A review of the importance of the Caribbean region in Oligo-Miocene low latitude planktonic foraminiferal biostratigraphy and the implications for modern biogeochronological schemes

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Abstract

Planktonic foraminifera are widely used in marine biostratigraphy thanks to their small size, limited stratigraphic range and abundance in oceanic sediments. The utility of planktonic foraminifera in biostratigraphy was first fully recognised within the Caribbean region during the middle of the 20th century. The area was critical for the subsequent development of the low latitude biostratigraphic schemes and remains fundamental for modern day biogeochronologies. This study presents a historical review of the Oligo-Miocene component of these biostratigraphic schemes, including the first proposed scheme of Cushman and Stainforth (1945) and the subsequent development. The work of Hans Bolli and Walter Blow is particularly highlighted due to their heavy influence on modern day biostratigraphy, including these authors initially recognising the biostratigraphic utility of a number of bioevents still applied today. These Caribbean-centric schemes are correlated to the modern-day low latitude biogeochronology of Wade et al. (2011), with this synthesis highlighting that a number of bioevents (e.g. Top *Paragloborotalia kugleri* and Top *Catapsydrax dissimilis*) have been applied consistently since their initial recognition. This in turn allows the recognisability of these bioevents to be deduced based on how consistently applied each datum has been. In addition, the range charts of six studies focusing heavily on the Caribbean have been reassessed to determine whether there is potential to apply a given bioevent, and the original author merely did not recognise the biostratigraphic utility of the species or favoured another bioevent.

In considering this historical review, a number of amendments to Wade et al. (2011) and future priorities to planktonic foraminifera biogeochronologies are suggested. Most notably, the re-introduction of Base *Globigerinatella insueta* as a primary bioevent due to the historical biostratigraphic importance of this species. This event now defines early Miocene Subzone M3b (*Gt. insueta*/*Ct. dissimilis* PRZ) dividing Zone M3 into an upper Subzone M3b (Base *Gt. insueta*) and lower Subzone M3a (Base *Globigerinatella* sp.). Finally, the Miocene to Recent timescale of Wade et al. (2011) has been recalibrated following more recent updates to the magnetostratigraphy (Kochhann et al., 2016; Ogg et al., 2016; Drury et al., 2017; Beddow et al., 2018) and cyclostratigraphy (Wilkens et al., 2017). The overall effect on the planktonic foraminifera biogeochronology is minor but our results become the suggested biostratigraphic framework for the low latitudes.

Key words. biostratigraphy, planktonic foraminifera, Caribbean, evolution, extinction

1. Introduction

The Caribbean region has been critical in the development of Oligocene to Recent low latitude planktonic foraminifera biostratigraphy. At the basic level, 40 species described from the region have some biostratigraphic utility within this timeframe according to the current biogeochronology of Wade et al. (2011). These 40 species collectively account for 20 primary bioevents and 37 secondary bioevents with certain species (e.g. *Neogloboquadrina acostaensis* and *Paragloborotalia kugleri*) having multiple events based upon their origination, extinction or a morphological change (i.e. coiling direction), as summarised in Figure 1. However, the region is arguably the catalyst in the recognition and utility of planktonic foraminifera in biostratigraphy, with the first major attempts at using the group stemming from the Caribbean in the 1940s. This study provides a detailed review of the role of the Caribbean in the original and subsequent low latitude planktonic foraminiferal biozonations providing a compilation of historically important schemes. An attempt has also been made to assess which bioevents can be considered the most and least recognisable, at least within the Caribbean region. A reassessment of the range charts from key biozonations has also been undertaken in order to determine whether certain bioevents were recognisable. A number of potential amendments to the low latitude biogeochronology of Wade et al. (2011) have been suggested based upon the historical importance of certain bioevents, as well as updating the Miocene component to more recent magnetochronologies (Kochhann et al., 2016; Ogg et al., 2016; Drury et al., 2017; Beddow et al., 2018) and astronomically tuned records (Wilkens et al., 2017).

The chronostratigraphic terminology applied throughout this study follows Wade et al. (2011) and Backman et al. (2012) where Base (B) and Top (T) respectively refer to the origination and extinction of a given taxa. Tc refers to Top common and Bc to Base Common, while X denotes a change in coiling direction (see also Figure 1). The nomenclature for the type of biostratigraphic zone follows Wade et al. (2011) with Taxon Range Zone (TRZ), Concurrent-range Zone (CRZ), Lowest-occurrence Zone (LOZ), Highest-occurrence Zone (HOZ) and Partial-range Zone (PRZ) being applied. The acronym SZ refers to a subzone and has be used in conjunction with the nomenclature listed above (i.e. HOSZ would mean Highest-occurrence Subzone).

2. A historic review of the role of the Caribbean in low latitude biostratigraphy

The majority of the research in the Caribbean was the result of oil and gas prospecting, with researchers of note generally employed within the industry. Earlier studies tended not to define zones in the same way as today (i.e. the nomenclature discussed above), but the zone type (i.e. TRZ, CRZ, LOZ etc) has been inferred from the range charts and descriptions of the original authors and are included in brackets after the relevant zonal schemes and zones. The originally defined zonal names are given here as opposed to the current generic assignment (see genera abbreviations in Figure 1), which has changed for most of the species.

2.1. The first zonations (1940s)

Pioneering attempts to apply planktonic foraminifera in biostratigraphy within the Caribbean were based primarily on material collected in southern Trinidad and to a lesser extent north east Venezuela. The origins for many of the related studies can be traced to Hans Kugler and his interest in using foraminifera as a biostratigraphic tool (e.g. Higgins, 1996; Finger, 2013; Hottinger, 2013). This led Kugler to set up a laboratory in 1929 in Pointe-à-Pierre (southern Trinidad) while in the employment of Trinidad Leasehold Limited (TLL) (Bolli, 1974). In the late 1930s, TLL hired Hans Renz and Robert Stainforth and the first attempt at a biostratigraphic zonation for the Cipero Formation in southern Trinidad resulted (Cushman and Stainforth, 1945). This consisted of 3 planktonic foraminifera zones based on exposures of the Cipero Formation, namely Zone I (*Globigerina concinna* Zone), Zone II (*Globigerinatella insueta* Zone) and Zone III (*Globorotalia fohsi* Zone), which were all thought to be Oligocene in age and would now be recognised as TRZs (Figures 2 and 3). Following this initial zonation, a *Globigerina dissimilis* Zone (=HOZ) (Cushman and Renz, 1947) and a *Globorotalia menardii* Zone (=PRZ) (Stainforth, 1948) were added with the former being between Zones I and II, while the latter was placed above Zone III (Figures 2 and 3). The base of the *Gr. menardii* Zone marked the suggested boundary between the Oligocene and Miocene in the early Trinidadian studies. Renz (1948) recognised the *Gr. fohsi* Zone (i.e. Zone III) in the Pozon Formation in the State of Falcón, eastern Venezuela and also attempted to correlate this to other Caribbean sections including Trinidad, Barbados, Jamaica and Cuba. However, Renz and Stainforth predominantly relied on benthic foraminifera for their zonations which were insufficient to describe the complex Trinidadian stratigraphy.

2.2. The early work of Hans Bolli, Paul Brönnimann and Walter Blow (1950s)

In 1945 Paul Brönnimann and Hans Bolli were hired by TLL and a more detailed and widespread study across the Cipero and Lengua formations of southern Trinidad was undertaken. Although primarily concerned with taxonomy, Brönnimann was the first to divide the *Globorotalia menardii* Zone, with the lower section becoming the *Globorotalia mayeri* Zone (=HOZ) which overlaid the *Gr. fohsi* Zone (Figure 3). The base of the *Gr. mayeri* Zone formed the Oligocene-Miocene boundary (Brönnimann, 1951a, 1951b). Suter (1951) recognised a *Globigerina apertura* Zone, suggesting this was the most basal zone of the Cipero Formation (i.e. below Zone I of Cushman and Stainforth, 1945). In the same year, Bolli split the *Gr. fohsi* Zone into four subzones defined by the base of the nominate taxon (=LOZ), namely the *Gr. fohsi robusta* (although this would be considered a TRZ)*, Gr. fohsi lobata, Gr. fohsi fohsi* and *Gr. fohsi barisanensis* Subzones (Bolli, 1951) (Figure 3). Bolli (1957) expanded these zonations and while the top 7 zones (*Gr. menardii* to *Gt. insueta*) remained unchanged (although the aforementioned *Fohsi* subzones were elevated to zonal status) an additional 4 zones were described based upon newly described species (Figures 2 and 3). These included the *Catapsydrax stainforthi* Zone (=PRZ), *Globorotalia kugleri* Zone (=TRZ), *Globorotalia opima opima* Zone (=HOZ) and *Globorotalia ampliapertura* Zone (=HOZ) which replaced the *Gg. apertura* Zone of Suter (1951). Following the reasons outlined in Bolli (1954), *Globigerina ciperoensis ciperoensis* replaced the previously applied *Gg. concinna* (Zone I) as the nominate taxon for this Zone (i.e. it became the *Gg. ciperoensis ciperoensis* Zone (=IZ)). The aforementioned zone represented the interval between the overlying *Gr. kugleri* Zone and underlying *Gr. opima opima* Zone. Perhaps most importantly, Bolli recognised the error of the previous schemes in defining the Oligocene-Miocene boundary and amended his scheme, placing the boundary at the top of his newly described *Gr. kugleri* Zone. This level is much more consistent with the current base of the

Aquitanian close to Base *Paragloborotalia kugleri* (Zone M1) (Steininger et al. 1997; Wade et al. 2011).

While Walter Blow worked briefly in Trinidad for TLL, the majority of his earlier publications stemmed from his PhD studies of the upper to lower Miocene sequence of the Pozon-El Mene section. This was situated in close proximity to the section studied by Renz (1948) in the State of Falcón, eastern Venezuela. Blow (1959), published during his employment with British Petroleum, recognised eight zones (Figures 2 and 3) and correlated the majority directly to those from Trinidad. In addition, Blow suggested the biostratigraphic utility of the bases of *Globigerinoides triloba*, *Globigerinoides bispherica* (which Blow (1969) considered a junior synonym of *Globigerinoides sicanus*), *Globorotalia lenguaensis* and *Globigerina nepenthes* which were used to form subzones (LOSZ) in the *Gt. insueta* and *Gr. mayeri* Zones respectively. New zones above the *Gr. menardii* Zone were also recognised; namely the *Sphaeroidinella seminulina* Zone (HOZ) and *Globigerina bulloides* Zone (PRZ) due to the Pozon Formation still featuring an abundance of planktonic foraminifers while the group was more or less absent above the Lengua Formation (e.g. above the *Gr. menardii* Zone) in southern Trinidad. In the same year, Bolli (1959) discussed the potential of planktonic foraminifera as a correlative biostratigraphic tool globally and highlighted the increasingly important role of microfossils in dating seafloor sediments, which later become the foundation of more recent microfossil biostratigraphic schemes (e.g. Berggren et al., 1995; Berggren and Pearson, 2005; Wade et al., 2011).

2.3. The expansion of the Caribbean biostratigraphic schemes

In the succeeding years there was a need for more detailed zonal schemes, so localities within the wider Caribbean (particularly Jamaica and elsewhere in Venezuela) and further afield (e.g. Java, Indonesia) became increasingly important (Figure 2). Both Bolli (Bolli and Bermudez, 1965; Bolli, 1966a, 1970; Bolli and Premoli Silva, 1973) and Blow (Banner and Blow, 1965a; Blow, 1969) proposed zonal schemes for the problematic late

Miocene interval, as well as amending their earlier schemes. One of the key differences was that Bolli named zones using species, whereas Blow used alpha-numeric codes (e.g. Zone N12) with a longer formal name (e.g. *Globorotalia fohsi* PRZ) (Figures 2 and 3). This alphanumeric nomenclature donated Palaeogene biozones with a letter P and Neogene as an N and became the standard convention in later biostratigraphic schemes (e.g. Berggren et al., 1985, 1995; Wade et al., 2011), although these later schemes referred to Miocene, Pliocene and Pleistocene zones as M, Pl and Pt respectively.

