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Chapter 2

OLIGOCENE CHRONOSTRATIGRAPHY AND PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY: HISTORICAL REVIEW AND CURRENT STATE-OF-THE-ART

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ABSTRACT

We review past and recent advances in Oligocene chronostratigraphy (and its internal subdivisions) and geochronology, the so-called "missing" Oligocene debate of the 1960s, and planktonic foraminiferal biostratigraphies of (sub)tropical and austral biogeographies. The Oligocene spans the interval from Chron C13r.0.14 to Subchron C6Cn.2n$_{(o)}$, corresponding to astronomical cycles 84$_{\text{Ol-C13n}}$ to 58$_{\text{Ol-C6Cn}}$. It is currently subdivided into two (Rupelian and Chattian) ages/stages. The planktonic foraminiferal biostratigraphy is characterized by a 7-fold (sub) tropical and 4-fold austral zonation, respectively.

INTRODUCTION

We present an overview of Oligocene chronostratigraphy and planktonic foraminiferal biostratigraphy. We have divided this paper into two parts: Part 1: in view of the rather complex and colorful history that has characterized the Oligocene we consider it appropriate, and opportune, to provide an abbreviated review of the vicissitudes that Oligocene chronostratigraphy and planktonic foraminiferal biostratigraphy have experienced; Part 2: the second part of this paper includes an updated planktonic foraminiferal biostratigraphic framework and its calibration to magnetostratigraphic and astronomic geochronologies (based on Wade and others, 2011). As the *Atlas of Oligocene Planktonic Foraminifera* (this work) incorporates coverage of planktonic foraminiferal taxa that extend above/beyond the Oligocene/Miocene boundary we include the zonal biostratigraphy from mid-Miocene Zone M5/N8 to upper Eocene Zone E15. This paper has been accordingly prepared to serve as a background to, and framework for, the data presented in this *Atlas of Oligocene Planktonic Foraminifera*.

Part 1: OLIGOCENE CHRONOSTRATIGRAPHY

The Oligocene was introduced by Beyrich (1854) for marine, brackish, freshwater and continental sediments/strata in northern Europe believed to lie stratigraphically between the Eocene and Miocene of Lyell (1833). The internal (chrono)stratigraphic subdivision (Lattorfian, Rupelian and Chattian Stages and their equivalents in the Paris and Aquitaine Basins and elsewhere) and boundary denotation(s) engaged European stratigraphers throughout the 19th and well into the 20th century. Lyell never recognized the Oligocene of Beyrich (1854), although he discussed it at length (Lyell, 1857). In substituting the term "lower Miocene" for what had been heretofore called "upper Eocene" and transferring to it several units (e.g., the Hempstead Beds of England and the Fontainebleau Sands and *Calcaire de Beauce* of the Paris Basin and "Oligocene" strata of northern Germany), Lyell's action may be seen as having been an attempt to sidestep Beyrich: rather than accept the inclusion of a new term to the exclusive Lyellian hagiography of standard Cenozoic periods, he chose a more convoluted solution. Alternatively, Lyell may have simply wished to get the classification right to his way of thinking. One may wonder what Lyell might have thought when Schimper (1874), a year before Lyell's death, introduced the term Paleocene below his Eocene and included, *inter alia*, several of his favorite lower Eocene units.

Historical reviews of the term Oligocene have been presented by Csepreghy-Meznerics (1964a, b), Korobkov (1964) and Berggren (1971a). The reader is cautioned, however, to read carefully the review and critique by Drooger (1964) of problems associated with mid-Tertiary correlations and in particular with those of Eames and others (1962) and the (unfortunate and misguided) attempt by Csepreghy-Meznerics (1964a, b) to equate the Chattian and Aquitanian Stages!

Below we review the chronostratigraphic subdivisions/boundaries of the Oligocene.

THE EOCENE/OLIGOCENE BOUNDARY

The Global Stratotype Section and Point (GSSP) of the E/O boundary is located at the 19 m level in the Massignano Quarry section in the northern Apennines near Ancona (Odin and Montanari, 1988; Premoli Silva and others, 1988 a, b; Premoli Silva and Jenkins, 1993) and was ratified by the IUGS at the 29th International Geological Congress (Kyoto) in 1992. It was denoted by the stratigraphically highest occurrence (HO) and last appearance datum (LAD) of the planktonic foraminiferal genus *Hantkenina* (Nocchi and others, 1988) at Chron C13r (0.14) (= top of Zone E16 of Berggren and Pearson, 2005, 2006) and is also linked with (and slightly above) the HO of the *Turborotalia cerroazulensis* and related forms (Toumarkine and Bolli, 1970; Toumarkine and Luterbacher, 1985; Berggren and Pearson, 2005, 2006). Note, Zone P17 (by Berggren and others, 1995) is not a valid biostratigraphic zone (see Berggren and Pearson, 2005). Unfortunately, no reference was made at the time to stage-level boundaries (Priabonian, Rupelian; upon which the higher order categories are dependent) or to the geohistorical framework that formed the basis of this decision (Pomerol and Premoli Silva, 1986; Premoli Silva and others, 1988 a,b), opening the lid on a veritable Pandora's Box of complications which are too lengthy to discuss here but have been reviewed elsewhere (Brinkhuis, 1992; Berggren, 2007; Fluegeman, 2007; Coxall and Pearson, 2007). Nevertheless, pertinent observations are:

a. Subsequent dinoflagellate cyst biostratigraphy (Brinkhuis, 1992; Brinkhuis and Biffi, 1993; Brinkhuis and Visscher, 1995) revealed that the E/O boundary GSSP level at Massignano is stratigraphically correlative with a level within the middle to upper part of the Priabonian limestones of Priabona and ~10m below the top of the Bryozoan Limestone (Jaramillo-Vogel and others, 2012), commonly accepted as the highest stratigraphic unit of the Priabonian Stage! The base of the standard Rupelian Stage of Belgium would appear to be stratigraphically correlative with the top of the Bryozoan Limestone of Priabona (just below the contact with Rupelian denominative *Nummulites fichteli*) and cycle TA4.4, magnetochron C13n and the $\delta^{18}O$ maximum commonly referred to as "Oi-1" (Miller and others, 1991; see Coxall and Pearson, 2007, for a discussion of this term) with an estimated age ~0.2 myr younger than the designated GSSP level at Massignano at Chron C13r. 0.14.

b. Dinocyst stratigraphic studies on a 39 m corehole, 'Massicore', near Massignano (Van Mourik and Brinkhuis, 2005) have correlated the E/O GSSP level to level 19.95 m (coredepth). These authors questioned the utility of the *Hantkenina* extinction for long-distance correlation, suggesting that it is locally controlled or diachronous, although no evidence was presented in support of that assertion. They also argued for the selection of the $\delta^{18}O$ increase (Oi-1) as the denotative criterion of the E/O boundary (base Rupelian) as marked by the LAD of the dinocyst *Aerosphaeridium diktyoplokum*. Van Mourik and Brinkhuis (2005) also observed that the Oi-1 isotopic shift is NOT visible/present in the Massignano Quarry outcrop requiring a new/revised GSSP in a more complex section. However these suggestions are problematic in several respects: Oi-1 is not an "event" but an "interval", at least as originally defined by Miller and others (1991), and given that it has been used in several different senses, as an isotope zone, an isotope shift or excursion and as an isotope maximum, its precise meaning would need to be defined (see Coxall and Pearson, 2007, for discussion). The LAD of *A. diktyoplokum* occurs at a considerably higher level in the section than the level correlative with the isotope excursion, i.e. near the top of Chron C13n rather than its base (as pointed out by Coxall and Pearson, 2007). The Hantkeninidae extinction is actually five simultaneous extinctions (four species of *Hantkenina* and one of *Cribrohantkenina*; Pearson and others, 2008; Wade and Pearson, 2008). The closely spaced *Hantkenina* and *Turborotalia* biohorizons can be correlated globally except in the high latitudes and their positions relative to the oxygen and carbon isotope stratigraphy have now been determined (Pearson and others, 2008). Moreover, the GSSP level also corresponds precisely to the last common occurrence and size reduction of the planktonic foraminifer *Pseudohastigerina micra* which provides an alternative means of correlation if *Hantkenina* is absent (Wade and Pearson, 2008; Miller and others, 2008; Wade and Olsson, 2009; Wade and others, 2011). Finally, recent evidence from Tanzania suggests that the coordinated extinction of several groups of larger foraminifera (*Asterocyclina*, *Discocyclina*, some species of *Nummulites*) is closely correlative with the extinction of the Hantkeninidae (and hence the GSSP level) rather than the higher/subsequent oxygen isotope maximum, indicating that the environmental changes associated with the Eocene / Oligocene boundary proper affected more than just the plankton (Pearson and others, 2008; Cotton and Pearson, 2011). This affords a means of correlating the GSSP with the larger benthic foraminifera (LBF) zonal schemes for application in shallow water carbonate facies e.g., Calcar di Nago Formation in Nago and San Valentino in northern Italy (Jaramillo-Vogel and others, 2012:370, fig. 6. Note however in this figure the *Discocyclina* LAD is reported in the Oligocene, well above the LAD of *Hantkenina*), the Melinau Limestone of Sarawak (Cotton and others, 2014) and the classic Priabona section as well.

c. Fluegeman (2007) has argued for retention of the E/O boundary GSSP as currently defined at Massignano based on the fact that the stratotype remains accessible and that there has been no violation of accepted stratigraphic principles discovered after ratification of the GSSP and the fact that *Hantkenina* remains a distinct and easily identifiable component of (terminal) Eocene microfaunas, thereby lending stability to the current status quo.

The E/O (Priabonian/Rupelian Stage) boundary is associated with Chron C13r (0.14) with an age estimate of:

a. 33.7±0.7 Ma (based on a linear regression on radioisotopic ages in lower Oligocene and upper Eocene ashes in the northeastern Apennines (Montanari and others, 1988); Jovane and others (2006, 2007) derive an age of 33.714 Ma for the E/O boundary based on orbital tuning of the Massignano-Monte Cagnero record;
b. Berggren and others (1995) derived an estimated age of 33.7 Ma for the E/O boundary based on: a) an age of 65 Ma (rather than 66 Ma) for the K/Pg boundary; b) an astronomical age of 5.23 Ma for the older end of Subchron C3n.4n (Thvera Subchron; Hilgen, 1991) and a cubic spline fit to 9 calibration points (Cande and Kent, 1992) with marine biostratigraphic constraints for correlation;
c. 33.79 Ma (Pälike and others, 2006) based on astronomical tuning of the record at Ocean Drilling Program (ODP) Site 1218;
d. 33.9±0.1 Ma (based on a spline fit of 17 age estimates/dates ranging from Chron C33r (base; 84.40 Ma) to Subchron C6An.1r (base; 20.34 Ma; Agterberg, 2004).

Hilgen and Kuiper (2009) have reviewed the age data around the E/O boundary. The problems associated with deriving consistent numerical ages for the boundary are due to the fact that the current crop of ^{40}Ar/^{39}Ar ages and astronomically tuned ages are inconsistent with each other when recalculated to a revised and astronomically calibrated age for the Fish Canyon Tuff (FCT) sanidine standard, and the advisability of using the recently revised calibration of the FCT sanidine (28.201±0.022 Ma of Kuiper and others, 2008. The more recent estimated age of 28.305±0.036 Ma for the FCT by calibrating the ^{40}Ar/^{39}Ar system with current measurements of ^{40}K and ^{238}U decay constants; Renne and others, 2010) results in older ages for previously measured ashes. A recent revised astrochronologic dating/age estimate of 27.93 Ma of the early/middle

Pleistocene Matuyama/Brunhes boundary (Channell and others, 2010) results in younger ages for the FCT and previously measured ashes.

