formosa* Lowest-occurrence Zone

Definition: Biostratigraphic interval between the LO of the nominate taxon *Morozovella formosa* and the LO of *Morozovella aragonensis*.

Magnetostratigraphic calibration: Chron C24r–Chron C23r.

Estimated age: 54.0–52.3 Ma (as per [Cande and Kent, 1995](#)); 54.4–52.3 Ma (as per [Luterbacher et al., 2004](#)); early Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Zone E3. *Morozovella marginodentata* Partial-range Zone

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the HO of *Morozovella velascoensis* and LO of *Morozovella formosa*.

Magnetostratigraphic calibration: Chron C24r.

Estimated age: 54.5–54.0 Ma (as per [Cande and Kent, 1995](#)); 54.9–54.4 Ma (as per [Luterbacher et al., 2004](#)); early Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Zone E2. *Pseudohastigerina wilcoxensis*/*Morozovella velascoensis* Concurrent-range Zone

Definition: Biostratigraphic interval characterized by the concurrent ranges of the nominate taxa between the LO of *Pseudohastigerina wilcoxensis* and the HO of *Morozovella velascoensis*.

Magnetostratigraphic calibration: Chron C24r.

Estimated age: 55.4–54.5 Ma (as per [Cande and Kent, 1995](#)); 55.7–54.9 Ma (as per [Luterbacher et al., 2004](#)); early Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Zone E1. *Acarinina sibiyaensis* Lowest-occurrence Zone

Definition: Biostratigraphic interval between the LO of the nominate taxon *Acarinina sibiyaensis* and the LO of *Pseudohastigerina wilcoxensis*.

Magnetostratigraphic calibration: Chron C24r.

Estimated age: 55.5–55.4 Ma (as per [Cande and Kent, 1995](#)); 55.8–55.7 Ma (as per [Luterbacher et al., 2004](#)); early Eocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

3.3. Amendment to the Paleocene P zones

Zone P5. *Morozovella velascoensis* Partial-range Zone

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the HO of *Globanomalina pseudomenardii* and the LO of *Acarinina sibiyaensis*.

Magnetostratigraphic calibration: Chron C25n–Chron C24r.

Estimated Age: 55.9–55.5 Ma (as per [Cande and Kent, 1995](#)); 56.7–55.8 Ma (as per [Luterbacher et al., 2004](#)); late Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Zone P4. *Globanomalina pseudomenardii* Taxon-range Zone.

Definition: Biostratigraphic interval characterized by the total range of the nominate taxon *Globanomalina pseudomenardii*.

Magnetostratigraphic calibration: Chron C26r–Chron C25n.

Estimated age: 59.4–55.9 Ma (as per [Cande and Kent, 1995](#)); 60.2–56.7 Ma (as per [Luterbacher et al., 2004](#)); middle–late Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Subzone P4c. *Acarinina soldadoensis*/*Globanomalina pseudomenardii* Concurrent-range Subzone.

Definition: Concurrent range of the nominate taxa from the LO of *Acarinina soldadoensis* to the HO of *Globanomalina pseudomenardii*.

Magnetic calibration: Chron C25r–Chron C25n.

Age estimate: 56.5–55.9 Ma (as per [Cande and Kent, 1995](#)); 57.3–56.7 Ma (as per [Luterbacher et al., 2004](#)); late Paleocene.

Remarks: The definition of this subzone remains the same as that of BKSA95.

Subzone P4b. *Acarinina subsphaerica* Partial-range Subzone

Definition: Partial range of the nominate taxon *Acarinina subsphaerica* from the HO of *Parasubbotina variospira* to the LO of *Acarinina soldadoensis*.

Magnetic calibration: Chron C26r–Chron C25r.

Age estimate: 59.2–56.5 Ma (as per [Cande and Kent, 1995](#)); 60.0–57.3 Ma (as per [Luterbacher et al., 2004](#)); middle–late Paleocene.

Remarks: The definition of this subzone remains the same as that of [Berggren et al. \(2000\)](#).

Subzone P4a. *Globanomalina pseudomenardii*/*Parasubbotina variospira* Concurrent-range Subzone

Definition: Concurrent range of the nominate taxa from the LO of *Globanomalina pseudomenardii* to the HO of *Parasubbotina variospira*.

Magnetic calibration: Chron C26r.

Age estimate: 59.4–59.2 Ma (as per [Cande and Kent, 1995](#)); 60.2–60.0 Ma (as per [Luterbacher et al., 2004](#)); middle Paleocene.

Remarks: The definition of this subzone remains the same as that of [Berggren et al. \(2000\)](#).

Zone P3. *Morozovella angulata* Lowest-occurrence Zone

Definition: Biostratigraphic interval between the LO of *Morozovella angulata* and the LO of *Globanomalina pseudomenardii*.

Magnetostratigraphic calibration: Chron C27n–Chron C26r.

Estimated age: 61.0–59.4 Ma (as per [Cande and Kent, 1995](#)); 61.7–60.2 Ma (as per [Luterbacher et al., 2004](#)); early–middle Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Subzone P3b. *Igorina albeari* Lowest-occurrence Subzone

Definition: Biostratigraphic interval from the LO of *Igorina albeari* to the LO of *Globanomalina pseudomenardii*.

Magnetic calibration: Chron C26r–Chron C26.

Age estimate: 60.0–59.4 Ma (as per [Cande and Kent, 1995](#)); 60.8–60.2 Ma (as per [Luterbacher et al., 2004](#)); middle Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Subzone P3a. *Igorina pusilla* Partial-range Subzone

Definition: Biostratigraphic interval defined by the partial range of *Igorina pusilla* between the LO of *Morozovella angulata* and the LO of *Igorina albeari*.

Magnetic calibration: Chron C27n–Chron C26r.