Bolli's scheme remained unchanged for the most part from Bolli (1957) but he added a lower Oligocene *Cassigerinella chipolensis- Pseudohastigerina micra* Zone (=CRZ) (renamed after the *Globigerina oligocaenica* Zone of Blow and Banner (1962)). In addition, Bolli used both Base *Praeorbulina glomerosa* (=LOZ) and the top Miocene occurrence of *Globigerinoides ruber* (=HOZ) (=Top *Globigerinoides subquadratus*) to define mid Miocene zones which respectively divided the upper part of Bolli's (1957) *Gt. insueta* Zone and lower part of the *Gr. mayeri* Zone (Figures 2 and 3). The *Gs. ruber* Zone was recognised in Java, Indonesia (Bolli, 1966b) but was not found in Trinidad due to an apparent hiatus between the Cipero and Lengua formations (Bolli, 1966a). Two late Miocene zones were also added; namely a lower *Globorotalia acostaensis* Zone (=LOZ) and upper *Globorotalia dutertrei*/*Globigerinoides obliquus extremus* Zone (=LOZ) (Bolli and Bermudez, 1965). The latter was defined solely on Base *Gg. dutertrei* in Bolli and Premoli Silva (1973), which in turn was amended to the *Globorotalia humerosa* Zone (=LOZ) (Bolli and Saunders, 1985).

Banner and Blow (1965a) and Blow (1969) retained a number of zonal markers with a few key differences compared to Bolli's zonation (Figures 2 and 3). The "holotype" biozone localities given by Blow (1969) for the Oligocene and Miocene (~Zones N1-N17) were all from the Caribbean region, namely southern Trinidad, eastern Venezuela or eastern Jamaica (Figure 3). Blow's formal names were long and had a tendency to be based on multiple species (i.e. CRZ or PRZ). The same biozonation scheme was also applied by Berggren (1969) in the first major attempt to correlate planktonic foraminiferal bioevents with palaeomagnetics. The major differences in Blow's (1969) biozonation compared to Bolli's (Bolli and Bermudez, 1965; Bolli, 1966a) included:

1. Using the origination of *Globigerinoides primordius* as a means of dividing the *Gr. kugleri* Zone into Zones N3 and N4 respectively, marking the Oligocene-Miocene boundary (Blow, 1969).
2. Base *Orbulina suturalis* in defining mid Miocene Zone N9 (Banner and Blow, 1965a) equivalent to the uppermost part of the *Pr. glomerosa* Zone and the entirety of the *Gr. fohsi barisanensis* Zone of Bolli (1966).
3. Following Blow and Banner's (1966) description of *Globorotalia peripheroacuta* and *Globorotalia praefohsi*, the first occurrences of these species were taken to mark the bases of mid Miocene Zone N10 and N11 respectively. While Bolli (1967:509) accepted these species, he rejected their use as zonal markers suggesting they offered "practically no advantage" but could be used to define subzones.
4. Mid Miocene Zone N13 was marked by the origination of *Sphaeroidinellopsis subdehiscens* (Banner and Blow, 1965a), which was equivalent to the upper limits of the *Gr. fohsi robusta* and *Gs. ruber* Zones of Bolli and Saunders (1985).

The upper Miocene zones varied greatly with Blow (1969), suggesting his and Bolli's (1966a) zones could not be correlated. Blow thought Bolli's *Gr. acostaensis* Zone had horizons referable to his N16-N17 zones, despite using the same species to mark the base of Zone N16. Blow also suggested Bolli's *Globorotalia dutertrei*/*Globigerinoides obliquus extremus* Zone (=*Gr. humerosa* Zone) had horizons referable to Zones N16 to N18, with Blow using Base *Globorotalia plesiotumida* to mark the base of Zone N17. In contrast, Bolli and Saunders (1985, figure 4) appeared to infer that both Zones N16 and N17 directly correlated to the *Gr. acostaensis* and *Gr. humerosa* Zones although state that these correlations are as close as stratigraphically possible considering the use of different zonal markers. The difficulty in upper Miocene zonations was reflected in Lamb and Beard (1972) who applied a *Globorotalia acostaensis* Zone (=LOZ) across the entirety of the upper Miocene in their zonation of the Caribbean and the Gulf of Mexico. They stated that Base *Gr. acostaensis* represented an excellent datum for worldwide correlation, although they did subdivide the *Gr. acostaensis* Zone into a lower *Sphaeroidinellopsis seminulina* Subzone (=HOSZ) and upper *Sphaeroidinellopsis sphaeroides* Subzone (=LOSZ) although the equivalent interval in their Mediterranean zonation is an undefined zone.

Stainforth et al. (1975:96) retained the *Gr. acostaensis* Zone but not the subzones. They acknowledged the potential of Bolli's (1966a) upper Miocene zones but stated that difficulty might arise because "they are based on recognition of several steps in the gradual evolutionary change from *Globorotalia acostaensis* to *Globorotalia humerosa*". The same study also stated that the *Globorotalia merotumida* to *Globorotalia plesiotumida* lineage applied in the recognition of Zones N16 and N17 in Banner and Blow (1965a) and Blow (1969) is "difficult to recognize because of the close similarity of the subspecies upon which the zonal definitions are based." The biozone schemes for the Oligocene to middle Miocene in Stainforth et al. (1975) more closely resembled that of Bolli, with the authors suggesting Bolli's scheme had priority and while Blow's schemes had merits, particularly the introduction of the *Globigerinoides* and *Orbulina* datums, the overall change to the total zonation was minor. In addition, Stainforth et al. (1975:76) highlighted the preference for using Bolli's single species names in defining zones, as opposed to Blow's "formal and usually lengthy title…to name and define the unit" which was "too cumbersome for routine use" and while they found the alphanumeric N and P zones "convenient" this system offered "no inherent clue to stratigraphic level". In particular citing the issue regarding the earliest Neogene zone being Zone N4 as opposed to Zone N1, although this issue was resolved by Berggren et al. (1985). Postuma (1971) erected an Oligo-Miocene zonation and while this retained certain datums, it was fairly different to schemes previously mentioned and was less influential in forming later biostratigraphic schemes.

2.4. Later zonations and reliance on ocean research drilling

The Caribbean region formed the basis of low latitude schemes (e.g. Berggren et al., 1995; Wade et al., 2011), however, the higher resolution sampling associated with ocean research drilling and recognition of more suitable outcrop samples have allowed planktonic foraminiferal datums to be calibrated with other stratigraphic frameworks. Initially this tended to be palaeomagnetic studies (e.g. Berggren and van Couvering, 1974; Opdyke et al., 1974) but cyclostratigraphy has become increasingly important (e.g. Shackleton et al., 1999; Hilgen et al., 2000). Unfortunately, one of the major drawbacks of the Caribbean type localities is the lack of such stratigraphic methods that can be used in conjunction with the excellent biostratigraphy of the region. While some upper Miocene palaeomagnetic reversals have been identified in Buff Bay (Jamaica) this is limited to Chron C5r, which in itself is incomplete (Miller et al., 1994) and is hampered by the overprinting of present day magnitisation, which makes interpretation difficult. In addition, the Caribbean sequences tend to be discrete outcrop samples as opposed to continuous cored samples.

Despite this, the bioevents applied by Bolli, Blow and others in their respective Caribbean schemes have remained remarkably consistent across planktonic foraminiferal biochronologies, as shown in Figures 2 and 3. Of the 24 primary Oligo-Miocene bioevents applied in Wade et al. (2011), eleven were first recognised in Trinidad, five in Venezuela and two in Jamaica (Figure 2). If these are considered with respect to the author who first recognised the bioevent (Figure 3) fourteen were from authors presenting Caribbean centric findings. To break this down further Bolli recognised five bioevents (Bolli, 1951, 1957, 1966a; Bolli and Bermudez, 1965), Blow applied seven (Blow, 1959, 1969, 1979; Banner and Blow, 1965a), three were given by Cushman and other researchers (Cushman and Stainforth, 1945; Cushman and Renz, 1947) and one bioevent was first applied by Brönnimann (Brönnimann, 1950).

3. Correlating the Caribbean zonations

To assess which boundaries have generally been well recognised throughout initial and subsequent biozonations, and which boundaries are slightly more contentious, a total of fourteen planktonic foraminiferal schemes from Bolli (1957) to Wade et al. (2011) were compared. These included those based predominantly on bioevents observed in the Caribbean (Bolli, 1957; Blow, 1959; Banner and Blow, 1965a; Bolli, 1966; Blow, 1969; Postuma, 1971; Stainforth et al., 1975; Blow, 1979; Bolli and Saunders, 1985) and from other localities, particularly ocean drilling expeditions (Kennett and Srinivasan, 1983; Spezzaferri, 1994; Berggren et al., 1995; Berggren and Pearson, 2005; Wade et al., 2011). Most of these zonations span the whole Oligocene and Miocene, with four only partially covering this interval (Blow, 1959; Kennett and Srinivasan, 1983; Spezzaferri, 1994; Berggren and Pearson, 2005). As the focus is on the bioevent applied, as opposed to the timing of the bioevent, all the datums for the zonations are based on the primary and secondary datums listed by Wade et al. (2011). In cases where the zonal boundary is ambiguous due to bioevents now considered diachronous, a dashed line is used. Biozone types based upon our opinion are illustrated by braces (e.g. {TRZ}). When authors described the type of zone in the text but did not include this in the formal name of the biozone, the type of zone appears in parentheses (e.g. (TRZ)). No brackets are used where the author included the type of zone in their formal zone name.

Figures 4-7 illustrate the biostratigraphic correlations through the Oligocene to late Miocene. Table 1 summarises the various primary and secondary bioevents according to Wade et al. (2011), the number of times they were applied relative to the number of schemes with coverage through the given interval and finally the percentage of times the given datum has been used. This allows an assessment of which datums have been applied most consistently, which may be considered the most recognisable in the low latitudes and whether authors favoured particular bioevents in cases where the use of a bioevent was not ubiquitous. While the majority of species were described before the first zonation considered (Bolli, 1957) a few species were described in the succeeding years. These new species were often subdivisions of earlier species concepts (e.g. *Pg. pseudokugleri* within *Pg. kugleri*, and *F. peripheroacuta* and *F. "praefohsi"* within *F. fohsi*), meaning these later species have been retrospectively applied to all the zonations. In addition, the compilations highlight instances where a given biozone does not correlate to later biogeochronologies (e.g. between Zones N1 and N2 of Banner and Blow (1965a) and Blow (1969); Figure 4) due to discrepancies in the range of the bioevents applied, where the taxonomic concept of a certain author has changed (e.g. *Tb. bisphericus* of Blow (1959) was later considered a junior synonym of "*Tb. sicanus"* by Blow (1969); Figure 5). These, and other relevant notes, are highlighted by square bracketed letters in Figures 4 to 7, which are discussed in the figure captions.

4. Assessing biostratigraphic recognisability

The following section discusses the recognisability of the bioevents applied in Figures 4-7 and instances where discrepancies exist. This section is organised by first discussing those which are the most consistently applied (Section 4.1), before focusing a bioevents defined by a lineage (Sections 4.2 to 4.5) or genera (Section 4.6). Finally, Section 4.7 discusses the Late Miocene interval, while Section 4.8 deals with other bioevents which do not fall naturally into the previous sections. As mentioned in Section 3 and illustrated in Figures 4-7, the taxonomic concepts applied through time have not always remained stable which in some cases can be problematic where the taxonomy and/or synonymies applied has not been fully discussed. The correlation charts (Figures 4-7) assume that the historical taxonomic concept has not drastically changed through time (unless otherwise stated) and has remained stable. In order to ensure that this is the case, a number of residue samples applied in the Caribbean zonation schemes have been re-examined as part of this study, while museum collections housed at the Natural History Museum (NHM) in London and the Smithsonian National Museum of Natural History (USNM) in Washington D.C. have been re-examined. The slides include material collected and illustrated by Bolli (1957), Blow (1959), as well as unillustrated material from Blow. This allows an assessment to be made on whether the specimens recognised by the author as a given species fits within the concept applied at present. Figure 8 illustrates the sample IDs for the residues and slides which have been re-examined and are discussed within this section, relative to the biozonations of Wade et al. (2011), Blow (1969/1979), Blow (1959) and Bolli (1957), in order to place these samples in a stratigraphic context. The corresponding biozone for each residue relative to Wade et al. (2011) is based upon our re-examination relative to the bioevents applied in the aforementioned zonation. As the slides examined tended to consist of few specimens of a single species, the zone given by the original analyst has been applied. Plate 1 illustrates select specimens from some of the key samples discussed in Section 4.1 to 4.8 and includes new illustrations of material from Bolli (1957) which has previously only been figured via drawings.