THE LOWER/UPPER OLIGOCENE (RUPELIAN/ CHATTIAN STAGE) BOUNDARY

The base of the Chattian stage has recently been defined (Coccioni and others, in press). The Rupelian and Chattian stages of the Oligocene have been studied by previous workers from exposed outcrops and subsurface cores of northern Europe (e.g., Vandenberghe and others, 2001, Van Simaeys, 2004; Van Simaeys and others, 2004). Changes in sea-level in these shallow water settings result in unconformities, and there are few complete Oligocene sections with well-preserved planktonic and benthic foraminifera, particularly through the "mid" Oligocene (~29-27 Ma). Sequence stratigraphy indicates one of the most extensive sea-level falls of the Cenozoic occurred in the "mid" Oligocene (TA-TB supercycle boundary, Haq and others, 1988). This third order sequence boundary has been correlated extensively across Oligocene sections in France and Belgium (Wilpshaar and others, 1996). More recent chronostratigraphic control has shown that this unconformity is between the top of the Rupelian and base of the Chattian (Van Simaeys and others, 2005; de Man and others, 2010) and correlates to the late Oligocene glacial maxima.

The HO of *Pseudohastigerina* in the middle part of Rupelian (Rupel 3) and the alleged HO of *Chiloguembelina* at the top of the Rupelian (Rupel 4) led Ritzkowski (1982) to suggest that the lower/upper (Rupelian/Chattian) Oligocene boundary should be placed at the biostratigraphic position of the latter, rather than the former (cf. Jenkins and Orr, 1972; Hardenbol and Berggren, 1978:fig. 4). This was followed by Berggren and others (1985b:fig. 6) and Berggren and others (1995:fig. 2). The extinction of *C. cubensis* as a reliable stratigraphic event has been questioned by Van Simaeys and others (2004). Indeed, younger occurrences of *C. cubensis* have been reported in Oligocene sections at ODP Sites 628 and 803 (Leckie and others, 1993). More recently Wade and others (2007, 2011) and Coccioni and others (2008) have confirmed that the highest common occurrence (HCO) of *C. cubensis* is a robust biostratigraphic marker for the mid-Oligocene and associated with Subchron C10n.1n with an estimated age of 28.4 Ma (as per Cande and Kent, 1995) or 28.0 Ma (as per Pälike and others, 2006; Wade and others, 2011:fig. 2b). Observations by the working group (see Chapter 17, this volume) and King and Wade (2017) confirms the persistence of rare *Chiloguembelina cubensis* beyond its HCO.

THE OLIGOCENE/MIOCENE (NEOGENE) BOUNDARY

1. In the late 1940s and early 1950s the O/M boundary was considered to be approximately equivalent to the contact between the *Globorotalia fohsi* Zone and the overlying *Globorotalia menardii* Zone (=Helvetian/ Tortonian boundary; Drooger, 1956, 1960), but it subsequently experienced a gradual lowering and became associated with a level below the Langhian Stage (lower-middle Miocene and below the *Orbulina* datum (Drooger, 1966).

2. Bolli (1957) placed the O/M bounday at the top of his *Globorotalia kugleri* Zone (corresponding to the HO of the nominate taxon) (and was initially followed by most workers in this).

3. At their initial meeting in Vienna in 1959 (and reaffirmed at their subsequent meeting in Bologna in 1967), the Committee on Mediterranean Neogene Stratigraphy (CMNS) recommended that the St. Jean d'Etampes (Moulin de l'Église-La-Brède) section in the Valley of Saucats, Aquitaine Basin of southwest France be accepted as the stratotype of the Aquitanian Stage and to define the base of the Miocene.

4. Blow and Banner (1962) and Banner and Blow (1965) placed the O/M boundary at the base of their Zone P20-N1 (*Globigerina ampliapertura* Zone). Subsequently, Blow (1969), following the recommendations of the CMNS, considered that the base of the stratotype Aquitanian =Miocene) lies near the base of the *G. kugleri* Zone (his Zone N4; at the supposed first appearance datum (FAD) of *Globigerinoides primordius*) (Fig. 1).

5. Jenkins (1964, 1966) recorded the taxa *angulisuturalis* and *ciperoensis* in the lower Aquitanian stratotype in southwest France and placed the O/M boundary between the *opima* and *ciperoensis* Zones (N2 and N3) of Banner and Blow (1965).

6. Saito and Bé (1964) placed the O/M boundary

within the *opima* Zone based on the occurrence of the bryozoan *Cupuladria canariensis* Lagaaij (Lagaaij, 1963), considered at the time indicative of the O/M boundary in the U.S. Gulf Coast, Caribbean and Europe. This was essentially the same level at which Berggren (1963) considered the O/M boundary to lie at the time.

7. Berggren (1969) studied the planktonic foraminifera from the stratotype localities of the Rupelian and Chattian Stages of the Netherlands and northern Germany, respectively. His results suggested that:

a. the upper Chattian is still pre-Zone N2 and probably in the uppermost part of Zone N1; the top of the Chattian was provisionally equated with the N1/N2 boundary;
b. there are probably either one or two planktonic foraminiferal zones (N2-N3 [= P21-22 of Blow, 1969, 1979; Berggren and Miller, 1988; = O4-O7 of Wade and others, 2011]) between the Aquitanian Stage s.s. (stratotypified in the Tethyan realm of SW France) and the Chattian Stage s.s. (stratotypified in the boreal realm of northern Germany).

Berggren (1969) suggested alternative possibilities for determination of the O/M boundary:

a. equating the base Aquitanian Stage with the base of the *ciperoensis* Zone (N3) or the *Globorotalia kugleri* (N4) Zone. The top of the Oligocene (Chattian) could then be extended upward to include the *G. opima* (N2) Zone, and perhaps Zone N3 with the boundary being placed between either N2/3 or N3/4 on the basis of the principle that "base defines stage".
b. equating the base Aquitanian Stage with the top of the Chattian in the area of the type Chattian, i.e., approximately top of Zone N1. The boundary would then be placed between Zones N1/N2.

8. Delineation and correlation of Zone N4 to the base of the Aquitanian Stage (=base Neogene) proved difficult to resolve for the following reasons:

a. Contrary to Blow (1969:25; 1979:fig. 53), Berggren and others (1983) and Berggren and others (1985b:191) found that the genus *Globigerinoides* appeared within Chron C7n (~25.8 Ma) roughly 2 myr prior to *Globorotalia kugleri* s.s. within Subchron C6n.2n (~23.7 Ma) (cf. Bolli and Saunders, 1985:165) and required a redefinition of Zone N4 (*Globigerinoides primordius/Globorotalia kugleri* Concurrent-range Zone) based on the supposed lowest occurrence (LO) of *G. primordius* within the range of *G. kugleri*. Indeed, Stainforth and Lamb (1981:10, 11) recognized that the LO of *Globigerinoides quadrilobatus primordius* was within the range of *Globorotalia kugleri* s.l. (incl. *G. mendacis* and *G. pseudokugleri*).
b. With the recognition that late Oligocene forms of *kugleri* s.l., are in fact, referable to *Paragloborotalia pseudokugleri* (FAD in Chron C8n; 25.9 Ma) and the insertion/introduction of the *Paragloborotalia pseudokugleri* (Zone O7) above the (amended) *Globigerina ciperoensis* (O6) Zone (Wade and others, 2011), the dilemma appears to have been resolved. However it is important that a relatively broad concept of *P. pseudokugleri* is taken (to include the relatively 'advanced' morphology of the holotype (Pearson and Chaisson, 1997; Pearson and Wade, 2009; Chapter 5, this volume)

9. The GSSP of the O/M boundary is now placed at the 35 m level (as measured down from the top) in the Lemme–Carrosio section of northern Italy, associated with a (questionable) Subchron C6Cn.2n (see comment by Langereis in Shackleton and others, 2000:450), 2 m below the LO of *Paragloborotalia kugleri,* and bracketed by the LO and HO of *Sphenolithus delphix* 12 m below and 4 m above the boundary level, respectively (Steininger, 1997; Steininger and others, 1997). The LO of *P. kugleri* is within Subchron C6Cn.2n (Steininger and others, 1997). Thus the uppermost Oligocene Zone O7 extends into the Miocene and there is a short stratigraphic interval between the base of the Miocene as designated by the base of Subchron C6Cn.2n and the LO of *P. kugleri* (Wade and others, 2011).

a. Several sites were drilled across the Oligocene/Miocene boundary during ODP Leg 154 (Ceara Rise, western equatorial Atlantic Ocean). Planktonic foraminiferal and nannofossil biostratigraphy was provided by Pearson and Chaisson (1997) and Backman and Raffi (1997). The sites lack magnetostratigraphy but do possess a well-defined cyclostratigraphy, especially through the Miocene and Oligocene (Weedon and others, 1997). Shackleton and others (1999) derived an orbitally tuned age (~0.9 m. yr.) younger for the FAD of *Paragloborotalia kugleri* (= O/M boundary) than that (23.8 Ma) in Berggren and others (1995).

b. The orbitally tuned age of the O/M boundary at Subchron C6Cn.2n was subsequently modified (Shackleton and others, 2000) to 22.92±0.04 Ma (conservatively expressed as 22.9±0.1 Ma) based on linear extrapolation of Astronomical Time Scale (ATS) derived ages at DSDP Site 522 (South Atlantic Ocean) of the FAD and LAD of the short-lived *Sphenolithus delphix* and the FAD of *S. disbelemnos*.

c. Tuning of the ATS at ODP Site 926 (Ceara Rise, equatorial western Atlantic Ocean) to the La_{2003} solution (Laskar and others, 2004) has since yielded a revised age estimate of the O/M boundary of 23.03 Ma (Lourens and others, 2004:410, 413, 433-435).

d. Support for this chronology (within one obliquity cycle) over the interval of Chrons C7n through C6Bn is seen when the spline ages used by Cande and Kent (1995) are revised to the La_{2003} calculation and the ODP Site 1090 (subantarctic South Atlantic Ocean) $\delta^{18}O$ record is tuned to obliquity (Billups and others, 2004).

e. The O/M boundary occurs shortly after the isotope event/interval Mi-1 of Miller and others (1991) (see Beddow and others, 2016).

RECENT ADVANCES IN OLIGOCENE STRATIGRAPHY

Recent deep sea drilling in the equatorial Pacific Ocean (e.g., Leg 199, Expedition 320/321) has significantly advanced Oligocene chronostratigraphy. ODP Site 1218 drilled an expanded Oligocene sedimentary succession, with orbital cycles (Wade and Pälike, 2004; Pälike and others, 2006), biostratigraphy (Wade and others, 2007; King and Wade, 2017) and an uninterrupted set of geomagnetic chrons (Lanci and others, 2005). High resolution (<6 kyr) benthic and planktonic foraminiferal oxygen isotopes (Wade and Pälike, 2004; Pälike and others, 2006), coupled with lithological cycles, contain the full suite of orbital (Milankovitch) cycles and have led to the extension of the astronomical age calibration and an orbitally tuned magnetochronology for the Oligocene (Pälike and others, 2006). Further refinements have been made through the integration of bio-, chemo- and magnetostratigraphic data from multiple sites (Westerhold and others, 2012).