Age estimate: 61.0–60.0 Ma (as per [Cande and Kent, 1995](#)); 61.7–60.8 Ma (as per [Luterbacher et al., 2004](#)); early Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Zone P2. *Praemurica uncinata* Lowest-occurrence Zone

Definition: Biostratigraphic interval between the LO of *Praemurica uncinata* and the LO of *Morozovella angulata*.

Magnetostratigraphic calibration: Chron C27r–Chron C27n.

Estimated age: 61.4–61.0 Ma (as per [Cande and Kent, 1995](#)); 62.1–61.7 Ma (as per [Luterbacher et al., 2004](#)); early Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Zone P1. *Eoglobigerina edita* Partial-range Zone

Definition: Partial range of the nominate taxon between the HO of *Parvularugoglobigerina eugubina* and the LO of *Praemurica uncinata*.

Magnetostratigraphic calibration: Chron C29r–Chron C27r.

Estimated age: 64.8–61.4 Ma (as per [Cande and Kent, 1995](#)); 65.2–62.1 Ma (as per [Luterbacher et al., 2004](#)); early Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in [Berggren and Pearson \(2005\)](#).

Subzone P1c. *Globanomalina compressa* Lowest-occurrence Subzone (herein amended and renamed = Subzone P1c [*Globanomalina compressa*/*Praemurica inconstans* Lowest-occurrence Subzone] of Berggren and Pearson, 2005; = Subzone P1c [*Globanomalina compressa*/*Praemurica inconstans*–*Praemurica uncinata* Subzone] of BKSA95).

Definition: Biostratigraphic interval between the LO of *Globanomalina compressa* and the LO of *Praemurica uncinata*.

Magnetic calibration: Chron C28n–Chron C27r.

Age estimate: 62.9–61.4 (as per Cande and Kent, 1995); 63.5–62.1 Ma (as per Luterbacher et al., 2004); early Paleocene.

Remarks: The definition used here removes the operational ambiguity inherent in the “and/or” designation in Berggren and Pearson (2005) in which the Subzone was defined as the biostratigraphic interval between the LO of *Globanomalina compressa* and/or *Praemurica inconstans* and the LO of *Praemurica uncinata*.

Subzone P1b. *Subbotina triloculinoides* Lowest-occurrence Subzone (herein amended = Subzone P1b [*Subbotina triloculinoides* Lowest-occurrence Subzone] of Berggren and Pearson, 2005; = Subzone P1b [*Subbotina triloculinoides*–*Globanomalina compressa*/*Praemurica inconstans* Interval Subzone] of BKSA95).

Definition: Biostratigraphic interval between the LO of *Subbotina triloculinoides* and the LO of *Globanomalina compressa*.

Magnetic calibration: Chron C29n–Chron C28n.

Estimated age: 64.3–62.9 (as per Cande and Kent, 1995); 64.7–63.5 Ma (as per Luterbacher et al., 2004); early Paleocene.

Remarks: The definition used here removes the operational ambiguity inherent in the “and/or” designation in Berggren and Pearson (2005) in which the subzone was defined as the biostratigraphic interval between the LO of *Subbotina triloculinoides* and the LOs of *Globanomalina compressa* and/or *Praemurica inconstans*.

Subzone P1a. *Parasubbotina pseudobulloides* Partial-range Subzone

Definition: Partial range of the nominate taxon between the HO of *Parvularugoglobigerina eugubina* and the LO of *Subbotina triloculinoides*.

Magnetic calibration: Chron C29r–Chron C29n.

Estimated age: 64.8–64.3 (as per Cande and Kent, 1995); 65.2–64.7 Ma (as per Luterbacher et al., 2004); early Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005).

Zone Pα. *Parvularugoglobigerina eugubina* Taxon-range Zone

Definition: Biostratigraphic interval characterized by the total range of the nominate taxon *Parvularugoglobigerina eugubina*.

Magnetochronologic calibration: Chron C29r.

Estimated age: 64.97–64.8 (as per Cande and Kent, 1995); 65.46–65.2 Ma (as per Luterbacher et al., 2004); early Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005).

Zone P0. *Guembelitra cretacea* Partial-range Zone

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the HO of Cretaceous taxa (e.g., *Globotruncana*, *Rugoglobigerina*, *Globigerinelloides*) and the LO of *Parvularugoglobigerina eugubina*.

Magnetochronologic calibration: Chron C29r.

Estimated age: 65.0–64.97 (as per Cande and Kent, 1995); 65.5–65.46 Ma (as per Luterbacher et al., 2004); early Paleocene.

Remarks: The nomenclature and definition of the zone remains the same as in Berggren and Pearson (2005).

4. Conclusions

We compile 187 revised calibrations of planktonic foraminiferal bioevents for the Cenozoic and provide calibrations to the GPTS of the Cenozoic and ATS of the Neogene and late Paleogene. Our compilation provides a template for Cenozoic magnetobio- and magnetobioastronomy. With recent progress in astronomical tuning, it is clear that high resolution biostratigraphic work and integrated biochronol-

ogies are needed to reduce the uncertainty of a number of events and study potential diachrony between the Atlantic and Pacific oceans. Future developments in radioisotopic and astronomical dating will undoubtedly lead to further revision and refinements in Cenozoic planktonic foraminiferal biochronology.