4.1. The most consistently applied bioevents

As seen in Table 1, the most consistent bioevents are Top *Pg. mayeri* (including *Pg. siakensis*; Zone M12), Base *F. peripheroacuta* (Zone M7) and Top *Cs. dissimilis* (Zone M4). These were applied in all the schemes with coverage through the respective intervals and so can be considered extremely recognisable in planktonic foraminifera biostratigraphy. However, the *Pg. mayeri* HOZ should be amended to the *Pg. siakensis* HOZ (see Section 6 for further discussion). The next most consistently applied datums (applied in >90%) are Top *Pg. kugleri* (Zone M2), Top *Pg. opima* (Zone O6) and Top *Ps. naguewichiensis* (Zone O2; although considered to represent pseudohastigeriniids as a whole). Of these, three represented lineage extinctions namely *Pg. siakensis*, *Pg. kugleri* and *Ps. naguewichiensis*, with the latter also being the extinction of a genus. Top *N. acostaensis* (Subzone M13a) was applied in ~90% of the schemes but was not recognised as a bioevent by Blow (1959) in his original description. However, Base *N. acostaensis* was later used by the same author to mark Base Zone N16 (Banner and Blow, 1965a; Blow 1969/1979). This shows the species is likely a robust marker and that the biostratigraphic value was not initially recognised.

4.2. The *Fohsi* bioevents

Base *F. peripheroacuta* (Zone M7; 100%) was the most commonly applied of the *Fohsi* datums. The higher percentage is due to some authors (e.g. Bolli, 1967; Stainforth et al., 1975) including *F. "praefohsi"* and *F. fohsi* within their *F. peripheroacuta* concepts (see Si and Berggren (2017) for a discussion on the taxonomic differences between *F. praefohsi* and *F. "praefohsi*"). This in turn explains the significantly lower frequency of these two species (~55% and ~45% respectively, Table 1). This creates a combined Zone M7-M9a if considered in respect to Wade et al. (2011) (see Figure 5 and the zonations of Bolli (1957), Blow (1959), Bolli (1966), Stainforth et al. (1975) and Bolli and Saunders (1985)). Blow and Banner (1966) described *F. peripheroacuta* (Sample RM 19367; see Figure 8) and *F. praefohsi* (Sample RM 19410; Figure 8) from the Pozon Formation. Blow (1969, 1979) also found forms consistent with both species in samples from the Cipero Formation in Trinidad, (sample JS 1567, Figure 8). Regarding this sample Blow (1969:236) stated "sample JS.1567 has not been found to contain any carinate forms referable either to *G. (G.) fohsi* or to *G. (G.) praefohsi*, but it does contain the non-carinate, acutely-margined but fully perforate *G. (T.) peripheroacuta.*" Analysis of specimen slides made by Blow from this sample in the Micropalaeontology collections of the Natural History Museum (London), shows many specimens consistent with *F. peripheroacuta* (Plate 1, Figures 1a-c)*,* although forms described as *F. "praefohsi"* were found in the sample which were identified by Desai and Banner (NHMUK PM BP 2668; Plate 1, Figures 2a-c) which is contrary to Blow's original observation.

Blow (1969) found specimens consistent with *F. peripheroacuta* and *F. "praefohsi*" in the type sample of Bolli's (1957) *Gr. fohsi fohsi* Zone (Sample Bo 185A; Figure 8). Additionally Blow and Banner (1966) reassigned the forms from this sample illustrated as *Gr. fohsi fohsi* in Bolli (1957; plate 28, figures 9a-c and 10a-10c) to *Globorotalia* (*Gr.*) "*praefohsi"* and *Globorotalia* (*Tr.*) *peripheroacuta*. Our restudy of these specimen slides (USNM P5668; Plate 1, Figures 3a-c) and P5567; Plate 1, Figures 4a-c)) agrees with Blow and Banner's (1966) observations of the specimens being referable to *F. peripheroacuta* and *F. "praefohsi"* respectively. Our analysis of the residue of this sample (Bo 185A) found this to be a rich in planktonic foraminifera and while a form consistent with *F. fohsi* was found (Plate 1, Figures 5a-c) this was the only specimen found and may be a product of reworking or merely shows *F. fohsi* is very uncommon this sample. Likewise Olsson (1971) found forms consistent with only *F. peripheroacuta* and *F. "praefohsi"* in sample Bo 185A. Therefore, Bolli's *Gr. fohsi fohsi* Zone type sample is considered consistent with Zone M8 (Base *F. "praefohsi"*) rather than Subzone M9a (Base *F. fohsi*).

Bolli did later recognise *F. peripheroacuta* and *F. "praefohsi"* as subspecies of *F. fohsi* (Bolli and Saunders, 1985) but retained a *F. fohsi* s.l. concept in the definition of their *F. fohsi* Zone. The range charts (e.g. figure 9) presented in Bolli and Saunders (1985) showed that *F. peripheroacuta*, as expected, originated first but Base *F. fohsi* was found prior to Base *F.* "*praefohsi"* therefore under this concept Zone M8 would not be recognisable (see also Section 5). This is contrary to Blow (1969), Olsson (1971) and this study which all found that a sample with *F. "praefohsi*" and the absence of *F. fohsi* s.s. illustrating that the Zone M8 interval is apparent in the Cipero Formation. Despite Bolli's *F. fohsi* Zone not being equivalent to Subzone M9a, the type sample for Bolli's *F. lobata* Zone (JS 32; Figure 8) contains forms consistent with *F. fohsi*, while Cushman and Stainforth (1945) type sample Rz 425 (Figure 8) for Zone III (*Gr. fohsi* Zone) was taken from the same section and again had forms consistent with both *F. fohsi* and *F. lobata* (Plate 1, Figures 6a-c). This therefore illustrates that horizons within Subzone M9a are found within the Cipero Formation and merely reflects the differing taxonomic concepts applied by Bolli and Blow.

The use of Base *F. robusta* (~13.13 Ma; ~64%) and Base *F. lobata* (~13.20 Ma; 54%) represent two of the more problematic datums in the Miocene which is probably because they originate in a short timeframe (~70 Ka apart) and the continual gradual evolution of the *fohsi* group (e.g. Norris, Corfield and Cartlidge, 1996). Contrary to earlier studies where *F. lobata* is considered ancestral to *F. robusta* (e.g. Blow and Banner, 1966; Stainforth et al., 1975; Kennett and Srinivasan, 1983; Aze et al., 2011), Si and Berggren (2017, figure 2) considered *F. lobata* and *F. robusta* to not be phylogenetically related with *F.*

robusta being descended from *F. fohsi* via *F. "praefohsi"*, while *F. praefohsi* is ancestral to *F. lobata*. Regardless the two morphospecies are historically important in biostratigraphy. In the eight zonations that use these species, five opt to apply both datums although three of these are studies from Bolli (Bolli,1957, 1966a; Postuma, 1971; Bolli and Saunders, 1985; Berggren et al., 1995). Two apply Base *F. robusta* only (Blow, 1959; Wade et al., 2011) while Stainforth et al. (1975) solely applies Base *F. lobata*. Both would present biostratigraphically useful datums, although Base *F. lobata* currently lacks an astronomically calibrated datum (Wade et al., 2011). The *fohsi* group are well represented in a number of low latitude oceanic core sections that are palaeomagnetically or astronomically calibrated (e.g. ODP Leg 130, Site 806 (Chaisson and Leckie, 1993; Eisenach and Kelly, 2006); ODP Leg 154, Sites 925 and 926 (Chaisson and Pearson, 1997; Pearson and Chaisson, 1997); ODP Leg 184, Site 1148 (Li, et al., 2004)). An effort should be made to calibrate Base *F. lobata* in future biostratigraphic studies due to the historical significance of this bioevent. This would require an amendment of the zonal number although this is discussed further in Section 6.

Top *F. fohsi* (Zone M10) was applied in ~80% of the zonations with the exception of Banner and Blow (1965a) and Blow (1969), who instead opted to apply Base *Sphaeroidinellopsis subdehiscens* in defining the nearest equivalent bioevents, although this was applied significantly less (~18%). However, it is important to note that here we considered Top *F. fohsi* to represent the extinction of the whole *fohsi* group (i.e. the extinction of the lineage) rather than just *F. fohsi* (see Section 5). This is because several studies suggested Top *F. fohsi* to occur prior to Top *F. robusta* (e.g. Bolli, 1957; Blow, 1959; Postuma, 1971; Stainforth et al., 1975; Bolli and Saunders, 1985). Indeed Wade et al., (2011:133) state "the HO (Top) of *Fohsella robusta* and *F. fohsi* are estimated to be at the same stratigraphic level" but they apply Top *F. fohsi* due to the lack of an astronomically calibrated datum for Top *F. robusta* from ODP Leg 154 Site 925 (Chaisson and Pearson, 1997). Conversely, Berggren et al. (1995) applied Top *F. robusta* based on the datum from DSDP Leg 82 Site 563 (Berggren, Kent and van Couvering, 1985), although this site was at a higher latitude than ODP Site 925 (~33°N compared to ~5°N). It is likely that Top *F. fohsi* and *F. robusta* are near synchronous, but a calibrated datum for both would provide a better means of assessing the most suitable zonal marker for Base M10.

4.3. The use of *Globigerinatella*

The base of *Gt. insueta* s.s. was commonly applied (~75%) and marked the base of Zone M3 in Berggren et al. (1995) , while the zonations which did not apply Base *Gt. insueta* were Blow (1959), Postuma (1971) and Wade et al. (2011). The latter considered this a secondary datum and opted to apply the first occurrence of primitive forms of *Globigerinatella* (referred to as *Globigerinatella* sp.) as Base M3, although this is unique to Wade et al. (2011). This change in datum was based on Chaisson and Leckie (1993), Spezzaferri (1994), Pearson (1995) and Pearson and Chaisson (1997) who described evolutionary trends in *Globigerinatella*. Pearson (1995) suggested forms that possessed areal apertures (*Gt. insueta* s.s.) or lacked areal apertures (*Globigerinatella* sp.) could be a useful means of subdividing the early Miocene. However, based on the datums provided in Wade et al. (2011), the use of Base *Gt. insueta* would create a condensed zone prior to Top *Cs. dissimilis*, which could easily be missed if the sampling resolution was not high enough. Unfortunately, due to limited number of images in studies applying Base *Gt. insueta* as a zonal marker, it is not possible to accurately deduce whether the forms referred to as *Gt. insueta* in these studies possessed or lacked areal apertures without re-examining original material used to define each zone. Our reanalysis of Cushman and Stainforth's (1945) type sample for the *Gt. insueta* Zone (Rz 108; Figure 8), which is also the type locality for the genus and species, found only forms possessing areal apertures (i.e. *Gt. insueta*) (Plate 1, Figures 7a-c), a conclusion also noted by Pearson (1995) in his analysis of the holotype and paratypes of *Gt. insueta*, as well as the illustrated “topotypes” from Stainforth et al. (1975; figure 125.5-6). Forms referable to *Globigerinatella* sp. have been illustrated within the Caribbean region from the Pozon Formation, albeit tentatively (Blow, 1959; plate 15, figure 95), and ODP Site 999 on the Kogi Rise, western Caribbean Sea (Chaisson and D’Hondt, 2000; plate 2, figure 11). Due to the historical application of *Gt. insueta,* a subdivision of Zone M3 into Subzone M3a (=Base *Globigerinatella* sp.) and Subzone M3b (=Base *Gt. insueta*) may be beneficial for correlative purposes despite the extremely condensed zone (~50 Ka) this would create (see Section 6). However, a study focusing on the *Globigerinatella* evolutionary trends may prove useful to better constrain the concepts applied to these morphotypes, as well as formally naming a species for forms currently referred to as *Globigerinatella* sp.