Wade and Pälike (2004) initiated a new cycle naming scheme, based on Earth's long term eccentricity cycle (405 kyr), which is considered the most stable orbital component over geological time (Laskar, 1999). The cycles are defined by the 405 kyr minima from Laskar and others (2004), starting with count number 1 for the most recent cycle, and increasing in number back in time. Each cycle is subscripted by the geological epoch and magnetochron.

Planktonic foraminiferal zonal boundaries for the entire Cenozoic are reported to the astronomical cycles of Wade and Pälike (2004) in Wade and others (2011), though few of these bioevents have yet been tested in records with an orbitally tuned chronology. One of the exceptions is the important Oligocene biostratigraphic marker, the HO of *Paragloborotalia opima*, which is calibrated to cycle $67_{\text{Ol-9n}}$ (Wade and others, 2011) and within an obliquity cycle to 26.923±0.00039 myr (Wade and others, 2007).

SUMMARY OF OLIGOCENE CHRONOSTRATIGRAPHY

The Oligocene spans ~10.7 to 10.9 myr and ranges around 33.7 - 33.9 Ma to 23.0 Ma, corresponding to astronomical cycles $84_{\text{Ol-C13n}}$ to $58_{\text{Ol-C6Cn}}$ (Pälike and others, 2006; Wade and others, 2011). Additional information/historical review of problems associated with delineating the Oligocene/Miocene boundary on the basis of calcareous plankton can be found in Berggren and others (1985c:216-220).

THE " MISSING" OLIGOCENE

The 1960s was a period of social experimentation and civic disturbance which was echoed in the world of stratigraphy by the dramatic announcement by a quartet of British Petroleum (BP) paleontologists that the Oligocene Series was missing in the Caribbean (including the US Gulf Coast) and Tethyan regions (Eames and others, 1960, 1962; see also rebuttal by Stainforth and defense by Eames and others, in Stainforth,1960a, b). The most controversial aspects/conclusions of the study include the suggestion of: 1) a major unconformity/hiatus within the (upper Eocene) San Fernando Formation in Central Trinidad; 2) a major unconformity/hiatus between the Jackson and Vicksburg Formations of the Gulf Coast and assignment of the latter to the lower Miocene (Aquitanian) based on the absence of true *Nummulite*s in Vicksburg beds; 3) the absence of "newly described" Oligocene planktonic foraminiferal faunas/zones from East Africa of Blow and Banner (1962) in Central America; 4) the correlation of Caribbean *Globorotalia fohsi-G. fohsi lobata* and *G. fohsi robusta* Zones with the Burdigalian Stage; 5) the evolution of *Orbulina* within the uppermost Aquitanian of the Mediterranean and Australia and in the upper "e" stage of the LBF zonation of the Far East; and 6) the LBF *Pliolepidina* in Trinidad and Venezuela (of late Eocene age), interpreted by Eames and others (1960, 1962) as indicative of Miocene (Aquitanian) age. On the basis of an exhaustive literature review and new analysis of LBF and planktonic foraminifera of the Caribbean-Central America the authors indicate that "few of them can be correlated with any Oligocene faunas in the Old World, but that almost all can be correlated with Old World Miocene faunas. No restricted Old World Oligocene fossils of any group have as yet been recorded from marine beds in Central America" (Eames and others, 1962:1). In actual fact Eames (1953, 1954, 1955) had expressed doubts about the evidence for the development of "Oligocene" in earlier papers and stated that he had reservations on the subject for "nearly 30 years" (Eames in Eames and others, 1962:22). However, it was not until the early 1960s that these reservations/doubts were given full expression (in print).

Needless to say a vigorous debate ensued on this issue. Rather mild reviews/comments on the controversial paper were made by Berggren (1963) and more animated and critical comments on the issue by Stainforth (1960a, b), Drooger (1964), Szöts and others (1962) and Szöts (1964). Indeed, the latter authors showed that the characteristic Oligocene-lower Miocene zones *Globigerina ampliapertura-Catapsydrax stainforthi* of the Caribbean region (Cipero Formation, Trinidad) occur in the Leon 3 well of the Aquitaine Basin in contradistinction to the interpretation(s) of Eames and others (1960, 1962). (It should be recalled that, in agreement with Stainforth (1960a) they placed the O/M boundary in the *Globigerinatella insueta* Zone, now linked with the Burdigalian; Berggren and others, 1985a, 1995; Lourens and others, 2004.) Indeed, Banner and Eames (1966) still argued as late as the mid-1960s that the Oligocene was essentially absent in the Gulf Coast-Caribbean area. Finally, on the occasion of the First International Conference on Planktonic Microfossils held in Geneva (1967), Stainforth and Blow amicably "buried the hatchet"; Stainforth observed/convinced the BP paleontologists that the *Pliolepidina*-rich Peñas Blancas limestones and overlying Roblecito Shale of Eastern Venezuela are an upper Eocene-Oligocene (not Miocene) sequence, while at the same time conceding that the O/M boundary may indeed be lower than his (now) preferred choice/preference at the base of Zone N4 (i.e., LO of *Globorotalia kugleri* = *Paragloborotalia pseudokugleri*), even as low as the "N2" or "*opima*" level. For his part Blow stated that he now accepted "the recommendation of the Comité du Néogène to denote the O/M boundary by the *Globigerinoides*-datum" (Blow, 1969:420) while maintaining, as had Stainforth, that some faunal elements of the Zone N2-N3 interval do exhibit Neogene, rather than Paleogene, affinities (see also McGowran and others, 2009:256). The complete text of the discussion by Blow and Stainforth can be seen in Blow, 1969:419-420). Subsequent studies of some larger foraminifera from Central Americas further clarified this issue (Eames and others, 1968).

More recent work has shown the faunal/floral affinities, regional/global correlation and temporal/ATS values of stage boundaries of the Oligocene, but it is well to remember the complex historical vicissitudes that returned the instability of the 1960s to the present day (relatively) stable chronostratigraphy.

We reaffirm our preference for retaining the terms Paleogene and the historically justified Miocene-Recent Neogene (see Appendix by Steininger in McGowran and others, 2009:256-259) at Period level in a flexible hierarchy in which the late Pliocene and early and late Pleistocene comprise the Quaternary Subperiod (with the concomitant loss/elimination of the Tertiary) as cogently argued by Hilgen (2008), Lourens (2008), Aubry and others (2009) and McGowran and others (2009).

PART 2: PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY

The use of planktonic foraminifera in the age-determination and correlation of tropical and subtropical, marine, Oligocene stratigraphies was mostly conducted in conjunction with, or as part of, attempts to develop/improve upon Paleogene and/or Paleogene-Neogene correlations and has been a mostly post-World War II enterprise essential to petroleum exploration in the Caribbean region (Cushman and Stainforth, 1945; Stainforth 1948, Bolli, 1957, 1966; Blow, 1969, 1979).

Since then zonal schemes have been developed for all regions of the world and its oceans to encompass and reflect regional, climate-controlled biogeography. Berggren (1969), Blow (1969, 1979), Stainforth and others (1975), Poore (1984), Bolli and Saunders (1985), Berggren and Miller (1988), Spezzaferri, (1994), Berggren and others (1995), Berggren and Pearson (2005, 2006) and Wade and others (2011), have discussed and/or presented subtropical-tropical Oligocene planktonic foraminiferal biostratigraphies.

Below we present a condensed review of the main historical aspects of subtropical/tropical Oligocene planktonic foraminiferal zonation (Fig. 2.1) followed by a similar overview of recent developments in attempts to derive a satisfactory Oligocene zonation for high latitude and austral areas. Finally, we present a condensed version of the recently integrated low to mid-latitude planktonic foraminiferal biostratigraphy for the uppermost Eocene-lower Miocene (Wade and others, 2011) interval covered in this Atlas (Figs. 2.2 and 2.3) with minor modification(s) to reflect changes in generic assignment in this atlas. Primary and secondary events calibrated to multiple time scales are given in Table 2.1.

The earliest attempt to apply planktonic foraminiferal biozonation to the Oligocene, as it is now understood, was by Cushman and Stainforth (1945) and Cushman and Renz (1947) working in Trinidad (see Bolli and Saunders, 1985, for review). The first comprehensive scheme was the Trinidad zonation of Bolli (1957) who recognized for the first time the utility of three significant biohorizons within the epoch based on what were then previously undescribed species, namely LO and HO of *Globorotalia* (now *Paragloborotalia*) *opima*, and LO *Globorotalia* (now *Paragloborotalia*) *kugleri* (and/or *pseudokugleri*). These three biohorizons allowed Bolli (1957) to split the Oligocene into four zones (named the *ampliapertura*, *opima*, *ciperoensis*, and *kugleri* zones, Fig. 2.1). Bolli also recognized the stratigraphic utility of another of his new species, *Globigerina* (now *Turborotalia*) *ampliapertura*, the HO of which he placed slightly below LO of *opima* (whereas now it is placed slightly above). It is also important to note that the species *kugleri* was later divided into two species by Blow (1979) with successive LOs, namely *pseudokugleri* and *kugleri*, both of which are now regarded as important zone fossils (Wade and others, 2011). This means that the LO of *kugleri* sensu Bolli (1957) and his subsequent work up to Bolli and Saunders (1985) is conceptually the same as LO of *pseudokugleri* as now understood (Fig. 2.1).

Blow and Banner (1962) developed an alternative scheme for the lower Oligocene based on the stratigraphy of Tanzania. They employed two additional biohorizons, namely LO of *Globigerina oligocaenica* (now *Dentoglobigerina sellii*) and HO of *Pseudohastigerina micra* (which is conceptually equivalent to HO of *Pseudohastigerina naguewichiensis* in our study). They also ignited a significant controversy (described in Part 1 of this paper, above) by placing the base of the Aquitanian stage (and hence the Miocene and Neogene) at the base of their newly shortened *ampliapertura* zone. This view was reinforced by Banner and Blow (1965) who introduced for the first time an alphanumeric shorthand notation for the Neogene, starting with N1 for the (now truncated compared to Bolli's [1957]) *ampliapertura* zone (Fig. 2.1). It is now accepted that the base of the Aquitanian is at a much higher level, but the existence of this past controversy explains why Zones N1, N2 and N3 are alternatively referred to as P20, P21, and P22 in later schemes (with 'P' standing for Paleogene), and why the historical Neogene 'N' zones (e.g. Kennett and Srinivasan, 1983) start within Zone N4.

Blow and Banner (1962:68, 69) inserted the *Globigerina oligocaenica* Zone below the *Globigerina ampliapertura* Zone of Bolli (1957) that was characterized by the (supposed) total range of the nominate taxon but stated that the overlap of *Pseudohastigerina micra* and *Cassigerinella chipolensis* "seems to define the zone". This zone had a complex subsequent history (Fig. 2.1). Bolli (1966) pointed to the potential confusion in distinguishing between *oligocaenica* and related taxa such as *tapuriensis* and *binaiensis* and suggested that the most reliable way in which to distinguish/identify the lower Oligocene was the overlap of *micra* and *chipolensis,* and hence he renamed the zone the *Cassigerinella chipolensis/Pseudohastigerina micra* Zone accordingly. However, *G. oligocaenica* was subsequently shown (Blow, 1969) to be a junior synonym of *Globigerina* (=*Dentoglobigerina*) *sellii* (and to range higher in the Oligocene) and late stage *Pseudohastigerina* were recognized as a distinct species, *P. barbadoensis,* hence the name of the zone was changed to the *Globigerina sellii/Pseudohastigerina barbadoensis* (P19) Zone.