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References

- Aguirre, E., Pasini, G., 1985. The Pliocene–Pleistocene boundary. Episodes 8, 116–120.
- Backman, J., Raffi, I., 1997. Calibration of Miocene nannofossil events to orbitally-tuned cyclostratigraphies from Ceara Rise. In: Curry, W.B., Shackleton, N.J., Richter, C., Bralower, T.J. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, College Station, TX (Ocean Drilling Program), 154, pp. 83–99.
- Bandy, O.L., 1964. Cenozoic planktonic foraminiferal zonation. Micropaleontology 10, 1–17.
- Bandy, O.L., 1972. Origin and development of *Globorotalia* (*Turborotalia*) *pachyderma* (Ehrenberg). Micropaleontology 18, 294–318.
- Banner, F.T., Blow, W.H., 1965. Progress in the planktonic foraminiferal biostratigraphy of the Neogene. Nature 208, 1164–1166.
- Berggren, W.A., 1969. Cenozoic chronostratigraphy, planktonic foraminiferal zonation and the radiometric time scale. Nature 224, 1072–1075.
- Berggren, W.A., 1973. The Pliocene time scale: calibration of planktonic foraminiferal and calcareous nannoplankton zones. Nature 243, 391–397.
- Berggren, W.A., 1977. Late Neogene Planktonic Foraminiferal Biostratigraphy of DSDP Site 357 (Rio Grande Rise). Perch-Nielsen et al., Initial Reports of the Deep Sea Drilling Project XXXIX, pp. 591–614.
- Berggren, W.A., 1993. Neogene planktonic foraminiferal biostratigraphy of eastern Jamaica. In: Wright, R.M., Robinson (Eds.), Biostratigraphy of Jamaica: Geological Society of America Memoir, 182, pp. 179–217.
- Berggren, W.A., Miller, K.G., 1988. Paleogene tropical planktonic foraminiferal biostratigraphy and magnetobiochronology. Micropaleontology 34, 362–380.
- Berggren, W.A., Pearson, P.N., 2005. A revised tropical and subtropical Paleogene planktonic foraminiferal zonation. J. Foramin. Res. 35, 279–298.
- Berggren, W.A., Pearson, P.N., 2006. Tropical and subtropical planktonic foraminiferal zonation of the Eocene and Oligocene. In: Pearson, P.N., Olsson, R.K., Huber, B.T., Hemleben, C., Berggren, W.A. (Eds.), Cushman Foundation Special Publication, 41, pp. 29–40.
- Berggren, W.A., Hamilton, N., Johnson, D.A., Pujol, C., Weiss, W., Weiss, P., Cepek, P., Gombos Jr., A.M., 1983. Magnetobiostratigraphy of Deep Sea Drilling Project Leg 72, Sites 515–518, Rio Grande Rise (South Atlantic). Init. Rep. Deep Sea Drilling Proj. 72, 939–948.
- Berggren, W.A., Kent, D.V., Flynn, J.J., Van Couvering, J.A., 1985. Cenozoic geochronology. Geol. Soc. Am. Bull. 96, 1407–1418.
- Berggren, W.A., Hilgen, F.J., Langereis, C.G., Kent, D.V., Obradovich, J.D., Raffi, I., Raymo, M.E., Shackleton, N.J., 1995a. Late Neogene chronology: new perspectives in high-resolution stratigraphy. Geol. Soc. Am. Bull. 107, 1272–1287.
- Berggren, W.A., Kent, D.V., Swisher III, C.C., Aubry, M.-P., 1995b. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.-P., Hardenbol, J. (Eds.), Geochronology, Time Scales and Global Stratigraphic Correlation: A Unified Temporal Framework for an Historical Geology: SEPM Spec. Publ., vol. 54, pp. 129–212.
- Berggren, W.A., Aubry, M.-P., van Fossen, M., Kent, D.V., Norris, R.D., Quillévéré, F., 2000. Integrated Paleocene calcareous plankton magnetobiochronology and stable isotope stratigraphy: DSDP Site 384 (NW Atlantic Ocean). Palaeogeogr. Palaeoclimatol. Palaeoecol. 159, 1–51.
- Blow, W.H., 1957. Transatlantic correlation of Miocene sediments. Micropaleontology 3, 77–79.
- Blow, W.H., 1959. Age, correlation, and biostratigraphy of the upper Tocuyo (San Lorenzo) and Pown formations, eastern Falcon, Venezuela. Bulletins of American Paleontology 39, 67–251.
- Blow, W.H., 1969. Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. In: Brönnimann, P., Renz, H.H. (Eds.), Proceedings of the First International Conference on Planktonic Microfossils, 1. E.J. Brill, Leiden, pp. 199–422.
- Blow, W.H., 1979. The Cainozoic Foraminifera, v. I & 11. E. J. Brill, Leiden. 1413 pp.
- Blow, W.H., Banner, F., 1962. The Mid-Tertiary (Upper Eocene to Aquitanian) Globigerinaceae. In: Eames, F.E. (Ed.), Fundamentals of Mid-Tertiary Stratigraphical Correlation. Cambridge University Press, pp. 61–163.