4.4. The *Praeorbulina-Orbulina* bioevents

Although marginally more authors applied *Pr. sicana* (including sensu scrito (~18%) and sensu lato (~36%)) compared to Base *Pr. sicana* (~55% compared to ~45%), the application of *Pr. sicana* is perhaps one of the more difficult bioevents to accurately quantify due to the taxonomic concept being fairly unstable. Figures 2 and 3 show that Blow (1969) was the first to apply the origination of *sicana* as a bioevent, however as mentioned in Section 2.2, the concept applied regarded *Tb. bisphericus* as a junior synonym of *sicana*. Blow assigned to *sicana* to *Globigerinoides* (as *Globigerinoides sicanus*), as opposed to *Praeorbulina*, with forms with two to four sutural apertures included within his concept of the species. A similar view was shared by Stainforth et al. (1975), although they considered the species to have a single primary aperture on the umbilical side, with one or more smaller triangular sutural apertures on the spiral side. In contrast, Bolli and Saunders (1985) considered the two distinct species with *Globigerinoides bisphericus* (forms with two sutural apertures) giving rise to *Praeorbulina sicana* (forms with four sutural apertures), following the restudy of the holotype specimens by Jenkins et al. (1981), where the two were considered distinctly different. However, as noted by Turco et al. (2011) the holotype re-study does not account for the overall population variability and excludes forms with three sutural apertures. Instead they regarded forms with two to three sutural apertures as "*Globigerinoides sicanus*" with *Praeorbulina* being recognised by forms with four sutural apertures.

The taxonomy of *sicana* is not the focus of this study, although an issue does exist whereby the origination of *bisphericus* lacks a suitable age calibration. Therefore, the studies applying *sicana* s.l. (=Base *Tb. bisphericus*) in Figure 5 lack a definitive base and should be treated with uncertainty. Pearson and Chaisson (1997) discussed the difficulty in differentiation between *Tb. bisphericus* and *Pr. sicana*, and in some instances deduced that only via the means of SEM study was a differentiation able to be made. Likewise, Jenkins et al. (1981) concluded that neither the origination of *sicana* or *bisphericus* were suitable bioevents, instead suggesting the base of *Praeorbulina curva* was more suitable. While the use of *Pr. sicana* in defining the base of Subzone M5a in this study, this is on the basis that more work needs to be undertaken, with a potential conclusion being that Base *Pr. sicana* is unsuitable in biostratigraphy due to conflicts in taxonomy and generic assignment. Therefore, Zone M5 may be better served by the first irrefutable origination of *Praeorbulina* (i.e. *Pr. glomerosa* or *Pr. curva*), with the former being preferable due to the relative scarcity of the latter in the low latitude realm (e.g. Pearson and Chaisson, 1997).

The widely recognised *Orbulina* datum (Base M6) was readily applied (~64%) but is perhaps slightly negatively skewed because three of the four cases that Base *O. suturalis* was not used were the studies by Bolli (Bolli, 1957, 1966a; Bolli and Saunders, 1985). The remaining study was that of Blow (1959) but this was applied in later studies by the same author (Banner and Blow, 1965a; Blow, 1969). The closest zonal boundary suggested by the studies not applying the *Orbulina* was Top *Gt. insueta* (~36%) which occurs ~45 kyr after Base *O. suturalis* (Wade et al., 2011). Blow (1969/1979) opted to apply Base *O. suturalis* for the Base of Zone N9, from the sample in which Bolli (1957) used to define the base of the *Globorotalia fohsi barisanensis* Zone. Bolli and Saunders (1985) discussed the *Orbulina* datum but did not apply it, highlighting that it is less recognisable in the Pacific and temperate regions. Likewise Wade et al. (2011) did not define the datum from Ceara Rise (ODP Site 925) due to the rarity of *Orbulina* at the base of its range and instead retained the datum given in Berggren et al. (1995) based upon DSDP Leg 72 Hole 516F (Rio Grande

Rise; ~30°S). Due to the more temperate setting of Hole 516F, a lower latitude may provide a more suitable datum for use in tropical-subtropical biozonations.

4.5. The application of the *pseudokugleri-kugleri* lineage, and Zone M1

Top *Pg. kugleri* (Base Zone M2) represents one of the most consistently applied bioevents (~91%) while the *Pg. pseudokugleri-kugleri* lineage also accounts for the bases of Zones O7 (Base *Pg. pseudokugleri,* ~55%) and Subzone M1a (Base *Pg. kugleri,* 27%). However, most of the recent biozonations applied Base *Pg. kugleri* as a zonal marker (Spezzaferri, 1994; Berggren et al., 1995; Wade et al., 2011). While Bolli (1957, 1966a), Banner and Blow (1965a), and Bolli and Saunders (1985) used the base of "*kugleri*" to define a zone, this would now be consistent with Base *Pg. pseudokugleri* as these species were previously considered together prior to the description of *Pg. pseudokugleri* (Blow, 1969). However, Stainforth et al. (1975), Kennett and Srinivasan (1983) and Bolli and Saunders (1985) did not recognise *Pg. pseudokugleri* and thus continued to consider them synonymous. Bolli and Saunders (1985:203) stated that *Pg. kugleri* and *Pg. pseudokugleri* (along with *Globorotalia mendacis=Paragloborotalia birnageae* (see Leckie et al., 2018)) had "virtually the same range," were "difficult to distinguish" and so suggested the subdivision had no stratigraphic value. These two species do show a gradual evolutionary trend meaning differentiation can be challenging, which increases the need to apply consistent taxonomic concepts. Leckie et al. (2018) outlined a number of criteria for distinguishing between the two, which we followed in species designation. Unfortunately, where the two are considered synonymous it is not possible to tell whether both *Pg. pseudokugleri* and *Pg. kugleri* could have been observed based on the limited figures available (e.g. Bolli and Saunders, 1985). While Blow (1969, 1979, figure 9) differentiated between the two morphotypes, he suggested a synchronous origination, although tentatively, for Base *Pg. pseudokugleri* and Base *Pg. kugleri* within Zone N3 (=Zone O7). This may imply that even the describing author of *Pg. pseudokugleri* found it difficult to consistently differentiate between the two morphotypes.

Pearson and Wade (2009) collected a number of samples from Trinidad, including some close to Blow's (1969) co-type locality for the *kugleri* Zone and showed it was possible to recognise both the base of *Pg. kugleri* (Subzone M1a) and *Pg. pseudokugleri* (Zone O7). We undertook a reanalysis of a number of type sample residues from Bolli (1957) and the co-type locality of Blow (1969) which showed a similar result. The type locality of Bolli's (1957) *Globigerina ciperoensis ciperoensis* Zone (Bo 291a, Cipero Formation) contained a low diversity and rare planktonic foraminiferal assemblage which lacked forms consistent with both *Pg. pseudokugleri* and *Pg. kugleri*. In addition, *Pg. opima* was absent suggesting this sample would be consistent with Zone O6 (Figure 8). The next stratigraphically younger sample from Bolli's *G. ciperoensis* Zone (Bo 270; the type locality for *Catapsydrax unicavus*) contained a more diverse and abundant planktonic foraminifera assemblage. Here forms consistent with *Pg. pseudokugleri* (Plate 1, Figures 8a-c) but not *Pg. kugleri* were found suggesting this would now be considered within Zone O7 (Figure 8). Samples from the type locality of Bolli's *Globorotalia kugleri* Zone (Bo 274) and Blow's co-type locality in Mosquito Creek showed greatly contrasting degrees of foraminiferal abundance and preservation, with the latter being much richer with better preservation. However, both assemblages contain *Pg. pseudokugleri* and *Pg. kugleri* (Plate 1, Figures 9a-c), along with *Cr. ciperoensis* (the top of which is a secondary marker in the basal part of Subzone M1a; Figure 1) but lacked *Globoquadrina dehiscens* (the zonal marker for Subzone M1b), suggesting these two samples were in the more basal part of Subzone M1a (Figure 8).

While the Zone O7 to Subzone M1a interval appears to be represented in the Cipero Formation, no samples were found in which *Gq. dehiscens* co-occurred with *Pg. kugleri*, which is in agreement with samples analysed by Pearson and Wade (2009). This suggests Subzone M1b is probably absent in the Cipero Formation. Base *Gq. dehiscens* represents one of the lesser applied primary markers (~27%) and was not recognised in any of the Caribbean centric zonations. The range chart of Bolli (1957; figure 18) suggested this species originated at the base of the *Cs. stainforthi* Zone, the same level as Base *Gt. insueta* (within Zone M3). Our reanalysis of Bolli's figured hypotypes from the *Gr. fohsi lobata* Zone

(Js 32; Figure 8) (=Subzone M9a; USNM P5622) and *Gr. fohsi robusta* Zone (Js 46; Figure 8) (=Subzone M9b; USNM P5623) confirm his concept is consistent with *Gq. dehiscens*. Bolli and Saunders (1985) did amend the range of *Gq. dehiscens* but only to the base of the *Cs. dissimilis* Zone, the same level as Top *Pg. kugleri* (Zone M2), again suggesting the Subzone M1b interval was not apparent. While Blow (1969/1979; figure 7) found Base *Gq. dehiscens* extending down into Zone N4 (Zone M1), the author stated that the species did not become common until Zone N5 (Zone M2-M3) and does not discuss occurrences of *Gq. dehiscens* within individual localities. Postuma (1971, chart 3) suggested a short ranging co-occurrence of *Pg. kugleri* and *Gq. dehiscens*, within an interval of questionable occurrences of the former, creating uncertainty in whether Subzone M1b would be applicable. Unfortunately, no assessment can be made based on the range chart in Stainforth et al. (1975; figure 16) as the authors only discussed a *Globoquadrina dehiscens* Group and did not individually discuss each of the species but the synonym list included species now referable to *Dentoglobigerina* (*Dg. baroemoenensis* including *“Globoquadrina*” *langhiana Dg. larmeui* and *“Globoquadrina” obsea = Dg, selii*), as well *Globoquadrina quadraria* which is now considered a junior synonym of *Gq. dehiscens* (Wade et al., 2018a). In addition Wade et al. (2018a) considered the forms illustrated by Stainforth et al. (1975, figure 113) consistent with *Gq. dehiscens*. Regarding Subzone M1b It may be possible that there is a hiatus in the interval equivalent in the Cipero Formation, or that there is a level of diachrony in the origination of this species within the low latitude realm, which was observed by Spezzaferri (1994, figure 3) in different oceanic basins.