Blow (1970:265-267) cast doubt on the utility of HO *Pseudohastigerina* because of its supposedly diachronous extinction level (and to illustrate a general point that, in his view, extinction levels are less reliable for correlation than evolutionary transitions). Accordingly he formally combined Zones P19 and P20 as 'Zone P19/20', a usage which Berggren and Van Couvering (1974, 1978) and Blow (1979) followed (Fig. 2.1). Berggren and others (1985b) subsequently reinstated the *Pseudohastigerina* datum into the standard list but continued to refer to the (now truncated) zone above it as P19/20. Note that this new usage, by definition, actually excluded the interval previously recognized as Zone P19 by Blow (1969) and Berggren (1969) (Fig. 2.1): that was simultaneously subsumed into an expanded Zone P18 in their scheme. Subsequently, when the stratigraphic interval between HO *Pseudohastigerina* and HO *ampliapertura* was formally recognized, first by Spezzaferri (1994) (following Spezzaferri and Premoli Silva, 1991) and then, independently, by Berggren and others (1995), it was referred to as Zone P20 in the former and Zone P19 in the latter. This different application of the alphanumeric shorthand constitutes a potential booby trap for the stratigraphically naïve or unwary (Fig. 2.1).

For much of the history of the zonation schemes the relative positions of HO *T. ampliapertura*, LO *P. opima* and LO *C. angulisuturalis* were poorly known. Banner and Blow (1965) used LO *angulisuturalis* to define the base of their Zone N2, believing the level to be within the range of *ampliapertura* (see also discussion in Blow, 1979:295-296). Berggren and others (1995) identified a significant stratigraphic interval between HO *ampliapertura* and LO *angulisuturalis*: this is now denoted as Zone O3.

Blow (1969, 1970, 1979) formulated a zonal biostratigraphy for the Cenozoic of (predominantly) low latitude tropical-subtropical regions; the Oligocene segment of this zonation underwent a tortuous and complicated taxonomic and nomenclatural history. In its original formulation the Banner and Blow (1965) Neogene zonation extended down to the base of the Mediterranean Bormidian Stage (equivalent to the Chattian of Boreal Europe) (Zones N1–N3) which they considered to comprise the lowest part of the Neogene (Eames and others, 1960, 1962). Responding to criticism by Stainforth (1960a, b, and comment by Stainforth reported in Blow, 1969:419-420) and Berggren (1963) and the decision by the Committee on Mediterranean Neogene Stratigraphy (CMNS) in 1959 (and reinforced in 1967) to place the base of the Neogene at the base of the Aquitanian, Blow restricted the Neogene part of his (1969) and their (1965) zonation to Zones N4–N23, while designating the terminal part of the Paleogene zonation as Zones P21–P23 (= N1–N3; Blow, 1969). The remainder of the Paleogene consisted of Zones P1–P19 (Blow, 1969, 1970, 1979).

Berggren (1969) and Blow (1969:211) essentially introduced similar but separate zonal schemes for the Paleogene in 1969 (see Berggren, 1981, and Berggren and Miller, 1988:362 for an historical review of this anomalous situation). Blow (1969) introduced the *Globigerina tapuriensis* Consecutive-range Zone, subsequently amended to a Partial-range Zone (Blow, 1979:294) at the base of the Oligocene and denoted by the initial appearance of the nominate taxon (Fig. 2.1). Blow (1969:212; see also 214) noted the common occurrences of *Pseudohastigerina barbadoensis* and *P. naguewichiensis* (and relatively rare occurrence of *P. micra*) and *Cassigerinella chipolensis* as characteristic of this Zone.

The utility of the HO of *Chiloguembelina* for subdividing "Zone N2" of Banner and Blow (1965) (or Zone P21 of Blow, 1969) was recognized by Berggren (1971b) from studies of North Atlantic sediment cores (see also Berggren and Amdurer, 1973). At the same time, Jenkins and Orr (1972) recognized the same level in the Pacific Ocean and used it to subdivide Bolli's old *opima* zone into a new *Chiloguembelina cubensis* Zone (for the lower part) and a revised *Goborotalia opima* Zone (for the upper part). Berggren and Van Couvering (1974:170, fig. 15) first expressed this in alphanumeric notation as subzones P21a and P21b (although at the time it was inadvertently ascribed to Blow, 1969). These are now recognized as Zones O4 and O5 (Berggren and Pearson, 2005). Stainforth and others (1975) formulated a 4-fold Oligocene zonation essentially identical to that

FIGURE 2.1. Comparison of some low latitude zonal schemes plotted against the age of the events as now understood. Notes: [1] Prior to Blow (1979) all authors included what is now *P. pseudokugleri* within *P. kugleri* and some continued to do so afterwards, hence base *kugleri* is interpreted as base *pseudokugleri*. [2] Definition of base zone ambiguous / diachronous. [3] Interval of 'P17' is no longer recognized because *Cribrohantkenina* ranges higher than *Turborotalia*. [4] Berggren and others (1985b) reads 'N4' or P22 in error. [5] Scheme partly follows Berggren and Van Couvering (1974). *kug* = *kugleri*, *deh* = *dehiscens*, *pse* = *pseudokugleri*, *opi* = *opima*, *cub* = *cubensis*, *angu* = *angulisuturalis*, *amp* = *ampliapertura*, *nag* = *naguewichiensis*, *ala* = *alabamensis*, *ind* = *index*, *tri* = *trilobus*, *pri* = *primordius*, *angi* = *angiporoides*, *sel* = *sellii*, *cer* = *cerroazulensis*, *coc* = *cocoaensis*. BU. = Burdigalian.