- Blow, W.H., Banner, F., 1966. The morphology, taxonomy and biostratigraphy of *Globorotalia barisanensis* LeRoy, *Globorotalia fohsi* Cushman and Ellisor, and related taxa. *Micropaleontology* 12, 286–303.
- Bolli, H.M., 1957a. The genera *Globigerina* and *Globorotalia* in the Paleocene–Lower Eocene Lizard Springs Formation of Trinidad, B.W.I. In: Loeblich Jr., A.R., et al. (Eds.), *Studies in Foraminifera: Bulletin of the United States National Museum*, 215, pp. 61–82.
- Bolli, H.M., 1957b. Planktonic foraminifera from the Eocene Navet Formation and San Fernando Formations in Trinidad, B.W.I. In: Loeblich Jr., A.R., et al. (Eds.), *Studies in Foraminifera: Bulletin of the United States National Museum*, 215, pp. 155–172.
- Bolli, H.M., 1966. Zonation of Cretaceous to Pliocene marine sediments based on planktonic foraminifera: Boletín Informativo Asociacio'n Venezolana de Geologi'a. *Minerari'a y Petroleo* 9, 3–32.
- Bolli, H.M., Bermúdez, P.J., 1965. Zonation based on planktonic foraminifera of Middle Miocene to Pliocene warm-water sediments. *Boletín Informativo Asociacio'n Venezolana de Geologi'a. Minerari'a y Petroleo* 8, 119–149.
- Bolli, H.M., Saunders, J.B., 1985. Oligocene to Holocene low latitude planktic foraminifera. In: Bolli, H.M., Mayer, L.A., Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*, 1. Cambridge University Press, Cambridge, pp. 155–262.
- Brönnimann, P., 1951. *Globigerinita naparimaensis*, n. gen., n. sp., from the Miocene of Trinidad, B.W.I. *Contributions from the Cushman Foundation for Foraminiferal Research* 2, 16–18.
- Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *J. Geophys. Res.* 100, 6093–6095.
- Chaisson, W.P., Leckie, R.M., 1993. High-resolution Neogene planktonic foraminifer biostratigraphy of Site 806, Ontong Java Plateau (western Equatorial Pacific). In: Berger, W.H., Kroenke, L.W., Mayer, L.A., et al. (Eds.), *Proceeding of the Ocean Drilling Program: Scientific Results*, 130, pp. 137–178.
- Chaisson, W.P., Pearson, P.N., 1997. Planktonic foraminifer biostratigraphy at Site 925: Middle Miocene–Pleistocene. In: Shackleton, N.J., Curry, W.B., Richter, C., Bralower, T.J. (Eds.), *Proceeding of the Ocean Drilling Program: Scientific Results*, 154, pp. 3–31.
- Chaproniere, G.C.H., Styzyn, M.J., Sager, W.W., Nishi, H., Quinterno, P.J., Abrahamson, N., 1994. Late Neogene biostratigraphic and magnetostratigraphic synthesis. *Proceeding of the Ocean Drilling Program: Scientific Results*, 135, pp. 857–877.
- Cita, M.B., 1973. Pliocene biostratigraphy and chronostratigraphy. In: Ryan, W.F.F., et al. (Eds.), *Initial Reports of the Deep Sea Drilling Project*. Government Printing Office, Washington, D.C., pp. 1343–1379. 13.
- Cocconi, R., Marsili, A., Montanari, A., Bellanca, A., Neri, R., Bice, D.M., Brinkhuis, H., Church, N., Macalady, A., McDaniel, A., Deino, A., Lirer, F., Sprovieri, M., Maiorano, P., Monechi, S., Nini, C., Nocchi, M., Pross, J., Rochette, P., Sagnotti, L., Tateo, F., Touchard, Y., Van Simaey, S., Williams, G.L., 2008. Integrated stratigraphy of the Oligocene pelagic sequence in the Umbria-Marche basin (northeastern Apennines, Italy): a potential Global Stratotype Section and Point (GSSP) for the Rupelian/Chattian boundary. *Geol. Soc. Am. Bull.* 120, 487–511.
- Curry, W.B., Shackleton, N.J., Richter, C., et al., 1995. *Proceeding of the Ocean Drilling Program, Initial Reports*, 154. College Station, TX (Ocean Drilling Program).
- Cushman, J.A., Bermúdez, P.J., 1949. Some Cuban species of *Globorotalia*. *Contributions from the Cushman Foundation for Foraminiferal Research* 25, 26–45.
- Cushman, J.A., Stainforth, R.M.S., 1945. The foraminifera of the Cipero Marl Formation of Trinidad, British West Indies. *Cushman Laboratory for Foraminiferal Research. Special Publication*, 14. 75 pp.
- Dowsett, H.J., 1988. Diachrony of late Neogene microfossils in the Southwest Pacific Ocean: application of the graphic correlation method. *Paleoceanography* 3, 209–222.
- Edgar, K.M., Wilson, P.A., Sexton, P.F., Gibbs, S.J., Roberts, A.P., Norris, R.D., 2010. New biostratigraphic, magnetostratigraphic and isotopic insights into the Middle Eocene Climatic Optimum in low latitudes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 297, 670–682.