4.6. The use of *Globigerinoides*/*Trilobatus*

The *Globigerinoides* datum was first proposed in 1959 by the Comité du Néogène as a means of recognising the Oligocene-Miocene boundary based on Base *Globigerinoides primordius* (=*Trilobatus primordius*) (Blow, 1969/1979). However this boundary was later ratified at a level closest to the origination of *Pg. kugleri* (Steininger et al., 1997). The use of the *Globigerinoides* datum was fairly uncommon (~33% Base *Tb. primordius,* ~27% Base

Tb. trilobus) in the Caribbean (e.g. Blow, 1969/1979; Stainforth et al. 1975; Bolli and Saunders, 1985) and was also applied by Kennett and Srinivasan (1983). Postuma (1971, chart 3) instead used Base *Tb. trilobus* despite both being included in the range chart, with *Tb. primordius* having a synchronous origination with *Pg. pseudokugleri* (*Gr. kugleri* of the authors). As discussed by Stainforth et al. (1975) and Bolli and Saunders (1985), the *Globigerinoides* datum can be tricky to recognise due the earliest specimens being small with poorly formed supplementary apertures, prompting both of these studies to define the *Globigerinoides* datum based on when representative forms of the genus become more frequent (i.e. a Base common occurrence). Bolli and Saunders (1985) erected a zone where *Globigerinoides* specimens were absent or rare (*Gr. kugleri* Zone) overlain by the *Gs. primordius* Zone where the species becomes more abundant and well formed (see Figure 4). This is also reflected in the secondary datums for *Tb. primordius*, where Wade et al. (2011) provide two datums based upon Base *Tb. primordius* (~26.3 Ma, within Zone O6) and Base common *Tb. primordius* (~23.6 Ma, within Zone O7), while Base *Tb. Trilobus* s.l. is listed as occurring at the same level as *Pg. kugleri* (~22.96 Ma). However, Bolli and Saunders (1985) suggested that both Bc *Tb. primordius* and/or Base *Tb. trilobus* defined the base of their *Gs. primordius* Zone which creates a diachronous base for this zone, despite their range chart showing a clear offset in the confirmed ranges. Stainforth et al. (1975) in their description of their *Globorotalia kugleri* Zone (base defined by the *Globigerinoides* datum) did not specify which species was applied in their concept of the zone which is reflected in zonal comparisons where a diachronous boundary (Figure 5) is placed between the *Gg. ciperoensis* and *Gr. kugleri* Zones (see also Berggren, Kent and van Couvering. 1985, figure 2). However, the range chart of Stainforth et al. (1975, figure 16) shows this level is only coincidental with *Tb. primordius*. In addition, the authors suggest Base *Tb. trilobus* occurred within the mid part of their *Cs. dissimilis* Zone (equivalent to Zones M2/M3). However, two of the authors of the previous study (Lamb and Stainforth, 1976) later discussed the potential unreliability of the *Globigerinoides* datum, and amended their Oligocene zonations (Stainforth and Lamb 1981), applying Base *Pg. kugleri* s.s. in defining their *Gr. kugleri* Zone and not considering the *Globigerinoides* datum. This is acknowledged by Berggren, Kent and van Couvering (1985) who apply Base *Pg. kugleri* in defining Zone M1.

The application of Top *Gs. subquadratus* in the mid Miocene was applied by Bolli (1966a) and Postuma (1971), however the former referred to the relevant zone as the *Gs. ruber* Zone and was defined by on the highest Miocene occurrence of *Gs. ruber.* However, it is clear in Bolli and Saunders (1985) that Bolli included *Gs. subquadratus* within his concept of *Gs. ruber.* The *Gs. subquadratus* Zone of these studies, was equivalent to Zone M10 and the basal part of Zone M11. This extinction of this species is considered a secondary marker within the basal part of Zone M11 by Wade et al. (2011), with a datum close to Base *Go. nepenthes* (~9 kyr; discussed below).

4.7. The late Miocene interval

This interval relies heavily on low trochospiral forms, particularly the globorotaliids which account for all the zonal markers from Zone PL1 to Subzone M13b. The primary marker of Base *Gr. tumida* (~67%) occurs in a relatively close proximity (~30-40 kyr) to the preceding secondary datum of Base *Gr. margaritae* (~44%) (Berggren et al., 1995; Wade et al., 2011). Authors had a tendency to favour one or the other bioevent, for example Base *Gr. margaritae* (Bolli, 1966a; Stainforth et al., 1975; Bolli and Saunders, 1985) or Base *Gr. tumida* (Banner and Blow, 1965a; Blow, 1969/1979; Kennett and Srinivasan, 1983; Berggren et al., 1995; Wade et al., 2011). The exception is Postuma (1971) who suggested a synchronous origination for both species. Bolli and Saunders (1985; figure 10) also suggested the datums were synchronous, while the range charts of Stainforth et al. (1975; figure 19) and Kennett and Srinivasan (1983; figure 16) show the inverse to Berggren et al. (1995) and Wade et al. (2011) with Base *Gr. margaritae* occurring after Base *Gr. tumida*. Assessing which marker is more suitable is difficult without other age calibrated datums. As Base *Gr. plesiotumida* marks the base of Subzone M13b, the use of Base *Gr. tumida* would seem more logical as this will mean these datums are based upon a lineage. However, the species boundaries within the *Gr. merotumida-plesiotumida-tumida* lineage are not entirely clear (e.g. Malmgren et al., 1983; Hull and Norris, 2009) and so may require a similar criteria approach to Leckie et al.'s (2018) treatment of the *pseudokugleri-kugleri* lineage in ensuring consistent taxonomic concepts are applied.

Base *Gr. plesiotumida* has been readily applied across zonal schemes (~60%) (Banner and Blow, 1965a; Blow, 1969/1979, Postuma, 1971; Kennett and Srinivasan, 1983; Wade et al., 2011). The species was described by Banner and Blow (1965b), following Blow (1959), and is reflected in Blow's (1969/1979) amendment of the zonations for the Pozon Formation (figure 17) where he tentatively applies Base *Gr. plesiotumida* in sample RM 19864 (Figure 8; see also Plate 1, Figures 10a-c for an illustration from nearby sample RM 20077). However, Blow did not use this sample, or indeed the species type locality on Cubagua Island in Venezuela as the zonation holotype or paratype locality, instead using sample ER 146/40 (Buff Bay, Jamaica; see Figure 8). While Berggren et al. (1995) applied Base *Gr. plesiotumida* to mark the base of Subzone M13b, they also stated that this species and/or *Globigerinoides extremus* could be used, which is offset by ~30 kyr according to Wade et al. (2011). The only other instance of *Gs. extremus* being applied was by Bolli and Bermudez (1965), who used Base *Gs. extremus* and *Neogloboquadrina dutertrei*. However, Bolli (1966a) solely applied Base *Globorotalia dutertrei* as the bioevent between the preceding *Gr. acostaensis* Zone and succeeding *Gr. margaritae* Zone. He later amended this to Base *Neogloboquadrina humerosa* (Bolli and Saunders, 1985) which is now considered a secondary marker with a near synchronous origination with Base *Gr. plesiotumida* (~2 kyr offset; Wade et al. (2011)). In their zonal description for the *N. humerosa* Zone, Bolli and Saunders (1985:170) referenced Takayanagi and Saito's (1962) type description of *N. humerosa* stating the species was "an evolutionary earlier stage from *Neogloboquadrina dutertrei*". It is therefore likely that Bolli (1966a) included forms later referable as *N. humerosa* within the original concept of the *Gr. dutertrei* Zone. This is also reflected in the range chart in Bolli and Saunders (1985; figure 10) who show the origination of *N. dutertrei* s.l at the base of the *Gr. margaritae* Zone (~ Zones M14/PL1). However, Bolli

(1966a) and Bolli and Saunders (1985) are the only two instances applying Base *N. humerosa* as a marker datum (~22%). Stainforth et al. (1975) did not apply any species in dividing their *Gr. acostaensis* Zone, meaning this spanned an interval equivalent to Base Subzone M13a to Base Zone PL1.

The base of Zone M14 is defined by Top *Gr. lenguaensis* which, other than *Globigerinatella* sp., represents the least applied primary datum in the Oligo-Miocene (~22%), having only been applied by Berggren et al. (1995) and Wade et al. (2011). The majority of authors did not recognise a zone between Base *Gr. plesiotumida* (and alternative markers discussed above) and Base *Gr. tumida* (or Base *Gr. margaritae*). Kennett and Srinivasan (1983) did subdivide this interval using Base *Pulleniatina primalis*, a secondary marker which occurs ~50 kyr prior to Top *Gr. lenguaensis*, although this is unique to this study. However, as will be discussed later (Section 5), the range of *Gr. lenguaensis* given in a number of range charts would be consistent with the species potentially being applied if correlated to the current zonation of Wade et al. (2011).

4.8. Other bioevents

The bioevents which do not fall naturally into any of the previously discussed sections, predominantly because they are the single representatives from their genus and are used less frequently than the majority of the other datums (~35-55%) are discussed here. Base *Globoturborotalita nepenthes* (Base Zone M11) is the most commonly applied (~55%) but was not applied in the studies of Bolli (1957; 1966a), Bolli and Saunders (1985), Postuma (1971) or Stainforth et al. (1975). The range charts in all of these studies, except for Bolli (1966a; table 4 who only illustrates the ranges of marker taxa), suggests this datum could potentially be applied (see Section 5). Bolli (1957) illustrated a form referred to as *Globigerina nepenthes* (USNM PR5621; plate 24, figures 2a-c) from the *Globorotalia mayeri* Zone (sample KR 23422) which has been reimaged as part of this study (Plate 1, Figures 11a-c). Our restudy of the residue of this sample confirms this species is present with *Pg. siakensis*, conforming to Zone M11 (Figure 8). Analysis of residues from Bolli's type locality for the *Gr. menardii* Zone (KR 23425) finds *Go. nepenthes* without *Pg. siakensis,* which is in agreement of the potential recognition of Zone M12 in the Lengua Formation of southern Trinidad (Figure 8).

The remaining datums all fall within zones O2 to O5 in the Oligocene. The Top common occurrence of *Chiloguembelina cubensis* presents an interesting case in the Caribbean. Despite being applied as a marker for the lower/upper Oligocene at a number of sites globally (see King and Wade (2017) for an in depth discussion) as well as recently being used to define the base of the Chattian (Coccioni et al., 2018), this datum was only applied in ~36% of the discussed sections. In addition, those applying this datum were the four most recent studies considered (Spezzaferri, 1994; Berggren et al., 1995; Berggren and Pearson, 2005; Wade et al., 2011) as opposed to the Caribbean centric studies. While *Ch. cubensis* was described from Cuba (Palmer, 1934), the species was seldom discussed in the Caribbean studies focused on here. Only Beckmann (1957) and Blow (1969/1979) noted the species and its range, but neither gave ranges consistent with Wade et al. (2011) (see Section 5). Beckmann (1957; figure 16) found a range up to the top of the *Globorotalia opima opima* Zone (=Base Zone O6), while Blow found a range up to the base of Zone N4 (=Subzone M1a) for the *Ch. cubensis* group. Unfortunately, neither study gave abundances of the species, so it is unclear where there was a decline in abundance that may be applicable to a Tc bioevent for the species.

The base of Zone O4 is defined on Base *Cr. angulisuturalis,* which was first applied by Banner and Blow (1965a; see Figure 4). The bioevent was used in over half of the zonations (~55%) but was not applied at all by Bolli (Bolli, 1957, 1966a; Bolli and Saunders, 1985). He instead opted not to divide the *Gr. opima opima* Zone, a view shared in the zonation of Stainforth et al. (1975). The species range charts of Bolli (1957; figure 18), Stainforth et al. (1975; figure 16) and Bolli and Saunders (1985; figure 9) illustrate that Zone O4 can be recognised in their records (see Section 5) and in the Cipero Formation. This is consistent with our analysis of the residue of sample JS 20. While this sample was dominated by *Pg. opima* and *Pg. nana*, it also had a low abundance of *Cr. angulisuturalis* and *Cr. ciperoensis* suggesting this zone would be consistent with Zone O4-O5 (Figure 8).