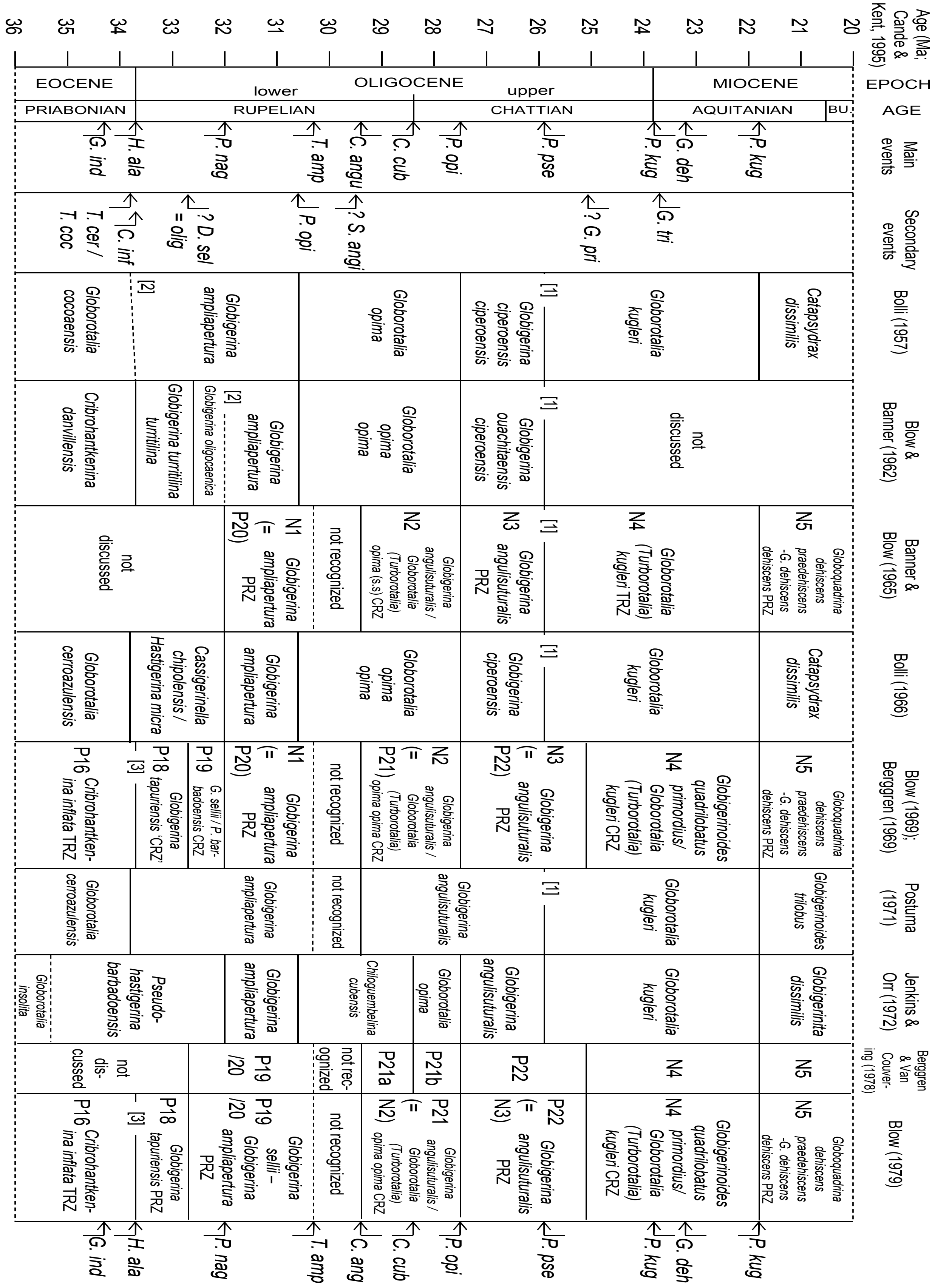

Figure 2.1a. Comparison of some low latitude zonal schemes

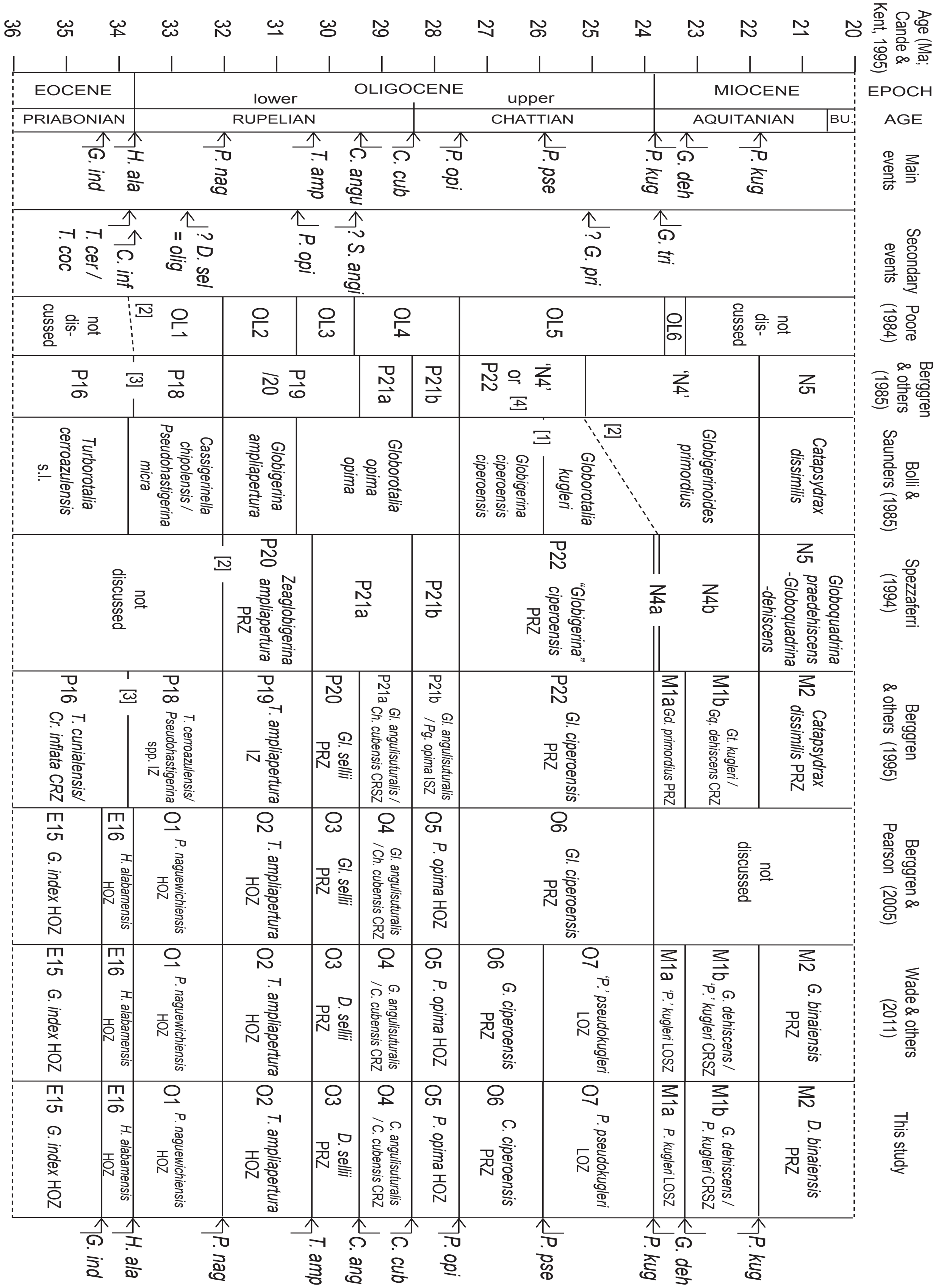

Figure 2.1b. Comparison of some low latitude zonal schemes

of Bolli (1957). The O/M boundary was placed at the base of the *G. kugleri* Zone and at the approximate level of the initial occurrence of *Globigerinoides*, although like other specialists they indicated they had seen sporadic occurrences of *Globigerinoides primordius* and related forms throughout the underlying *Globigerina ciperoensis* Zone. In a subsequent review and critique of extant Oligocene zones Stainforth and Lamb (1981), recognizing the failure of the *Globigerinoides* datum, placed the O/M boundary within the *G. kugleri* Zone at a level characterized, they said, by the FAD of *Globorotalia peripheroronda* and *Globoquadrina* sp. aff. *G. altispira*. (Subsequent studies have failed to document the validity of the FAD of *peripheroronda* as low as in the *kugleri* Zone and compressed forms of *siakensi*s may be/have been involved.)

Poore (1984) formulated a 6-fold Oligocene zonation of the mid-latitude South Atlantic Ocean (zones were denoted with the prefix "OL"; the sixth zone: OL6 = LO of *Globorotalia kugleri* to LO of *Globoquadrina dehiscens* was considered/assigned to the terminal Oligocene; Fig. 2.1). Berggren and Miller (1988) formulated a 5-fold Oligocene zonation based primarily on North Atlantic Ocean mid-latitude sites and Oligocene planktonic foraminiferal zonal schemes and provided a review and correlation of existing zonations. This zonal scheme was essentially repeated in Berggren and others (1995) with the minor amendation of Berggren and Miller's (1988) *Chiloguembelina cubensis-Pseudohastigerina barbadoensis*. Partial-range Zone (P18) to the *Turborotalia cerroazulensis-Pseudohastigerina* spp. Interval Zone (P18).

Berggren and Pearson (2005) renumbered the Oligocene Zones O1-O6, bringing the scheme into line with the Neogene alphanumeric system of Berggren and others (1995) which was based on epochs. They introduced one minor modification to the base of Zone O1 which was placed at the HO of *Hantkenina* and the Eocene / Oligocene boundary proper. Wade and others (2011) maintained the same zones but divided the 3.7 myr Zone O6 into Zone O6 and Zone O7 based on the LO of *Paragloborotalia pseudokugleri*. It is interesting to note here that 30 years ago Stainforth and Lamb (1981) observed that *pseudokugleri* has its LO below that of *kugleri* s.s., showing once again that history has a tendency of coming around full circle. These zones have proved robust during the Working Group's researches on Oligocene planktonic foraminifera and are employed in this study with some minor name changes because of new generic designations, as seen below. While the biozonation can be fairly readily applied to most low latitude open ocean settings, the interval is lacking in secondary markers.

AUSTRAL ZONATION

As part of a larger Cenozoic study devoted to establishing the (bio)stratigraphic range of some 103 species and subspecies of planktonic foraminifera for the Teurian to Waitakian Stages (Danian to lower Miocene) of New Zealand, Jenkins (1965) formulated a 14-fold zonation for this interval, three of which were correlated with the Oligocene (in ascending order): *Globigerina brevis* Total-range Zone, the *Globigerina angiporoides angiporoides* Highest Occurrence (HO) Zone (see Berggren and Pearson, 2005) and the *Globigerina euapertura* Partial-range Zone. This zonation was applied to a detailed investigation of the Oligocene of New Zealand. As subsequent deep sea drilling was to demonstrate, the gradual cooling in the late Eocene and early Oligocene in high austral latitudes led to the evolution of the Antarctic Ice Sheet and the Antarctic Circumpolar Current leading, in turn, to the isolation of the high southern latitudes from the global circulation pattern(s) and the development of strong latitudinal thermal gradients. The result was the development of low diversity, biogeographically distinct planktonic foraminiferal populations for which the low latitude zonal schemes were totally inadequate. Austral-Antarctic Oligocene planktonic foraminiferal faunas consisted characteristically of subbotinids (*angiporoides*), globoturborotalitids (*labiacrassata*), catapsydracids (*dissimilis, unicavus*), tenuitellids (*gemma, munda*), chiloguembelinids (*cubensi*s), and pseudohastigerinids (see, for instance, Jenkins, 1971; Kennett, 1978; Berggren, 1992).

Stott and Kennett (1990) developed a Paleogene zonal biostratigraphy for high austral latitudes (Maud Rise, Weddell Sea) which also found application (in modified form) in the southern Indian Ocean (Kerguelen Plateau) in studies by Huber (1991) and Berggren (1992). A 4-fold zonation for the Antarctic Oligocene (AO) was formulated by Huber and Quillévéré (2005, 2006) (in ascending order, here we modify the zonal names for consistency with the revised generic attributions of some of the species): AO1 - *Subbotina angiporoides* HO Zone; AO2 - *Chiloguembelina cubensis* HO Zone; AO3 - *Globoturborotalita labiacrassata* HO Zone;

AO4 - *Globoturborotalita euapertura* HO Zone and correlated with low latitude zonal schemes via the Integrated Magnetobiochonronologic Scale (IMBS) of Berggren and others, 1995 (see Huber and Quillévéré, 2005:43, fig. 3.1).

AN UPDATED OLIGOCENE AND LOWER MIOCENE PLANKTONIC FORAMINIFRERAL ZONATION

Berggren and Pearson (2005) presented a revised tropical/subtropical Paleogene planktonic foraminiferal zonation. For the Paleocene they renamed and/or nomenclaturally amended some of the seven zones and subzones of Berggren and others (1995) in order to derive an internally consistent Interval-zone nomenclature. For the Eocene they enumerated and defined 16 new Eocene zones that were meant to replace the 13 zones and subzones of Berggren and others (1995) and which was adopted in the *Atlas of Eocene Planktonic Foraminifera* (Pearson and others, 2006). At the same time Berggren and Pearson (2005) modified the five-fold Oligocene zonation of Berggren and others (1995) to a six-fold zonation with the elevation of (former) Subzones P21a and P21b to zonal status and the zonal components were renamed and/or nomenclaturally amended. An alphanumeric notation was introduced/provided with the prefix 'P', 'E' and 'O' standing for Paleocene, Eocene, Oligocene, respectively.

More recently, Wade and others (2011) presented an amended low latitude (subtropical and tropical) Cenozoic planktonic foraminiferal zonation. One hundred and eighty seven planktonic foraminiferal bioevents were treated and incorporated into a revised/integrated Cenozoic planktonic foraminiferal magnetobiochronology. These calibrations were then synthesized to the ATS of the Neogene and late Paleogene and the Cenozoic geomagnetic polarity time scale (GPTS). Recalibration of several early middle Eocene bioevents resulted in significant changes in the duration of Biochrons E7, E8 and E9; at the same time the introduction/addition of Zone O7 in the uppermost Oligocene altered/improved the biochronologic resolution of the late Oligocene. The Paleocene zonation remained the same as in Berggren and Pearson (2005) with the exception of minor emendations to Subzones P1b and P1c.

In order to provide the most up-to-date version of mid-Cenozoic planktonic foraminiferal biostratigraphy and biochronology we present here the revised Oligocene portion of the updated Cenozoic integrated astrobiomagnetochronology of Wade and others (2011) (Figs. 2.2 and 2.3). We also include lower Miocene zones (up to and including Zone M5/N8) here because the Oligocene Working Group decided to include/treat the upper/younger stratigraphic ranges of taxa that extended beyond the Oligocene/Miocene boundary in this Atlas.

The recent integrated magnetobiostratigraphic investigation on three lower–middle Miocene Italian and Mediterranean Sea sections and a revision of ODP Site 608 (summarized in Iaccarino and others, 2011) has resulted in age differences in the Integrated Magnetobiochronologic Scale (IMBS) (ranging from 0.5 to 1 myr) for some datum levels shown here. The differences relevant to this paper span the lower/middle Miocene boundary interval between approximately the FAD of *Praeorbulina sicana* (3 apertures, considered a senior synonym of *G. bisphericus*) and the FAD of *Orbulina suturalis* and include the FAD of *Praeorbulina glomerosa* s.s. between the two. A change to the chronology in any part of this relatively short interval would have reverberations/repercussions in the remainder of the time scale and it is beyond the scope of this paper to attempt a reconciliation of these different age estimates. Part of the resolution of this problem may relate to different taxonomic concepts of key species involved as understood by various workers. We have retained the biochronology developed in Wade and others (2011) in this paper for this interval as well as the remainder of this work for the sake of consistency and continuity.

EOCENE

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*.
Magnetochronologic calibration: Subchron C16n.2n-Chron C13r.
Astronomical cycle calibration: $89_{\text{Eo-C16n}}$ - $86_{\text{Eo-C13r.}}$
Estimated age: 35.8-34.3 Ma (as per Cande and Kent, 1995); 35.8-34.5 Ma (as per Ogg and Smith, 2004); 35.8-34.5 Ma (as per Pälike and others, 2006); late Eocene.
Remarks: The nomenclature and definition of the zone remain the same as in Berggren and Pearson (2005).