- Expedition 320/321 Scientists, 2010. Site U1337. In: Pälike, H., Lyle, M., Nishi, H., Raffi, I., Gamage, K., Klaus, A., and the Expedition 320/321 Scientists, *Proc. IODP, 320/321: Tokyo (Integrated Ocean Drilling Program Management International, Inc.)*. doi:10.2204/iodp.proc.320321.109.2010.
- Gibbard, P.L., Head, M.J., Walker, M.J.C., 2010. Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. *Journal of Quaternary Science* 25, 96–102.
- Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), 2004. *A Geologic Time Scale 2004*. Cambridge University Press, Cambridge, UK. 500 pp.
- Hancock, H.J.L., Chaproniere, G.C., Dickens, G.R., Henderson, R.A., 2002. Early Paleocene planktic foraminiferal and carbon isotope stratigraphy, Hole 762 C, Exmouth Plateau, northwest Australian margin. *J. Micropaleontology* 21, 29–42.
- Hedberg, H.D. (Ed.), 1976. *International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology and Procedure*. John Wiley and Sons, New York.
- Hilgen, F.J., Krijgsman, W., Raffi, I., Turco, E., Zachariasse, W.J., 2000. Integrated stratigraphy and astronomical calibration of the Serravallian/Tortonion boundary section at Monte Gibliscemi (Sicily, Italy). *Mar. Micropaleontol.* 38, 181–211.
- Hilgen, F., Brinkhuis, H., Zachariasse, W.-J., 2006. Unit stratotypes for global stages: the Neogene perspective. *Earth Sci. Rev.* 74, 113–125.
- Hodell, D.A., Kennett, J.P., 1986. Late Miocene–early Pliocene stratigraphy and paleoceanography of the South Atlantic and southwest Pacific Oceans: a synthesis. *Paleoceanography* 1, 285–311.
- Jenkins, D.G., 1966. Planktonic foraminiferal zones and new taxa from the Danian to Lower Miocene of New Zealand. *NZ J. Geol. Geophys.* 8, 1088–1126.
- Jenkins, D.G., 1967. Planktonic foraminiferal zones and new taxa from the lower Miocene to the Pleistocene of New Zealand. *NZ J. Geol. Geophys.* 10, 1064–1078.
- Jenkins, D.G., 1971. New Zealand Cenozoic planktonic foraminifera. *New Zealand Geological Survey Paleontological Bulletin* 42, 1–278.
- Jenkins, D.G., Saunders, J.B., Cifelli, R., 1981. The relationship of *Globigerinoides bisphericus* Todd 1954 to *Praeorbulina sicana* (de Stefani) 1952. *Journal of Foraminiferal Research* 11, 262–267.
- Kaneps, A.G., 1975. Cenozoic planktonic foraminifera from Antarctic Deep Sea sediments, Leg 28, DSDP. In: Hays, D.E., et al. (Eds.), *Initial Reports of the Deep Sea Drilling Project*. Government Printing Office, Washington, D.C., US, pp. 573–583. 28.
- Keigwin Jr., L.D., 1982. Neogene planktonic foraminifera from Deep Sea Drilling Project Sites 502 and 503. *Initial Reports of the Deep Sea Drilling Project*. Government Printing Office, Washington, D.C., US, pp. 269–288. 68.
- Kennett, J.P., Srinivasan, M.S., 1983. *Neogene Planktonic Foraminifera, A Phylogenetic Atlas*. Hutchinson Ross, Stroudsburg, Pennsylvania. 265 pp.
- Kennett, J.P., Srinivasan, M.S., 1984. Neogene datum planes: foraminiferal successions in Australia with reference sections from the Ninetyeast Ridge and the Ontong-Java Plateau. In: Ikebe, N., Tsuchi, R. (Eds.), *Pacific Neogene Datum Planes, Contributions to Biostratigraphy and Chronology*. Univ. of Tokyo Press, Tokyo, pp. 11–33.
- Krasheninnikov, V.A., 1971. Cenozoic foraminifera. In: Fischer, A.G., et al. (Eds.), *Initial Reports of the Deep Sea Drilling Project VI*, pp. 1055–1068.
- Larrasoana, J.C., Gonzalvo, C., Molina, E., Monechi, S., Ortiz, S., Tori, F., Tosquella, J., 2008. Integrated magnetobiochronology of the Early/Middle Eocene transition at Agost (Spain): implications for defining the Ypresian/Lutetian boundary stratotype. *Lethaia* 41, 395–415.
- Laskar, J., 1999. The limits of Earth orbital calculations for geological time-scale use. *Philos. Trans. R. Soc. London Ser. A* 357 (1757), 1735–1759. doi:10.1098/rsta.1999.0399.
- Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A., Levrard, B., 2004. A long term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics* 428, 261.
- Leckie, R.M., Farnham, C., Schmidt, M.G., 1993. Oligocene planktonic foraminifer biostratigraphy of Hole 803D (Ontong Java Plateau) and Hole 628A (Little Bahama Bank), and comparison with the southern high latitudes. In: Berger, W.H., Kroenke, L.W., Mayer, L.A. (Eds.), *Proceedings of the Ocean Drilling Program: Scientific Results*. Scientific Results, 130, pp. 113–127.