Finally, Top *Turborotalia ampliapertura* (Base O3) was applied in ~45% of the zonations, however, other than Bolli (1957) this datum was not applied in any other Caribbean zonation. Instead the later studies of Bolli (Bolli, 1966a; Bolli and Saunders, 1985) and Stainforth et al. (1975) applied Base *Pg. opima* in the nearest equivalent biohorizon and were the only studies to do so (~27%), which predates Base *Tr. ampliapertura* by ~40 kyr (Wade et al., 2011). While Banner and Blow (1965a) and Blow (1969/1979) applied Base *Cr. angulisuturalis* as a means of dividing Zone N1 (=Zone O2) and Zone N2 (=Zones O4/O5), these studies did not recognise an interval between Top *Tr. ampliapertura* and Base *Cr. angulisuturalis* (equivalent to Zone O4) (see Figure 4). The range charts in Blow (1969/1979; figure 1) suggested that Top *Tr. ampliapertura* occurred within the very basal region of the range of *Cr. angulisuturalis.* Postuma (1971; chart 4) shows a similar situation with an overlap in the range of the two species in their *Gg. angulisuturalis* Zone. Therefore, there is likely to be an issue with the concept of the author(s), an issue with reworking or that Top *Tr. ampliapertura* does occur at a younger stratigraphic level. The latter is unlikely as clear offsets can be seen in other range charts (e.g. Bolli, 1957, figure 19; Bolli and Saunders, 1985, figure 9; Berggren et al., 1995, figure 10), while a more marginal offset is seen in Stainforth et al. (1975; figure 16). The specimens figured in Blow (1969/1979; plate 12, figures 6-10) were from his “virtual topotype” locality (sample WHB 195) and are consistent with the *Gr. ampliapertura* Zone. Unfortunately, these specimens come from Zone N1 (=Zone O2), while no specimens are illustrated from the basal part of Zone N2 (Zone O4). The illustrated specimen from Postuma (1971; page 142) appears to be less consistent with *Tr. ampliapertura*. It possesses a symmetrical, umbilical aperture similar to one of Bolli’s (1957) paratype specimens (plate 22, figures 7a-b), which is no longer considered synonymous with *Tr. ampliapertura* (Pearson, Premec-Fucek and Premoli Silva, 2006). Unfortunately, Postuma did not provide any additional figures or a precise locality or zone for his figured specimen. It is possible that the author applied a broad concept to *Tr.*

ampliapertura, but this cannot be conclusively proven without additional images or re-examining the authors sample for the figured specimen. However, we restudied three residues from Bolli's *Gg. ampliapertura* Zone, and Blow's (1969/1979) previously mentioned "virtual topotype" sample. As would be expected, all these residue samples contained *Tr. ampliapertura* (Plate 1, Figures 12a-c) but not *Cr. angulisuturalis*, consistent with Zone O2 (Figure 8). Unfortunately, we did not find any samples equivalent to Zone O3 for analysis. However, Bolli's *G. opima opima* residue (JS 20) lacked *Tr. ampliapertura*, so was consistent with Zone O4- O5. Based upon the earlier hypotheses, and the exclusion of differing species concepts and an extended true range of *Tr. ampliapertura*, it is most likely that a sample observed by Blow and Postuma was reworked. This would not be unlikely for Trinidad due to the highly complex geology of the area.

5. Reassessing the Caribbean range charts

Here we focus on the range charts of six Caribbean centric studies (Bolli, 1957; Blow, 1959; Blow, 1969/1979; Postuma, 1971; Stainforth et al. 1975; Bolli and Saunders, 1985) in order to assess whether the primary marker taxa of Wade et al. (2011), as well as Base *Gt. insueta* and Base *F. lobata*, are present and whether the ranges would be consistent with the present level of the datums. Many of the primary datums (Table 1 and Figures 4-7) have remained stable throughout the zonations (e.g. Top *Pg. mayeri* and Top *Cs. dissimilis*) while a number of others have been less readily applied. We assume that the taxonomic concepts applied by authors is consistent and considers the relative biostratigraphy, as opposed to a biochronology due to the absence of other means of calibration in the majority of the zonations (e.g. cyclostratigraphy or magnetostratigraphy). Figures 9-14 show a comparison between the original zonation applied, the range of the marker taxa found by the author and finally the zonation if the bioevents were applied in context of Wade et al. (2011). In addition, this shows the key geological boundaries based on the original author's opinion. Table 2 is similar to Table 1 but instead shows instances where the range of the primary markers is consistent with their application for each of the studies.

Of the 24 primary bioevents recognised between zones O3 to PL1, fifteen occur ubiquitously (100%) at a level consistent with Wade et al. (2011). Of the nine taxa that are applicable in less than 100% of the zonal schemes, three represent forms within a lineage, namely Base *F. fohsi* (~70%), Base *F. “praefohsi”* (~25%) and Base *P. kugleri* (0%), where the authors applied a broader concept which was inclusive of these forms. However, as discussed in Sections 4.2 and 4.5, a differentiation can be made between members of the fohsellids and *Pg. kugleri-pseudokugleri* lineage illustrating that these lower percentages are false representations and merely a reflection on the species concepts applied. This is supported by the fact that the majority of the zonations have grouped O7-M1a and M7-M9a Zones (Figures 9 and 13). Although Bolli and Saunders (1985) differentiate between the *fohsi* group, they suggest Base *F. “praefohsi”* occurs after Base *F. fohsi* meaning Zone M8 could not be recognised (Figure 13). Similarly, the issues surrounding the use of *Globigerinatella* were highlighted in Section 4.3, which explains why Zones M2-M3 have been grouped in all the zonations discussed (Figures 9-14) and why none of the schemes applied Base *Globigerinatella* sp. (Table 2). The concepts applied for *Pr. sicana* have differed between authors (as discussed in Section 4.4), with more authors opting to apply *sicana* s.l. (including *Tb. bisphericus*; 50%) as opposed to *Pr. sicana* s.s. (~33%) as applied by Wade et al. (2011). The former (Base *Tb. bisphericus*) currently lacks an age calibration and so would be unsuitable for use. The differences in concepts applied and often difficult means of differentiation between *Pr. sicana* and *Tb. bisphericus* using a light microscope (e.g. Pearson and Chaisson, 1997) may hamper the use of the suitability of the species as a suitable bioevent.

Other datums that show lower percentages for reasons which are not explained by the above, include *Globoquadrina dehiscens* (~40%), with only Blow (1969/1979) (Figure 11) and Postuma (1971) (Figure 12) finding the basal occurrence prior to Top *Pg. kugleri* (i.e. a level consistent with Subzone M1b). Postuma (1971) noted questionable occurrences of both *Gq. dehiscens* and *Pg. kugleri* meaning Subzone M1b can only tentatively be applied. Stainforth et al. (1975) did not differentiate between *Gq. dehiscens* and similar forms, which suggests this datum may have to be treated with a degree of caution at least within the Caribbean area. Top (common) *Ch. cubensis* has been discussed previously (Section 4.8) and should be treated with caution in the Caribbean due to the lack of recognition of this species within the region. Zone O5 has only been tentatively applied relative to Bolli's (1957) and Beckmann's (1957) (Figure 8) range where *Ch. cubensis* and *Pg. opima* show a concurrent range and synchronous extinction. The complications in the range of *Tr. ampliapertura* (Section 4.8) make the robustness of this boundary difficult to determine and reflect the low percentage where this could be applicable (~40%). In addition to the issues discussed with range charts of Blow (1969, 1979) and Postuma (1971), the ranges of Bolli and Saunders (1985) show that Zone O3 could not be determined. Although there is no overlap in Top *Tr. ampliapertura* and Base *Cr. angulisuturalis*, these two datums occur at the same stratigraphic level (Figure 13). While *Gr. lenguaensis* was recognised in all the zonations, Zone M14 could not be applied based on the ranges of Postuma (1971) and Bolli and Saunders (1985), who both find the top of this species to occur within Subzone M13a.

6. Recalibration and amendments of Neogene biogeochronology

The zonal comparisons (Figure 4-7) and the revaluation of the original range charts (Figures 9-14) highlight the historical importance of predominantly the primary bioevents applied in Wade et al. (2011). In considering these, particularly the historical factors, a number of potential amendments to the Neogene to Quaternary biozonations are presented, including the addition of a new subzone defined by the evolution of the *Globigerinatella* lineage (Figures 15-18; Table 3). While potentially less reliable datums within at least the Caribbean in the Oligocene have been presented (e.g. Tc *Ch. cubensis*) a recent review on Oligocene was presented by Berggren et al. (2018) and so we do not re-evaluate this series. In contrast, while the Pliocene to Recent was not the focus of this study, these biozones have been included and recalibrated for completeness and to ensure the Miocene and younger is relative to the same chronostratigraphic framework.

The magnetostratigraphic Chron ages applied here are based on the studies of Drury et al. (2017) within the late Miocene (8.125-6.023 Ma; Base Subchron C4n.2n to Top Subchron C3An.1n), Kochhann et al. (2017) spanning the mid to early Miocene (17.676-13.174 Ma; Base Subchron C5Dr.1n to Base Chron C5AAn to) and Beddow et al. (2018) through the early Miocene (23.040-21.985 Ma; Base Subchron C6Cn.2n to Base Subchron C6Bn.1n). The intervals which are not covered by these studies are based upon Ogg et al. (2016). The bioevents which are calibrated via palaeomagnetism have been updated based upon a direct comparison between the ages presented by Wade et al. (2011) to the relevant magnetostratigraphic framework. The updated magnetostratigraphy does not affect the bioevents dated by cyclostratigraphy, which are discussed in more detail below.

A large proportion of the datums presented in the Wade et al. (2011) timescale are based upon the cyclostratigraphic record from ODP Leg 154 (Ceara Rise, western equatorial Atlantic Ocean) presented by Shackleton and Crowhurst (1997) and Shackleton et al., (1999), and planktonic foraminiferal biostratigraphy of Chaisson and Pearson (1997), Pearson and Chaisson (1997) and Turco et al. (2002). The datums from Turco et al. (2002) were previously refined by Zeeden et al. (2013) following an update for the splice of ODP Site 926 between 14.4-5.0 Ma. The splice for all the ODP Leg 154 Sites (Sites 925-929) has since been revised by Wilkens et al. (2017) for the interval between 14.4-0.0 Ma. By recalibrating the datum depths applied by Wade et al. (2011) from Chaisson and Pearson (1997), Pearson and Chaisson (1997) and Turco et al. (2002) to the new composite offsets and ages from Wilkens et al. (2017) a refinement on the bioevent ages has been achieved. For the Ceara Rise datums older than 14.4 Ma, the astronomical calibrations of Shackleton et al. (1999) have been applied. A large proportion of the datums do not change or there is only a minor change in age (0.01-0.05 Ma). Some of the most notable changes (>0.10 Ma) include Top *Dg. altispira* (3.00 Ma), Top *Ss. seminulina* (3.05 Ma), Base *Gr. tumida* (5.82

Ma), Base *Gr. plesiotumida* (0.19 Ma) and Base *Pr. glomerosa* s.s. (16.14 Ma). In the case of Base *Clavatorella bermudezi,* Wade et al. (2011:116) remarked "Note mistake in Shackleton et al. (1999) where 14.8 Ma should read 15.8 Ma." However, the depth given by Pearson and Chaisson (1997) is consistent with the original ages from Shackleton et al. (1999). In addition, extending the spliced records of Wilkens et al. (2017) via linear interpolation also yields an age closer to 14.6 Ma. The age given is this study is 14.63 Ma based on the depths from ODP Hole 926B and the astronomical tuning of Shackleton et al. (1999). It is also important to note that the bioevent recalibration and revised magnetostratigraphy applied in this study does alter the Chron calibration of certain bioevents.

In the case of Top *Dg. altispira* (Base Zone PL5; Atlantic) and Top *Ss. seminulina* (Base Zone PL4; Atlantic) the bioevent was observed between the same sample interval in ODP Hole 925B (Chaisson and Pearson, 1997) and so the upper and lower depth age bounds (3.00 Ma and 3.05 Ma respectively) have been applied in order to avoid a combined biozone. Likewise, the upper and lower depth age bounds, as opposed to the depth midpoint, has been applied for Base *Gr. plesiotumida* (Base Subzone M13b; 8.77 Ma) and Base *Gs. extremus* (8.83 Ma), and for Top *Dg. binaensis* (19.26 Ma) and Base *Globigerinatella* sp. (Base M3a; 19.31 Ma) as these were not considered synchronous by Wade et al. (2011).