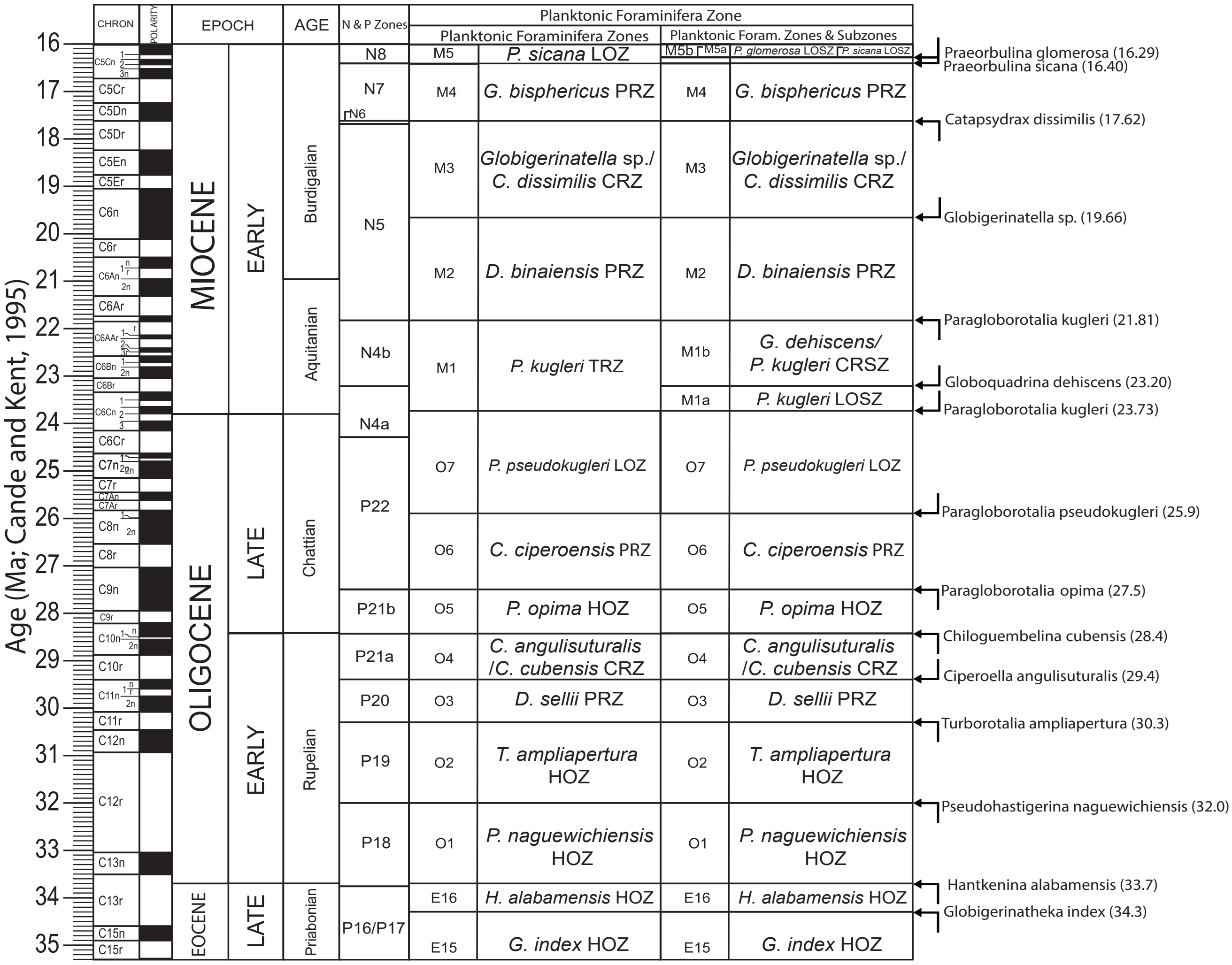

FIGURE 2.2. Primary planktonic foraminiferal bioevents for the late Eocene to early Miocene against the polarity time scale of Cande and Kent (1995), after Wade and others (2011).

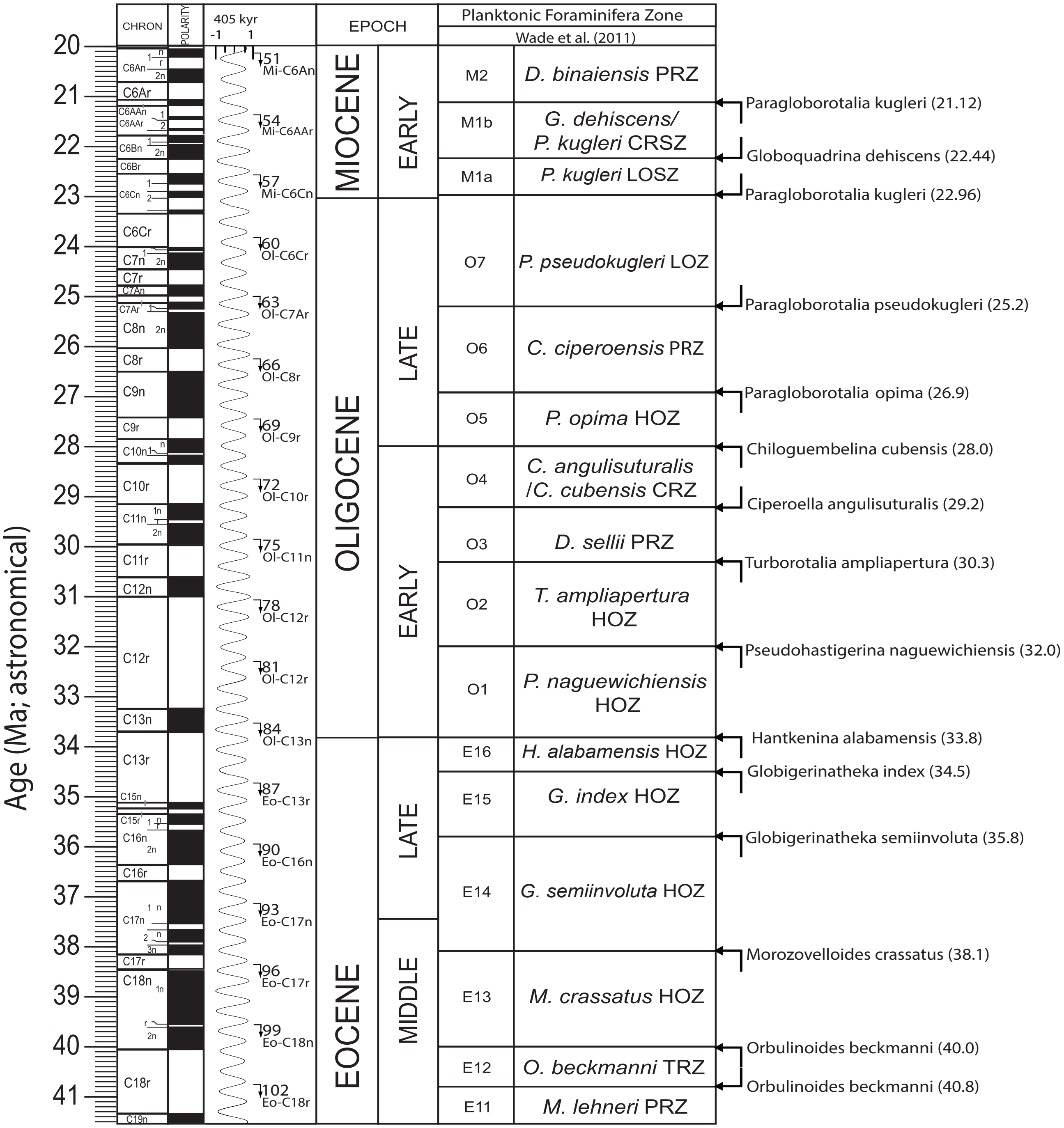

FIGURE 2.3. Primary planktonic foraminiferal bioevents for the early Miocene to middle Eocene against the astronomical time scale of Lourens and others (2004, until base of Subchron C6Cn.2n) and Pälike and others (2006, from top Subchron C6Cn.3n until base Chron C19n). The ~405 kyr eccentricity cycle numbers are counted from the present (after Wade and others, 2011).

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*.
Magnetochronologic calibration: Chron C13r-Chron C12r.
Astronomical cycle calibration: $86_{\text{Eo-C13r}}$ - $84_{\text{Ol-C13n.}}$
Estimated age: 34.3-33.7 Ma (as per Cande and Kent, 1995); 34.5-33.9 Ma (as per Ogg and Smith, 2004); 34.5-33.8 Ma (as per Pälike and others, 2006); late Eocene.
Remarks: The nomenclature and definition of the zone remain the same as in Berggren and Pearson (2005).

OLIGOCENE

Zone O1. *Pseudohastigerina naguewichiensis* Highest-occurrence Zone

Definition: Biostratigraphic interval between HO of *Hantkenina alabamensis* and HO of the nominate taxon *Pseudohastigerina naguewichiensis* (Berggren and Pearson, 2005).
Magnetochronologic calibration: Chron C13r-Chron C12r.
Astronomical cycle calibration: $84_{\text{Ol-C13n}}$ - $80_{\text{Ol-C12r.}}$
Estimated age: 33.7-32.0 Ma (as per Cande and Kent, 1995); 33.9-32.2 Ma (as per Ogg and Smith, 2004); 33.8-32.0 Ma (as per Pälike and others, 2006); early Oligocene.
Remarks: The nomenclature and definition of the zone remain the same as in Berggren and Pearson (2005).

Zone O2. *Turborotalia ampliapertura* Highest-occurrence Zone

Definition: Biostratigraphic interval between the HO of *Pseudohastigerina naguewichiensis* and the HO of the nominate taxon *Turborotalia ampliapertura*.
Magnetochronologic calibration: Chron C12r-Chron C11r.
Astronomical cycle calibration: $80_{\text{Ol-C12r}}$ - $76_{\text{Ol-C11r.}}$
Estimated age: 32.0-30.3 Ma (as per Cande and Kent, 1995); 32.2-30.4 Ma (as per Ogg and Smith, 2004); 32.0-30.3 Ma (as per Pälike and others, 2006); early Oligocene.
Remarks: The nomenclature and definition of the zone remain the same as in Berggren and Pearson (2005).

Zone O3. *Dentoglobigerina sellii* Partial-range Zone

Definition: Partial range of the nominate taxon between the HO of *Turborotalia ampliapertura* and the LO of *Ciperoella angulisuturalis*.
Magnetochronologic calibration: Chron C11r-Subchron C11n.1n.
Astronomical cycle calibration: $76_{\text{Ol-C11r}}$ - $73_{\text{Ol-C10r.}}$
Estimated age: 30.3–29.4 Ma (as per Cande and Kent, 1995); 30.4-29.5 Ma (as per Ogg and Smith, 2004); 30.3-29.2 Ma (as per Pälike and others, 2006); early Oligocene
Remarks: The nomenclature and definition of the zone remain the same as in Berggren and Pearson (2005).