- Li, Q., Radford, S.S., Banner, F.T., 1992. Distribution of microperforate tenuitellid planktonic foraminifera in Holes 747A and 749B, Kerguelen Plateau. *Proceedings of the Ocean Drilling Program: Scientific Results*, 120, pp. 569–602.
- Li, Q., Jian, Z., Li, B., 2004. Oligocene–Miocene planktonic foraminifer biostratigraphy, Site 1148, northern South China Sea. In: Prell, W.L., et al. (Eds.), *Proceedings of the Ocean Drilling Program: Scientific Results*, 184.
- Lourens, L.J., Hilgen, F.J., Shackleton, N.J., Laskar, J., Wilson, D., 2004. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), *Geological Time Scale 2004*. Cambridge University Press, pp. 409–440.
- Lowrie, W., Alvarez, W., Napoleone, G., Perch-Nielsen, K., Premoli Silva, I., Toumarkine, M., 1982. Paleogene magnetic stratigraphy in Umbrian pelagic carbonate rocks: the Contessa sections, Gubbio. *Geol. Soc. Am. Bull.* 93, 414–432.
- Luciani, V., Giusberti, L., Agnini, C., Fornaciari, E., Rio, D., Spofforth, D.J.A., Palike, H., 2010. Ecological and evolutionary response of Tethyan planktonic foraminifera to the middle Eocene climatic optimum (MECO) from the Alano section (NE Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 292, 82–95.
- Luterbacher, H.P., Ali, J.R., Brinkhuis, H., Gradstein, F.M., Hooker, J., Monechi, S., Ogg, J.G., Powell, J., Röhl, U., Sanfilippo, A., Schmitz, B., 2004. The Paleogene Period. In: Gradstein, F., Ogg, J., Smith, A. (Eds.), *A Geologic Time Scale 2004*. Cambridge University Press, pp. 384–408.
- Lyle, M., Raffi, I., Pälike, H., Nishi, H., Gamage, K., Klaus, A., the Expedition 320/321 Scientists, 2009. *Pacific Equatorial Transect IODP Preliminary Report 321*. doi:10.2204/iodp.pr.321.2009.
- McGowan, B., 2005. *Biostratigraphy: Microfossils and Geological Time*. Cambridge University Press, Cambridge. 459 pp.
- McGowan, B., Berggren, W.A., Hilgen, F., Steininger, F., Aubry, M.-P., Lourens, L., Van Couvering, J., 2009. Neogene and Quaternary coexisting in the geological time scale: the inclusive compromise. *Earth Sci. Rev.* 96, 249–262.
- Miller, K.G., Aubry, M.-P., Khan, M.J., Meililo, A.J., Kent, D.V., Berggren, W.A., 1985. Oligocene–Miocene biostratigraphy, magnetostratigraphy, and isotope stratigraphy of the western North Atlantic. *Geology* 13, 257–261.
- Miller, K.G., Feigenson, M.D., Wright, J.D., Clement, B.M., 1991. Miocene isotope reference section, Deep Sea Drilling Project Site 608: an evaluation of isotope and biostratigraphic resolution. *Paleoceanography* 6, 33–52.
- Miller, K.G., Browning, J.V., Aubry, M.-P., Wade, B.S., Katz, M.E., Kulpecz, A.A., Wright, J.D., 2008. Eocene–Oligocene global climate and sea-level changes: St. Stephens Quarry, Alabama. *Geol. Soc. Am. Bull.* 120, 34–53.
- Mix, A.C., Le, J., Shackleton, N.J., 1995. Benthic foraminiferal stable isotope stratigraphy of Site 846: 0–1.8 Ma. In: Pisias, N.G., Mayer, L.A., Janecek, T.R., Palmer-Julson, A., van Andel, T.H. (Eds.), *Proceeding of the Ocean Drilling Program: Scientific Results*, 138, pp. 839–854.
- Molina, E., Alegret, L., Apellaniz, E., Bernaola, G., Caballero, F., Dinares-Turell, J., Hardenbol, J., Heilmann-Clausen, C., Larrasoana, J.C., Luterbacher, H., Monechi, S., Ortiz, S., Orue-Etxebarria, X., Payros, A., Pujalte, V., Rodríguez-Tovar, F.J., Tori, F., Tosquella, J., Uchman, A., submitted for publication. Proposal for the Global Standard Stratotype-section and Point (GSSP) for the base of the Lutetian Stage at the Gorronatxe section (Spain). Episodes.
- Muttoni, G., Kent, D.V., 2007. Widespread formation of cherts during the early Eocene climate optimum. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 253, 348–362.
- Nicholas, C.J., Pearson, P.N., Bown, P.R., Dunkley, J., Huber, B.T., Karega, A., Lees, J.A., McMillan, I.K., O'Halloran, A., Singano, J.M., Wade, B.S., 2006. Stratigraphy and sedimentology of the Upper Cretaceous to Paleogene Kilwa Group, Tanzania. *J. Afr. Earth Sci.* 45, 431–466.
- Olsson, R.K., 1972. Growth changes in the *Globorotalia fohsi* lineage. *Eclogae Geol. Hel.* 65 (1), 165–184.