The suggested amendments for the low latitude biogeochronology are presented in Figures 15-18 and Table 3. These are:

- The reassignment of the base of Zone M12 to Top *Paragloborotalia siakensis* rather than Top *Paragloborotalia mayeri* due to the prevalence of *Pg. siakensis* in low latitudes (King, 2019). The formal name for this zone is amended to the *Globoturborotalita nepenthes*/*Paragloborotalia siakensis* Concurrent-range Zone.

- While Zone M9 is maintained as the *Fohsella fohsi* TRZ, a degree of caution is required as nearly all the Caribbean centric range charts presented show an extended biostratigraphic range of *F. robusta* compared to *F. fohsi* (e.g. Bolli, 1957; Blow, 1959; Blow, 1969; Postuma, 1971; Stainforth et al., 1975; Figures 9-13). Wade et al. (2011) discussed the ambiguity involved in the "and/or" biozones where multiple species have been applied in defining the base of a zone. In the absence of an astronomically calibrated age for Top *F. robusta*, Top *F. fohsi* is retained pending further analysis.
- Due to the historical importance and distinctiveness of *Fohsella lobata* (Figure 6, Table 1) the base of the species is likely to be a useful primary bioevent. While we retain the species as a secondary datum in this study (partly due to the lack of an astronomical calibration), obtaining an age would be highly beneficial and should be an area of priority for future low-latitude biochronology.
- As discussed in Sections 4.4, the use of Base *Praeorbulina sicana* may be unsuitable due to the historical and ongoing differences in taxonomic concepts applied (i.e. where *Tb. bisphericus* is included as a junior synonym) and in turn the generic assignment (*Praeorbulina* vs. *Trilobatus*). The base of Zone M5 may better be served by the first unequivocal *Praeorbulina* species (*Pr. circularis* or *Pr. glomerosa*). Resolving the taxonomy was not the aim of this study, and while Base *Pr. sicana* is upheld this is on a sensu stricto basis due to the lack of an astronomical calibration for Base *Tb. bisphericus*. Top *Pr. sicana* (previously 14.53 Ma) has been removed for these reasons.
- Base *Globigerinatella insueta* has been reinstated to a primary bioevent due to the historic utility and robustness of this event (Figure 5, Table 1). The recalibration of this datum shows no change from Wade et al. (2011) (17.59 Ma). The use of Base *Globigerinatella* sp. is still retained as a primary datum

(19.30 Ma), however efforts should be made to formally define this species (i.e. the forms lacking aereal apertures) in order to avoid ambiguity in the taxonomic concepts applied.

- Removal of the secondary datums of X *N. atlantica* (sin-dex) (6.99 Ma), Base *Gr. zealandica* (17.26 Ma) and the younger datum for Top *Gr. praescitula* (11.90 Ma) given in Wade et al. (2011, table 1) as these were based on calibrations from high latitude sites (DSDP Sites 609 (~49°N) and 611 (~52°N), and ODP Sites 642 (~67°N) and 747 (~54°S), which are likely not indicative of the tropical-subtropical region.
- Removal of the quotations surrounding '*Paragloborotalia*' in the case of *Pg. kugleri* and *Pg. pseudokugleri* following Leckie et al. (2018) and references therein, showing unequivocal evidence of spinosity.
- A number of species generic name has changed following Wade et al. (2018b) and chapters therein.

7. Updated formal zone descriptions

Zone PL6 (Indo-Pacific). *Globigerinoidesella fistulosa* Partial-range Zone (Indo-Pacific) (herein renamed; equivalent to Zone PL6 (Indo-Pacific) [*Globigerinoides fistulosus* Highest-occurrence Zone (Indo-Pacific)] of Wade et al. (2011) and [*Globorotalia pseudomiocenica–Globigerinoides fistulosus Interval Zone*] of Berggren et al. (1995)).

Definition: Interval between Top *Globorotalia pseudomiocenica* and Top *Globigerinoidesella fistulosa,* the nominate taxon.

Magnetochronologic calibration: Chron C2r to Chron C2n

Astronomical cycle calibration: $6_{Pl–C2n}$ to $5_{Pt–C1r}$.

Estimated age: 2.30 to 1.88 Ma (as per Lourens et al., 2004); 2.32 to 1.88 Ma (as per Ogg et al., 2016 and Wilkens et al., 2017); late Pliocene.

Remarks: This zone remains unchanged with respect to age and bioevents applied, however is renamed following the assignment of *fistulosus* to *Globigerinoidesella* (e.g. Spezzaferri et al., 2015; Poole and Wade, 2019).

Zone PL6 (Atlantic). *Globigerinoidesella fistulosa* Partial-range Zone (Atlantic) (herein renamed; equivalent to Zone PL6 (Atlantic) [*Globigerinoides fistulosus* Highest-occurrence Zone (Atlantic)] of Wade et al. (2011) and [*Globorotalia miocenica–Globigerinoides fistulosus Interval Zone*] of Berggren et al. (1995)).

Definition: Interval between Top *Globorotalia miocenica* and Top *Globigerinoidesella fistulosa,* the nominate taxon.

Magnetochronologic calibration: Chron C2r to Chron C2n.

Astronomical cycle calibration: $7_{Pl–C2r}$ to $5_{Pt–C1r}$.

Estimated age: 2.39 to 1.88 Ma (as per Lourens et al., 2004); 2.37 to 1.88 Ma (as per Wilkens et al., 2017); late Pliocene.

Remarks: See remarks for PL6 (Pacific).

Zone M12. *Trilobatus trilobus* Partial-range Zone (herein renamed; equivalent to Zone M12 [*Globigerinoides trilobus*] of Wade et al. (2011) and Zone M12 [*Neogloboquadrina mayeri-Neogloboquadrina acostaensis* Interval Zone] of Berggren et al. (1995)).

Definition: Partial range of the nominate taxon between Top *Pg. siakensis* and Base *N. acostaensis*.

Magnetochronologic calibration: Subchron C5n.2n. to Subchron C5n.1n

Astronomical cycle calibration: $27_{Mi–C5n}$ to $25_{Mi-C4Ar}$

Estimated age: 10.46 to 9.83 Ma (as per Lourens et al., 2004); 10.53 to 9.81 Ma (as per Wilkens et al., 2017); late Miocene.

Remarks: Following Spezzaferri et al. (2015) description of *Trilobatus*, with *Tr. trilobus* as the type species, the formal name has been amended to reflect the generic reassignment. The biohorizons for the biozone remain unchanged from Wade et al. (2011).

Zone M11. *Globoturborotalita nepenthes*/*Paragloborotalia siakensis* Concurrent-range Zone (herein renamed; equivalent to Zone M11 [*Globoturborotalita nepenthes*/*Paragloborotalia mayeri* Concurrent-range Zone] of Wade et al. (2011) and [*Globoturborotalita nepenthes*/*Neogloboquadrina mayeri* Concurrent-range Zone] of Berggren et al. (1995)).

Definition: Concurrent range of the nominate taxa between Base *Go. nepenthes* and Top *Pg. siakensis*.

Magnetochronologic calibration: Subchron C5r.3r. to Subchron C5n.2n to

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

Estimated age: 11.63 Ma to 10.46 Ma (as per Lourens et al., 2004); 11.67 to 10.53 Ma (as per Wilkens et al., 2017); middle to late Miocene.

Remarks: This zone has been renamed to *Paragloborotalia siakensis* rather than *Paragloborotalia mayeri* as the nominate taxon. There has long been taxonomic controversy regarding the lineage, however following Leckie et al. (2018) the two can be considered distinct morphotypes. King (2019) conducted a detailed study on the morphotypes from a number of sites globally and found *Paragloborotalia siakensis* to be the dominant morphotype throughout the low latitudes.

Zone M3. *Globigerinatella* sp.-*Catapsydrax dissimilis* Concurrent-range Zone (herein re-defined; equivalent to the Zone M3 [*Globigerinatella* sp./*Catapsydrax dissimilis* Concurrent-range Zone] of Wade et al. (2011) and Zone M3 [*Globigerinatella insueta*/*Catapsydrax dissimilis* Concurrent Range Zone] and the upper part of Zone M2 [*Catapsydrax dissimilis* Partial Range Zone] of Berggren et al. (1995)).

Definition: Concurrent range of the nominate taxa between Base *Globigerinatella* sp. to Top *Catapsydrax dissimilis*.

Magnetochronologic interpretation: Chron C6n to Chron C5Dr.

Astronomical cycle calibration: $49_{\text{Mi-C6n}}$ to $44_{\text{Mi-C5Dn}}$.

Estimated age: 19.30 Ma to 17.54 Ma (as per Lourens et al., 2004); 19.31 to 17.51 Ma (as per Shackelton et al., 1999); early Miocene.

Remarks: This zone is directly equivalent to Zone M3 of Wade et al. (2011), however the zone is now divided into a lower Subzone M3a and upper Subzone M3b based on the evolution of the *Globigerinatella* lineage. Wade et al. (2011) opted to apply Base *Globigerinatella* sp. as a means of defining the Zone M2-M3 boundary to avoid a condensed biozone (~50 kyr) that would be applied if Base *Globigerinatella insueta* and Top *Catapsydrax dissimilis* were applied as primary bioevents. As shown in Figure 5 and discussed in Sections 2.3 and 6, *Gt. insueta* historically represents one of the most robust bioevents, therefore re-elevating the species to primary marker status is important for correlative purposes.

Subzone M3b. *Globigerinatella insueta-Catapsydrax dissimilis* Concurrent-range Zone (herein defined; equivalent to the uppermost part of Zone M3 [*Globigerinatella* sp./*Catapsydrax dissimilis* Concurrent-range Zone] of Wade et al. (2011) and Zone M3 [*Globigerinatella insueta*/*Catapsydrax dissimilis* Concurrent Range Zone] of Berggren et al. (1995).

Definition: Concurrent range of the nominate taxa between Base *Globigerinatella insueta* and Top *Catapsydrax dissimilis*.

Magnetochronologic calibration: Subchron C5Dr.2r.

Astronomical calibration: $44_{\text{Mi-C5Dn}}$

Estimated age: 17.59 to 17.54 Ma (as per Lourens et al., 2004); 17.57 to 17.51 Ma (as per Shackleton et al., 1999); early Miocene.

Remarks: As discussed above, while the use of Base *Gt. insueta* creates a short subzone, it represents an important bioevent for historical correlation purposes. While the interval is equivalent to Berggren et al.'s (1995) Zone M3, the Chron calibration in Wade et al. (2011) and this study (Chron C5Dr.2r) produces a younger age, and so more condensed zone, than what is suggested by Berggren et al. (1995), where the authors used an inferred age of Base *Gt. insueta* within Chron C5En.

Subzone M3a. *Globigerinatella* sp.*-Catapsydrax dissimilis* Concurrent-range Zone (herein defined; equivalent to all but the uppermost part of Zone M3 [*Globigerinatella* sp./Catapsydrax dissimilis Concurrent-range Zone] of Wade et al. (2011) and the upper part of Zone M2 [*Catapsydrax dissimilis* Partial Range Zone] of Berggren et al. (1995).

Definition: Concurrent range of the nominate taxa between Base *Globigerinatella* sp. prior to Base *Globigerinatella insueta*.

Magnetostratigraphic calibration: Subchron C5Dr.2r to Chron C6n.

Astronomical calibration: 44Mi-C5Dn to 49Mi-C6n

Approximate age: 19.30 to 17.59 Ma (as per Lourens et al., 2004), 19.31 to 17.57 Ma as per Shackelton et al., 1999); early Miocene.

Remarks: The reasons for Wade et al. (2011) opting to apply Base *Globigerinatella* sp. in marking Zone M3 have been discussed above. Here Subzone M3a is equivalent to all but the most upper part of Wade et al. (2011) Zone M3. The use of *Globigerinatella* sp. have been discussed in detail in Section 4.3 and Section 6, with future efforts being made to formally define *Globigerinatella* sp. in order to avoid conflicting or ambiguous species concepts.

Zone M2. *Dentoglobigerina binaiensis* Partial Range Zone (herein renamed; equivalent to Zone M2 [*Globoquadrina binaiensis* Partial-range Zone] of Wade et al. (2011) and the lower part of Zone M2 [*Catapsydrax dissimilis* Partial Range Zone] of Berggren et al. (1995)).