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

Definition: Concurrent range of the nominate taxa between the LO of *Ciperoella angulisuturalis* and the HCO of *Chiloguembelina cubensis*.
Magnetochronologic calibration: Subchron C11n.1n-C10n.1n.
Astronomical cycle calibration: $73_{\text{Ol-C10r}}$ - $70_{\text{Ol-C10n.}}$
Estimated age: 29.4-28.4 Ma (as per Cande and Kent, 1995); 29.5-28.3 Ma (as per Ogg and Smith, 2004); 29.2-28.0 Ma (as per Pälike and others, 2006); early Oligocene.
Remarks: Renamed here in accord with placing the species *angulisuturalis* in the genus *Ciperoella* (see Chapter 7, this volume). See Wade and others (2011) for discussion regarding the FAD of *angulisuturalis.*

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*.
Magnetochronologic calibration: Subchron C10n.1n-Chron C9n.
Astronomical cycle calibration: $70_{\text{Ol-C10n}}$ - $67_{\text{Ol-C9n.}}$
Estimated Age: 28.4-27.5 Ma (as per Cande and Kent, 1995); 28.3-27.3 Ma (as per Ogg and Smith, 2004); 28.0-26.9 Ma (as per Pälike and others, 2006); late Oligocene.
Remarks: The nomenclature and definition of the zone remain the same as in Berggren and Pearson (2005). Coccioni and others (2008, in press) have confirmed that the HCO of *C. cubensis* is a robust stratigraphic marker for the Oligocene (see also King and Wade, 2017). The age of the LAD of *P. opima* and LAD of *C. cubensis* have been revised as per Wade and others (2007).

Zone O6. *Ciperoella ciperoensis* Partial-range Zone (amended in Wade and others (2011) = lower part of Zone O6 [*Globigerina ciperoensis* 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*.
Magnetochronologic calibration: Chron C9n-Subchron C8n.1n.
Astronomical cycle calibration: $67_{\text{Ol-C9n}}$ - $63_{\text{Ol-C7Ar.}}$
Estimated age: 27.5-25.9 Ma (as per Cande and Kent, 1995); 27.3-25.4 Ma (as per Ogg and Smith, 2004); 26.9-25.2 Ma (as per Pälike and others, 2006); late Oligocene.
Remarks: Renamed here in accord with placing the species *ciperoensis* in the genus *Ciperoella*.

Zone O7. *Paragloborotalia pseudokugleri* Lowest-occurrence Zone (defined in Wade and others, 2011 = upper part of Zone O6 [*Globigerina ciperoensis* 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*.
Magnetochronologic calibration: Subchron C8n.1n-Subchron C6Cn.2n.
Astronomical cycle calibration: $63_{\text{Ol-C7Ar}}$ - $57_{\text{Mi-C6Cn.}}$
Estimated age: 25.9-23.73 Ma (as per Cande and Kent, 1995); 25.4-22.96 Ma (as per Gradstein and others, 2004); 25.2 (as per Pälike and others, 2006) -22.96 Ma (as per Lourens and others, 2004); late Oligocene-earliest Miocene.
Remarks: The recalibration of the LAD *Paragloborotalia opima* from 27.1 Ma (Berggren and others, 1995) to 27.5 Ma (Wade and others, 2007) increased the duration of Biochron O6 as per Berggren and Pearson (2005) from 3.3 to 3.7 myr. Wade and others (2011) 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.

LOWER MIOCENE

Zone M1. *Paragloborotalia kugleri* Taxon-range Zone (= Zone M1 [*Globorotalia kugleri* Total Range Zone] of Berggren and others, 1995).
Definition: Total range of the nominate taxon.
Magnetochronologic calibration: Subchron C6Cn.2n-Chron C6AAn.
Astronomical cycle calibration: $57_{\text{Mi-C6Cn}}$ - $53_{\text{Mi-C6Ar.}}$
Estimated age: 23.73-21.81 Ma (as per Cande and Kent, 1995); 22.96-21.12 Ma (as per Lourens and others, 2004); early Miocene.
Remarks: Renamed here to accord with assignment of the species *kugleri* to the genus *Paragloborotalia*.

Subzone M1a. *Paragloborotalia kugleri* Lowest-occurrence Subzone (= Subzone M1a [*Globigerinoides primordius* Interval Subzone] of Berggren and others, 1995).
Definition: Biostratigraphic interval between the LO of *Paragloborotalia kugleri* and the LO of *Globoquadrina dehiscens*.
Magnetochronologic calibration: Subchron C6Cn.2n-Chron C6Br.
Astronomical cycle calibration: $57_{\text{Mi-C6Cn}}$ - $56_{\text{Mi-C6Bn.}}$
Estimated age: 23.73-23.20 Ma (as per Cande and Kent, 1995); 22.96-22.44 Ma (as per Lourens and others, 2004); early Miocene.
Remarks: Renamed here to accord with assignment of the species *kugleri* to the genus *Paragloborotalia*.

Subzone M1b. *Globoquadrina dehiscens* / *Paragloborotalia kugleri* Concurrent-range Subzone (= Subzone M1b [*Globorotalia kugleri*/*Globoquadrina dehiscens* Concurrent-range Subzone] of Berggren and others, 1995).
Definition: Biostratigraphic interval between the LO of *Globoquadrina dehiscens* and the HO of *Paragloborotalia kugleri*.
Magnetochronologic calibration: Chron C6Br-Chron C6AAn.
Astronomical cycle calibration: $56_{\text{Mi-C6Bn}}$ - $53_{\text{Mi-C6Ar.}}$
Estimated age: 23.20-21.81 Ma (as per Cande and Kent, 1995); 22.44-21.12 Ma (as per Lourens and others, 2004); early Miocene.
Remarks: Renamed here to accord with assignment of the species *kugleri* to the genus *Paragloborotalia*. The subzone division is based upon the LO of *G. dehiscens*; this datum has been reported as diachronous in some parts of the world and cannot always be relied upon. A review of this problem by Iaccarino and others (1999) showed, for example, that the LO of *kugleri* s.s. preceded *dehiscens* s.s. consistently in North and South Atlantic Oceans (Berggren and others, 1995) as well as southwest Pacific Ocean biogeographies (Kennett and Srinivasan, 1983). In the GSSP section for the base Neogene (=Miocene) at the Lemme-Carrosio section,

Piedmont, Northern Italy, the LO of *kugleri* s.s. occurs 2 m above the base of Chron C6Cn.2n, whereas the LO of *dehiscens* s.s. is 10 m above that of *kugleri* s.s. in the middle of Chron C6Br. Morphotypes identified as/referred to *Globoquadrina dehiscens* forma *primitiva* occur below the LO of *kugleri* s.s. and/but appear to be referable to the [probably ancestral] *Dentoglobigerina larmeui*. Spezzaferri (1994) has reported an apparent preference for/prevalence of a reversed order for LO of *kugleri* s.s.-*dehiscens* s.s. in low latitude Pacific-Indian Ocean biogeographies but does not use *dehiscens* s.s in her biostratigraphic zonation. We point out that no (sub) zone is globally valid/applicable, also that problems with both datums require consistent taxonomic criteria which we hope this atlas will provide.

Zone M2. *Dentoglobigerina binaiensis* Partial-range Zone (amended in Wade and others (2011) = lower part of Zone M2 [*Catapsydrax dissimilis* Partial-range Zone] of Berggren and others, 1995).
Definition: Partial-range of the nominate taxon between the HO of *Paragloborotalia kugleri* and the LO of *Globigerinatella* sp.
Magnetochronologic calibration: Chron C6AAn-Chron C6n.
Astronomical cycle calibration: $53_{\text{Mi-C6Ar}}$ - $48_{\text{Mi-C6n.}}$
Estimated age: 21.81-19.66 Ma (as per Cande and Kent, 1995); 21.12-19.30 Ma (as per Lourens and others, 2004); early Miocene.
Remarks: The new concept of Zone M2 follows from developments in the understanding of the *Globigerinatella* lineage (see Wade and others (2011) for discussion). Renamed here to accord with assignment of the species *binaiensis* to the genus *Dentoglobigerina*.

Zone M3. *Globigerinatella* sp. / *Catapsydrax dissimilis* Concurrent-range Zone (defined in Wade and others (2011), equivalent to Zone M3 [*Globigerinatella insueta / Catapsydrax dissimilis* Concurrent-range Zone] and upper part of Zone M2 [*Catapsydrax dissimilis* Partial-range Zone] of Berggren and others, 1995).
Definition: Concurrent range of the nominate taxon between the LO of *Globigerinatella* sp. and the HO of *Catapsydrax dissimilis*.
Magnetochronologic calibration: Chron C6n-Chron C5Dr.
Astronomical cycle calibration: $48_{\text{Mi-C6n}}$ - $44_{\text{Mi-C5Dn.}}$
Estimated age: 19.66-17.62 Ma (as per Cande and Kent, 1995); 19.30-17.54 Ma (as per Lourens and others, 2004); early Miocene.
Remarks: The new concept of Zone M3 follows from developments in the understanding of the *Globigerinatella* lineage (see Wade and others, 2011 for discussion).

Zone M4. *Globigerinoides bisphericus* Partial-range Zone (= Zone M4 [*Catapsydrax dissimilis - Praeorbulina sicana* Interval Subzone] of Berggren and others, 1995).
Definition: Partial range of the nominate taxon between the HO of *Catapsydrax dissimilis* and the LO of *Praeorbulina sicana*.
Magnetochronologic calibration: Chron C5Dr-Subchron C5Cn.2n.
Astronomical cycle calibration: $44_{\text{Mi-C5Dn}}$ - $41_{\text{Mi-C5Cn.}}$
Estimated age: 17.62-16.40 Ma (as per Cande and Kent, 1995); 17.54-16.38 Ma (as per Lourens and others, 2004); early Miocene.
Remarks: Renamed in Wade and others (2011). Zone M4 was previously subdivided into Subzones M4a and M4b based on the LO of '*Globorotalia*' *birnageae.* Investigations by Spezzaferri (1994) and as part of the *Atlas of Oligocene Planktonic Foraminifera* (this volume) have revealed that the FAD of '*Globorotalia*' *birnageae* occurs in the uppermost Oligocene (Zone O7). We have therefore removed the subdivision of Zone M4.

Zone M5. *Praeorbulina sicana* Lowest-occurrence Zone (= Zone M5 [*Praeorbulina sicana – Orbulina suturalis* Interval Zone] of Berggren and others, 1995).
Definition: Biostratigraphic interval between the LO of *Praeorbulina sicana* and the LO of *Orbulina suturalis*.
Magnetochronologic calibration: Subchron C5Cn.2n-Subchron C5Bn.2n.
Astronomical cycle calibration: $41_{\text{Mi-C5Cn}}$ - $38_{\text{Mi-C5Bn.}}$
Estimated age: 16.40-15.10 Ma (as per Cande and Kent, 1995); 16.38-15.10 Ma (as per Lourens and others, 2004); early-middle Miocene.
Remarks: Renamed in Wade and others (2011).

Subzone M5a. *Praeorbulina sicana* Lowest-occurrence Subzone (= Subzone M5a [*Praeorbulina sicana - Praeorbulina glomerosa* sensu stricto Interval Subzone] of Berggren and others, 1995).
Definition: Biostratigraphic interval between the LO of *Praeorbulina sicana* and the LO of *Praeorbulina glomerosa*.