- Olsson, R.K., Hemleben, C., Berggren, W.A. (Eds.), 1999. Atlas of Paleocene Planktonic Foraminifera: Smithsonian Contributions to Paleobiology, 85, pp. 1–25.
- Ortiz, S., Gonzalvo, C., Molina, E., Rodríguez-Tovar, F.J., Uchman, A., Vandenberghe, N., Zeelmaekers, E., 2008. Palaeoenvironmental turnover across the Ypresian–Lutetian transition at the Agost section, southeastern Spain: in search of a marker event to define the Stratotype for the base of the Lutetian Stage. *Mar. Micropaleontol.* 69, 297–313.
- Ouda, K., Aubry, M.-P. (Eds.), 2003. The Upper Paleocene–Lower Eocene of the Upper Nile Valley: Part 1: Stratigraphy: *Micropaleontology*, v. 49, Supplement 1. 212 pp.
- Pälike, H., Norris, R.D., Herrle, J.O., Wilson, P.A., Coxall, H.K., Lear, C.H., Shackleton, N.J., Tripati, A.K., Wade, B.S., 2006. The heartbeat of the Oligocene climate system. *Science* 314 (5807), 1894–1898.
- Pälike, H., Nishi, H., Lyle, M., Raffi, I., Gamage, K., Klaus, A., the Expedition 320/321 Scientists, 2009. Pacific equatorial transect. IODP Preliminary Report 320. doi:10.2204/iodp.pr.320.2009.
- Payros, A., Bernaola, G., Orue-Etxebarria, X., Dinares-Turell, J., Tosquella, J., Apellaniz, E., 2007. Reassessment of the Early–Middle Eocene biomagnetostratigraphy based on evidence from the Gorrondatxe section (Basque Country, western Pyrenees). *Lethaia* 40, 183–195.
- Payros, A., Orue-Etxebarria, X., Bernaola, G., Apellaniz, E., Dinarès-Turell, J., Tosquella, J., Caballero, F., 2009. Characterization and astronomically calibrated age of the first occurrence of *Turborotalia frontosa* in the Gorrondatxe section, a prospective Lutetian GSSP: implications for the Eocene time scale. *Lethaia* 42, 255–264.
- Pearson, P.N., 1995. Planktonic foraminifer biostratigraphy and the development of pelagic caps on guyots in the Marshall Islands Group. In: Haggerty, J., Premoli Silva, I., Rack, F., McNutt, M.K. (Eds.), *Proceeding of the Ocean Drilling Program: Scientific Results*, 144, pp. 21–59.
- Pearson, P.N., 1998. Evolutionary concepts in biostratigraphy. In: Doyle, P., Bennett, M.R. (Eds.), *Unlocking the Stratigraphical Record*. John Wiley & Sons, New York, pp. 123–144.
- Pearson, P.N., Chaisson, W.P., 1997. Late Paleocene to middle Miocene planktonic foraminifer biostratigraphy of the Ceara Rise. In: Shackleton, N.J., Curry, W.B., Richter, C., Bralower, T.J. (Eds.), *Proceeding of the Ocean Drilling Program: Scientific Results*, 154, pp. 33–68.
- Pearson, P.N., Wade, B.S., 2009. Taxonomy and stable isotope paleoecology of well-preserved planktonic foraminifera from the uppermost Oligocene of Trinidad. *J. Foramin. Res.* 39, 191–217.
- Pearson, P.N., Nicholas, C.J., Singano, J.M., Bown, P.R., Coxall, H.K., van Dongen, B.E., Huber, B.T., Karega, A., Lees, J.A., Msaky, E., Pancost, R.D., Pearson, M., Roberts, A.P., 2004. Paleogene and Cretaceous sediment cores from the Kilwa and Lindi areas of coastal Tanzania: Tanzania Drilling Project Sites 1 to 5. *J. Afr. Earth Sci.* 39, 25–62.
- Pearson, P.N., Olsson, R.K., Huber, B.T., Hemleben, C., Berggren, W.A. (Eds.), *Atlas of Eocene Planktonic Foraminifera*, Cushman Foundation Special Publication, 41.
- Poore, R.Z., Berggren, W.A., 1975. Late Cenozoic planktonic foraminiferal biostratigraphy and paleoclimatology of Hatton–Rockall Basin, DSDP Site 116. *J. Foramin. Res.* 5, 270–293.
- Premoli Silva, I., Spezzaferri, S., 1990. Paleogene planktonic foraminifer biostratigraphy and paleoenvironmental remarks on Paleogene sediments from Indian Ocean Site, Leg 115. In: Duncan, R.A., Backman, J., Peterson, L.C., et al. (Eds.), *Proceeding of the Ocean Drilling Program: Scientific Results*, 115, pp. 277–314.
- Pujol, C., Duprat, J., 1983. Quaternary planktonic foraminifera of the southwestern Atlantic (Rio Grande Rise) Deep Sea Drilling Project Leg 72. In: Barker, P.F., Carlson, R.L., Johnson, D.A., et al. (Eds.), *Initial Reports of the Deep Sea Drilling Project 72*. U.S. Govt. Printing Office, Washington, pp. 601–615.
- Rögl, F., Egger, H., 2010. The missing link in the evolutionary origin of the foraminiferal genus *Hantkenina* and the problem of the lower–middle Eocene boundary. *Geology* 38, 23–26.
- Shackleton, N.J., Crowhurst, S., 1997. Sediment fluxes based on an orbitally tuned time scale 5 Ma to 14 Ma, Site 926. In: Shackleton, N.J., Curry, W.B., Richter, C., Bralower, T.J. (Eds.), *Proceeding of the Ocean Drilling Program: Scientific Results*, 154, pp. 69–82.
- Shackleton, N.J., Berger, A., Peltier, W.R., 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Philosophical Transactions of the Royal Society of Edinburgh, Earth Sciences* 81, 251–261.
- Shackleton, N.J., Baldauf, J.G., Flores, J.-A., Iwai, M., Moore Jr., T.C., Raffi, I., Vincent, E., 1995. Biostratigraphic summary for Leg 138. In: Pisias, N.G., Mayer, L.A., Janacek, T.R., et al. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, TX (Ocean Drilling Program), 138, pp. 517–536.
- Shackleton, N.J., Crowhurst, S.J., Weedon, G.P., Laskar, J., 1999. Astronomical calibration of Oligocene–Miocene time. *Philosophical Transactions of the Royal Society of London Series A-Mathematical Physical and Engineering Sciences* 357, 1907–1929.
- Shipboard Scientific Party, 1988. Sites 677 and 678. In: Becker, K., Sakai, H., et al. (Eds.), *Proceedings of the Ocean Drilling Program, Initial Reports* 111, pp. 253–346.
- Shipboard Scientific Party, 2002. Site 1218. In: Lyle, M., Wilson, P.A., Janacek, T.R., et al. (Eds.), *Proceedings of the Ocean Drilling Program, Initial Reports*, 199: College Station, TX (Ocean Drilling Program).