Zone (Wade & others) (base)	N & P zones		Datum		Age (Ma) Wade & others (2011) as per CK95	Published Age (Ma)	Reference				Astro-nomical Age	Reference	Age (Ma) Wade & others (2011) as Ogg & Smith (2004)
M6	**N9**	**B**	**Orbulina**	**suturalis**	**15.10**	**15.10**	**Berggren**	**&**	**others**	**1995**	**15.10**	**Wade & others 2011**	
		B	Clavatorella	bermudezi	15.76	15.80	Pearson	&	Chaisson	1997	15.73	Wade & others 2011	
		B	Praeorbulina	circularis	16.00	16.00	Berggren	&	others	1995	15.96	Wade & others 2011	
		B	Globorotalia	archeomenardii	16.29	16.20	Pearson	&	Chaisson	1997	16.26	Lourens & others 2004	
M5b		**B**	**Praeorbulina**	**glomerosa sensu stricto**	**16.29**	**16.20**	**Shackleton**	**&**	**others**	**1999**	**16.27**	Lourens & others 2004	
		B	Praeorbulina	curva	16.30	16.30	Berggren	&	others	1995	16.28	Wade & others 2011	
M5a	**N8**	**B**	**Praeorbulina**	**sicana**	**16.40**	**16.40**	**Berggren**	**&**	**others**	**1995**	**16.38**	**Wade & others 2011**	
		B	Globorotalia	zealandica	17.30	17.30	Berggren	&	others	1995	17.26	Wade & others 2011	
M4	**N7**	**T**	**Catapsydrax**	**dissimilis**	**17.62**	**17.50**	**Shackleton**	**&**	**others**	**1999**	**17.54**	**Lourens & others 2004**	
	N6	B	Globigerinatella	insueta s. str.	17.69	17.40	Pearson	&	Chaisson	1997	17.59	Lourens & others 2004	
		B	Globorotalia	praescitula	18.50	18.50	Berggren	&	others	1995	18.26	Wade & others 2011	
		T	Dentoglobigerina	binaiensis	19.43	19.10	Pearson	&	Chaisson	1997	19.09	Lourens & others 2004	
M3		**B**	**Globigerinatella**	**sp.**	**19.66**	**20.20**	**Pearson**	**&**	**Chaisson**	**1997**	**19.30**	**Lourens & others 2004**	
		B	Globigerinoides	altiaperturus	20.50	20.50	Berggren	&	others	1995	20.03	Wade & others 2011	
		T	Tenuitella	munda	21.40	21.40	Berggren	&	others	1995	20.78	Wade & others 2011	
		T	Ciperoella	angulisuturalis	21.60	21.60	Berggren	&	others	1995	20.94	Wade & others 2011	
M2	**N5**	**T**	**Paragloborotalia**	**kugleri**	**21.81**	**21.00**	**Shackleton**	**&**	**others**	**1999**	**21.12**	**Lourens & others 2004**	
		T	Paragloborotalia	pseudokugleri	22.04	21.10	Shackleton	&	others	1999	21.31	Lourens & others 2004	
M1b	**N4b**	**B**	**Globoquadrina**	**dehiscens**	**23.20**	**23.20**	**Berggren**	**&**	**others**	**1995**	**22.44**	**Wade & others 2011**	
		T	Ciperoella	ciperoensis	23.68	22.80	Shackleton	&	others	1999	22.90	Lourens & others 2004	
		B	Trilobatus	trilobus sensu lato	23.73	22.90	Shackleton	&	others	1999	22.96	Lourens & others 2004	
M1a		**B**	**Paragloborotalia**	**kugleri**	**23.73**	**22.90**	**Shackleton**	**&**	**others**	**1999**	**22.96**	**Lourens & others 2004**	
			Oligocene/Miocene boundary			*23.80*	*Berggren*	*&*	*others*	*1995*	*23.03*	Lourens & others 2004	
		T	Tenuitella	gemma	24.3	24.3	Berggren	&	others	1995	23.5	Wade & others 2011	23.6
	N4a	LCO	Trilobatus	primordius	24.3	24.3	Berggren	&	others	1995	23.5	Wade & others 2011	23.6
O7		**B**	**Paragloborotalia**	**pseudokugleri**	**25.9**	**25.9**	**Berggren**	**&**	**others**	**1995**	**25.2**	**Wade & others 2011**	**25.4**
		B	Trilobatus	primordius	26.7	26.7	Berggren	&	others	1995	26.1	Wade & others 2011	26.3
O6	**P22**	**T**	**Paragloborotalia**	**opima**	**27.5**	**27.5**	**Wade**	**&**	**others**	**2007**	**26.9**	**Wade & others 2011**	**27.3**
O5	**P21b**	**HCO**	**Chiloguembelina**	**cubensis**	**28.4**	**28.4**	**Wade**	**&**	**others**	**2007**	**28.0**	**Wade & others 2011**	**28.3**
O4	**P21a**	**B**	**Ciperoella**	**angulisuturalis**	**29.4**	**29.4**	**Berggren**	**&**	**others**	**1995**	**29.2**	**Wade & others 2011**	**29.5**
		T	Subbotina	angiporoides	30.0	30.0	Berggren	&	others	1995	29.8	Wade & others 2011	30.1
O3	**P20**	**T**	**Turborotalia**	**ampliapertura**	**30.3**	**30.3**	**Berggren**	**&**	**others**	**1995**	**30.3**	**Wade & others 2011**	**30.4**
		B	Paragloborotalia	opima	30.6	30.6	Berggren	&	others	1995	30.8	Wade & others 2011	30.8
O2	**P19**	**T**	**Pseudohastigerina**	**naguewichiensis**	**32.0**	**32.0**	**Berggren**	**&**	**others**	**1995**	**32.0**	**Wade & others 2011**	**32.2**
			Eocene/Oligocene boundary			*33.7*	*Berggren*	*&*	*others*	*1995*			
O1		**T**	**Hantkenina**	**alabamensis**	**33.7**	**33.7**	**Berggren**	**&**	**Pearson**	**2005**	**33.8**	**Wade & others 2011**	**33.9**
		HCO	Pseudohastigerina	micra	33.7	33.7	Wade	&	Pearson	2008	33.8	Wade & others 2011	33.9
	P18	T	Turborotalia	cerroazulensis	33.8	33.8	Berggren	&	Pearson	2005	33.9	Wade & others 2011	34.0
E16		**T**	**Globigerinatheka**	**index**	**34.3**	**34.3**	**Berggren**	**&**	**Pearson**	**2005**	**34.5**	**Wade & others 2011**	**34.5**
	P16	B	Turborotalia	cunialensis	35.3	35.3	Berggren	&	Pearson	2005	35.4	Wade & others 2011	35.4
E15		**T**	**Globigerinatheka**	**semiinvoluta**	**35.8**	**35.8**	**Berggren**	**&**	**Pearson**	**2005**	**35.8**	**Wade & others 2011**	**35.8**

Table 2.1. Planktonic foraminiferal bioevents for the early Miocene to late Eocene calibrated to the GPTS of Cande and Kent (1995) and Ogg and Smith (2004) and the ATS of Pälike and others (2006), from Wade and others (2011). Marker taxa are highlighted in bold. Previously published ages are on multiple time scales and refer to the data in each reference.

Magnetochronologic calibration: Subchron C5Cn.2n-Subchron C5Cn.1r.
Astronomical cycle calibration: $41_{\text{Mi-C5Cn.}}$
Estimated age: 16.40-16.29 Ma (as per Cande and Kent, 1995); 16.38-16.27 Ma (as per Lourens and others, 2004); early Miocene.
Remarks: Renamed in Wade and others (2011).

Subzone M5b. *Praeorbulina glomerosa* Lowest-occurrence Subzone (= Subzone M5b [*Praeorbulina glomerosa* sensu stricto – *Orbulina suturalis* Interval Subzone] of Berggren and others, 1995).
Definition: Biostratigraphic interval between the LO of *Praeorbulina glomerosa* and the LO of *Orbulina suturalis*.
Magnetochronologic calibration: Subchron C5Cn.1r-Subchron C5Bn.2n.
Astronomical cycle calibration: $41_{\text{Mi-C5Cn}}$ - $38_{\text{Mi-C5Bn.}}$
Estimated age: 16.29-15.10 Ma (as per Cande and Kent, 1995); 16.27-15.10 Ma (as per Lourens and others, 2004); early-middle Miocene.
Remarks: Renamed in Wade and others (2011).

SUMMARY/CONCLUSIONS

1. The Oligocene was introduced by Beyrich in 1854 for shallow marine, brackish and fresh water sediments in northern Europe generally attributed to the (stratigraphic) interval between Lyell's classic Eocene and Miocene described two decades earlier. Although Lyell subsequently transferred several units from his "upper Eocene" to a newly defined/expanded lower Miocene (including beds that were specifically included by Beyrich in his term Oligocene) and never officially recognized/accepted the term, the Oligocene has since found a home in the hierarchical subdivision of the Paleogene Period/System.
2. The Oligocene has experienced a more extensive/convoluted temporal (~26 - 10 myr duration) and stratigraphic (Helvetian/Tortonian boundary to Lattorfian-Rupelian/Priabonian boundary) range than any other chronostratigraphic entity of the Cenozoic. In fact for an anomalous decade-long interval (the 1960s) it was thought by some to lack local representation in much of the North American-Caribbean region.
3. The O/M boundary has gradually been lowered from a level approximately equivalent to the *fohsi/menardii* s.l zonal boundary (middle/late Miocene) in the 1950s and early 1960s, to a level near/slightly below the *Orbulina* datum (~/= Langhian/Burdigalian boundary) in the mid-1960s based on intercontinental correlations of LBF. Meanwhile, studies on planktonic foraminifera in the late 1950s had suggested that the O/M boundary was approximately equivalent to the HO of *Globorotalia kugleri* s.s. Concomitant studies by several planktonic foraminifera specialists led to correlation of the O/M boundary with a level at the base of the *ampliapertura* Zone (P20/N1), within, or at the top of, the *opima* Zone, believed at the time to be equivalent with the Chattian Stage of NW Europe and/or the base of the Aquitanian Stage of SW Europe, or at the (supposed) LO of *Globigerinoides primordius* (within the range of *Globorotalia kugleri* s.l.). With the recent recognition that the earlier concept of *kugleri* included the taxonomically ancestral form *pseudokugleri* (for which Zone O7 has been erected), and the delineation of a GSSP for the O/M boundary in the Lemme-Carrosio section of northern Italy, it is now recognized that the O/M boundary is located: ~2 m below the LO of *kugleri* s.s. and bracketed by the LO and HO of *Sphenolithus delphix*, 12 m below and 4 m above the boundary level, respectively.
4. The Eocene/Oligocene (E/O) boundary is delineated/characterized by the HO of a suite of hantkeninids (and the stratigraphically juxtaposed HO of several turborotaliids and the extinction of several biogeographically disjunctive, but demonstrably temporally concomitant, LBF (*Asterocyclina*, ?*Discocyclina*, and various nummulitids).
5. The Oligocene boundary is currently associated/correlated with Chrons C6n.2n$_{(o)}$ (top) and Chron C13r (0.14) (base) with age estimates ranging from 23.03 Ma (O/M) to 33.7±0.7 Ma to 33.9±0.1 Ma (E/O) depending on age calibration used on the Fish Canyon Tuff standard, for an approximate range/duration of ~10.7-10.9 myr).
6. Recent deep sea drilling in the equatorial Pacific Ocean has yielded a complete set of Oligocene geomagnetic chrons and orbital cycles, resulting

in an extension of the ATS and an orbitally tuned magnetochronology and a more refined IMBS.

7. An orbital cycle numerical scheme has been recently introduced for the late middle Eocene-present day (~ 41 myr) based on Earth's long tem eccentricity cycle (405 kyr). The numbers increase with age (from 1 at present) and the Oligocene is represented by cycles 58 to 84.
8. An updated 7-fold planktonic foraminiferal zonation has been introduced for the low latitude (subtropical and tropical) Oligocene and synthesized to the geomagnetic polarity time scale and astronomical time scale.

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