- Shipboard Scientific Party, 2004. Site 1264. In: Zachos, J.C., Kroon, D., Blum, P., et al. (Eds.), *Proceedings of the Ocean Drilling Program, Initial Reports*, 208: College Station, TX (Ocean Drilling Program), pp. 1–73.
- Spezzaferri, S., 1994. Planktonic foraminiferal biostratigraphy of the Oligocene and lower Miocene in the oceanic record. An overview. *Palaeontographia Italica* 81, 1–187.
- Srinivasan, M.S., Chaturvedi, S.N., 1992. Neogene planktonic foraminiferal biochronology of the DSDP sites along the Ninetyeast Ridge, northern Indian Ocean. In: Ishizaki, K., Saito, T. (Eds.), *Centenary of Japanese Micropaleontology*, pp. 175–188.
- Srinivasan, M.S., Kennett, J.P., 1981a. A review of Neogene planktonic foraminiferal biostratigraphy: applications in the equatorial and South Pacific. In: Warne, J.E., Douglas, R.G., Winterer, E.L. (Eds.), *The Deep-Sea Drilling Project: A Decade of Progress: Spec. Publ.–Soc. Econ. Paleontol. Mineral.*, 32, pp. 395–432.
- Srinivasan, M.S., Kennett, J.P., 1981b. Neogene planktonic foraminiferal biostratigraphy and evolution: equatorial to subantarctic South Pacific. *Mar. Micropaleontol.* 6, 499–533.
- Srinivasan, M.S., Sinha, D.K., 1992. Late Neogene planktonic foraminiferal events of the southwest Pacific and Indian Ocean: a comparison. In: Tsuchi, R., Ingle Jr., J.C. (Eds.), *Pacific Neogene: Environment, Evolution and Events*. Univ. Tokyo Press, Tokyo, pp. 203–220.
- Stainforth, R.M., Lamb, J.L., Luterbacher, H., Beard, J.H., Jeffords, R.M., 1975. Cenozoic planktonic foraminiferal zonation and characteristics of index forms: University of Kansas paleontological contributions. Article 62, 1–425.
- Steininger, F.F., Aubry, M.P., Berggren, W.A., Biolzi, M., Borsetti, A.M., Brzobohaty, R., Cartledge, J.E., Cati, F., Corfield, R., Gelati, R., Iaccarino, S., Mödden, C., Napoleone, D., Nolf, F., Ottner, B., Reichenbacher, B., Rögl, F., Roetzel, R., Spezzaferri, S., Tateo, F., Villa, G., Wielandt, U., Zevenboom, D., Zorn, I., 1997. The global stratotype section and point the GSSP for the base of the Neogene (the Paleogene/Neogene boundary). *Episodes* 20, 23–28.
- Stott, L.D., Kennett, J.P., 1990. Antarctic Paleogene planktonic foraminifer biostratigraphy: ODP Leg 113, Sites 689 and 690. In: Barker, P.F., Kennett, J.P., et al. (Eds.), *Proceedings of the Ocean Drilling Program 113*. Ocean Drilling Program. College Station, Texas, pp. 549–569.
- Subbotina, N.N., 1953. Iskopaemye foraminifery SSSR (Globigerinidy, Hantkeninidy i Globorotaliidy): *Trudy Vsesoyznogo Nauchno-Issledovatel'skogo Geologo-razvedochnogo Instituta (VNIGRI)*, 76, GOSTOPETEKHIZDAT, Leningrad, 295 p. Translated into English by E. Lees, 1971, *Fossil Foraminifera of the USSR: Globigerinidae, Hantkeninidae and Globorotaliidae*: Collet's Ltd., London and Wellingborough, 321 p.
- Thompson, P.R., Bé, A.W.H., Duplessy, J.-C., Shackleton, N.J., 1979. Disappearance of pink-pigmented *Globigerinoides ruber* at 120, 000 yr BP in the Indian and Pacific oceans. *Nature* 280, 554–558.
- Thunell, R., 1981. Late Miocene–early Pliocene planktonic foraminiferal biostratigraphy and paleoceanography of low-latitude marine sequences. *Mar. Micropaleontol.* 6, 71–90.
- Turco, E., Bambini, A.M., Foresi, L.M., Iaccarino, S., Lirer, F., Mazzei, R., Salvatorini, G., 2002. Middle Miocene high resolution calcareous plankton biostratigraphy at Site 926 (Leg 154, equatorial Atlantic Ocean): paleoecological and paleobiogeographical implications. *Geobios* 35, 257–276.
- Van Couvering, J.A., Castradori, D., Cita, M.B., Hilgen, F.J., Rio, D., 2000. The base of the Zanclean Stage and of the Pliocene Series. *Episodes* 23, 179–187.
- Van Couvering, J.A., Aubry, M.-P., Berggren, W.A., Gradstein, F.M., Hilgen, F.J., Kent, D.V., Lourens, L.J., McGowan, B., 2009. What, if anything, is Quaternary. *Episodes* 32, 125–126.
- Wade, B.S., 2004. Planktonic foraminiferal biostratigraphy and mechanisms in the extinction of *Morozovella* in the late Middle Eocene. *Mar. Micropaleontol.* 51, 23–38.
- Wade, B.S., Olsson, R.K., 2009. Investigation of pre-extinction dwarfing in Cenozoic planktonic foraminifera. In: Wade, B.S., Twitchett, R. (Eds.), *Extinction, Dwarfing and the Lilliput Effect: Palaeogeography, Palaeoclimatology, Palaeoecology*, Special Issue, 284, pp. 39–46.
- Wade, B.S., Pälike, H., 2004. Oligocene climate dynamics. *Paleoceanography* 19, PA4019. doi:10.1029/2004PA001042.
- Wade, B.S., Pearson, P.N., 2008. Planktonic foraminiferal turnover, diversity fluctuations and geochemical signals across the Eocene/Oligocene boundary in Tanzania. *Mar. Micropaleontol.* 68, 244–255.
- Wade, B.S., Berggren, W.A., Olsson, R.K., 2007. The biostratigraphy and paleobiology of Oligocene planktonic foraminifera from the equatorial Pacific Ocean (ODP Site 1218). *Mar. Micropaleontol.* 62, 167–179.
- Weaver, P.P.E., Clement, B.M., 1987. Magnetobiostratigraphy of planktonic foraminiferal datums, DSDP Leg 94, North Atlantic. In: Ruddiman, W.F., Kidd, R.B., Thomas, E., et al. (Eds.), *Init. Repts. DSDP, 94*. U.S. Govt. Printing Office, Washington, pp. 815–829.
- Zhang, J., Miller, K.G., Berggren, W.A., 1993. Neogene planktonic foraminiferal biostratigraphy of the northeastern Gulf of Mexico. *Micropaleontology* 39, 299–326.
- Zijderveld, J.D.A., Hilgen, F.A., Langeres, C.G., Verhallen, P.J.J.M., Zachariasse, W.J., 1991. Integrated magnetostratigraphy and biostratigraphy of the upper Pliocene–lower Pleistocene from the Monte Singa and Crotona areas in Calabria, Italy. *Earth and Planetary Science Letters* 107, 697–714.