Definition: Partial range of the nominate taxon between Top *Paragloborotalia kugleri* and Base *Globigerinatella* sp.

Magnetostratigraphic calibration: Chron C6n to Chron C6AAn..

Astronomical calibration: 49Mi-C6n to 54Mi-C6AAr

Age: 21.12 to 19.30 Ma (as per Lourens et al., 2004); 21.03 to 19.31 (as per Shackleton et al., 1999); early Miocene.

Remarks: This zone remains unchanged from Wade et al. (2011) in terms of biohorizon age and the bioevents applied but is amended to reflect the reassignment of *binaiensis* to *Dentoglobigerina* (e.g. Chaproniere, 1981; Fox and Wade, 2013; Wade et al., 2018a).

8. Conclusions

Our review illustrates the importance of the Caribbean region in the development of the low latitude planktonic foraminiferal biostratigraphy. The zonal comparisons highlight that a number of bioevents first recognised within the region have been consistently applied over the last 50+ years (e.g. Top *Catapsydrax dissimilis* and Top *Paragloborotalia siakensis*). These comparisons also highlight datums which may be less recognisable, at least within the Caribbean and potentially the wider Atlantic (e.g. Top common *Chiloguembelina cubensis* and Base *Globoquadrina dehiscens*). Some authors had a tendency to favour certain datums in their zonal schemes, so the revaluation of the range charts of a number of these studies show that some less readily applied bioevents could have potentially been applied if correlated to the biozonation of Wade et al. (2011) (e.g. Base *Globoturborotalita nepenthes and* Base *Ciperoella angulisuturalis*). This in turn suggests these can also be considered recognisable bioevents at least within the Caribbean. In considering the historical importance and recognisability of a number of bioevents, amendments to the Miocene component of the low latitude biogeochronology of Wade et al. (2011) have been suggested. Most notably the addition of Subzone M3b in order to reincorporate Base *Globigerinatella insueta* respectively as primary bioevents. The Wade et al. (2011) biogeochronology has been recalibrated to recent updates to the magneto- (Kochhann et al., 2016; Ogg et al., 2016; Drury et al., 2017; Beddow et al., 2018) and astrochronologies (Wilkens et al., 2017). We suggest that the ages in this study are followed in future planktonic foraminiferal biochronologies of the Miocene.

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Tables

Table 1. Primary and secondary datums (Wade et al. 2011) applied in timescales compared in Figures 4-7. Primary bioevents are shown in bold. Crosses (relevant bioevent was applied), dash (schemes did not apply the bioevent but had coverage through the interval) and greyed-out (given scheme did not have coverage though the interval). Abbreviations: Ba & Bl (1965a) = Banner and Blow (1965a), Sta et al. (1975) = Stainforth et al. (1975), Ke & Sr (1983) = Kennett and Srinivasan (1983), Bo & Sa (1985) = Bolli and Saunders (1985), Spez (1994) = Spezzaferri (1994), Berg et al. (1995) = Berggren et al. (1995), Be & Pe (2005) = Berggren and Pearson (2005), At. = Atlantic. Notes: [a] Partly based on Bolli and Bermudez (1965). [b] Bolli (1966a) include *N. humerosa* within his concept of *N. dutertrei*. [c] Includes *Pg. siakensis*. [d] Extinction of the *Fohsi* group. [e] Approximated age. [f] Some authors included *F. peripheroacuta* and *F. praefohsi* in their concept of *F. fohsi*. [g] Base *Tb. bisphericus* is poorly constrained and lacks an astronomical calibration. [h] Some authors included *Pg. pseudokugleri* in their concept of *Pg. kugleri*.

				Zonal Schemes															
Zone		Bioevent	Age (Ma)	Bolli (1957)	Blow (1959)	Ba & Bl (1965)	Bolli (1966) [a]	Blow (1969/79)	Postuma (1971)	Sta et al. (1975)	Ke & Sr (1983)	Bo & Sa (1985)	Spez (1994)	Ber et al. (1995)	Be & Pe (2005)	Wade et al. (2011)	Times Applied	No. of schemes	Percentage (%)
PL1	**B**	***Gr. tumida* (At.)**	**5.72**			**X**	**-**	**X**	**X**	**-**	**X**	**-**		**X**		**X**	**6**	**9**	**67**
	B	*Gr. margaritae*	6.08			-	X	-	X	X	-	X		-		-	4	9	44
M14	**T**	***Gr lenguaensis***	**6.13**			**-**	**-**	**-**	**-**	**-**	**-**	**-**		**X**		**X**	**2**	**9**	**22**
	B	*Pu. primalis*	6.60		-	-	-	-	-	-	X	-		-		-	1	10	10
	B	*N. humerosa* [b]	8.56		-	-	X	-	-	-	-	X		-		-	2	10	20
M13b	**B**	***Gr. plesiotumida***	**8.58**		**-**	**X**	**-**	**X**	**X**	**-**	**X**	**-**		**X**		**X**	**6**	**10**	**60**
	B	*Gs. extremus*	8.93		-	-	-	-	-	-	-	-		X		-	1	10	10
M13a	**B**	***N. acostaensis***	**9.83**		**-**	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**		**X**	**9**	**10**	**90**
M12	**T**	***Pg. mayeri* [c]**	**10.46**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**		**X**	**11**	**11**	**100**
	T	*Gs. subquadratus*	11.54	-	-	-	-	-	X	-	-	-		-		-	1	11	9
M11	**B**	***Go. nepenthes***	**11.63**	**-**	**X**	**X**	**-**	**X**	**-**	**-**	**X**	**-**		**X**		**X**	**6**	**11**	**55**
M10	**T**	***F. fohsi* [d]**	**11.79**	**X**	**X**	**-**	**X**	**-**	**X**	**X**	**X**	**X**		**X**		**X**	**9**	**11**	**82**
	B	*Ss. subdehiscens*	13.02	-	-	X	-	X	-	-	-	-		-		-	2	11	18
M9b	**B**	***F. robusta***	**13.13**	**X**	**X**	**-**	**X**	**-**	**X**	**-**	**-**	**X**		**X**		**X**	**7**	**11**	**64**
	B	*F. lobata* [e]	13.20	X	-	-	X	-	X	X	-	X		X		-	6	11	**55**
M9a	**B**	***F. fohsi***	**13.41**	**-**	**-**	**X**	**-**	**X**	**-**	**-**	**X**	**-**		**X**		**X**	**5**	**11**	**45**

M8	**B**	***F. "praefohsi"***	**13.77**	**-**	**X**	**X**	**-**	**X**	**X**	**-**	**X**	**-**		**-**		**X**	**6**	**11**	**55**
M7	**B**	***F. peripheroacuta* [f]**	**14.24**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**		**X**	**11**	**11**	**100**
	T	*Gt. insueta*	14.66	X	X	-	X	-	-	-	-	X		-		-	4	11	36
M6	**B**	***O. suturalis***	**15.10**	**-**	**-**	**X**	**-**	**X**	**X**	**X**	**X**	**-**		**X**		**X**	**7**	**11**	**64**
M5b	**B**	***Pr. glomerosa* s.s.**	**16.27**	**-**	**-**	**-**	**X**	**-**	**-**	**X**	**-**	**X**		**X**		**X**	**5**	**11**	**45**
M5a	**B**	***Pr. sicana* s.s.**	**16.38**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**		**X**		**X**	**2**	**11**	**18**
	B	*Tb. bisphericus* [g]	N/A	-	X	X	-	X	-	-	X	-		-		-	4	11	36
M4	**T**	***Cs. dissimilis***	**17.54**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**	**12**	**12**	**100**
	B	*Gt. insueta* s.s.	17.59	X	-	X	X	X	-	X	X	X	X	X		-	9	12	75
M3	**B**	***Globigerinatella* sp.**	**19.30**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**		**X**	**1**	**12**	**8**
M2	**T**	***Pg. kugleri***	**21.12**	**X**		**X**	**X**	**X**	**-**	**X**	**X**	**X**	**X**	**X**		**X**	**10**	**11**	**91**
M1b	**B**	***Gq. dehiscens***	**22.44**	**-**		**-**	**-**	**-**	**-**	**-**	**X**	**-**	**-**	**X**		**X**	**3**	**11**	**27**
	B	*Tb. trilobus*	22.96	-		-	-	-	X	X	-	-	X	-		-	3	11	27
M1a	**B**	***Pg. kugleri***	**22.96**	**-**		**-**	**-**	**-**	**-**	**-**	**-**	**-**	**X**	**X**		**X**	**3**	**11**	**27**
	Bc	*Tb. primordius*	23.6	-		-	-	X	-	X	X	X	-	-	-	-	4	12	33
O7	**B**	***Pg. pseudokugleri* [h]**	**25.4**	**X**		**X**	**X**	**-**	**X**	**-**		**X**	**-**	**-**	**-**	**X**	**6**	**11**	**55**
O6	**T**	***Pg. opima***	**27.3**	**X**		**X**	**X**	**X**	**-**	**X**		**X**	**X**	**X**	**X**	**X**	**10**	**11**	**91**
O5	**Tc**	***Ch. cubensis***	**28.3**	**-**		**-**	**-**	**-**	**-**	**-**		**-**	**X**	**X**	**X**	**X**	**4**	**11**	**36**
O4	**B**	***Cr. angulisuturalis***	**29.5**	**-**		**X**	**-**	**X**	**X**	**-**		**-**	**-**	**X**	**X**	**X**	**6**	**11**	**55**
O3	**T**	***Tr. ampliapertura***	**30.4**	**X**		**-**	**-**	**-**	**-**	**-**		**-**	**X**	**X**	**X**	**X**	**5**	**11**	**45**
	B	*Pg. opima*	30.8	-		-	X	-	-	X		X	-	-	-	-	3	11	27
O2	**T**	***Ps. naguewichiensis***	**32.2**			**X**	**X**	**X**	**-**	**X**		**X**	**X**	**X**	**X**	**X**	**9**	**10**	**90**

Table 2. Consistency of primary datums and selected secondary datums from Wade et al. (2011) relative to these bioevents occurring at a level consistent with their application in various Caribbean zonal schemes. Crosses (relevant bioevent was applied), Dash (schemes did not apply the bioevent but had coverage through the interval) and Greyed-out (given scheme did not have coverage though the interval). The stars (*) show instances where the bioevent was later recognised by the author or a later study (including our analyses) for the locality in question. Abbreviations: Sta et al. (1975) = Stainforth *et a.* (1975), Bo & Sa (1985) = Bolli and Saunders (1985), At. = Atlantic. Notes: [a] Includes *Pg. siakensis.* [b] Approximated age. [c] Some authors included *F. peripheroacuta* and *F. praefohsi* in their concept of *F. fohsi*. [d] Base of *Tb. bisphericus* lacks an astronomical calibration. [e] Some authors included *Pg. pseudokugleri* in their concept of *Pg. kugleri*.

				Zonal Schemes								
Zone		**Bioevent**	**Age (Ma)**	**Bolli (1957)**	**Blow (1959)**	**Blow (1969/79)**	**Postuma (1971)**	**Sta et al. (1975)**	**Bo & Sa (1985)**	**Times Applied**	**No. of schemes**	**Percentage**
PL1	B	*Gr. tumida* (At.)	5.72			X	X	X	X	4	4	100
M14	T	*Gr. lenguaensis*	6.13		X	X	-	X	-	3	5	60
M13b	B	*Gr. plesiotumuda*	8.58		*	X	X	X	X	4	4	100
M13a	B	*N. acostaensis*	9.83		X	X	X	X	X	5	5	100
M12	T	*Pg. mayeri* [a]	10.46	X	X	X	X	X	X	6	6	100
M11	B	*Go. nepenthes*	11.63	X	X	X	X	X	X	6	6	100
M10	T	*F. fohsi*	11.79	X	X	X	X	X	X	6	6	100
M9b	B	*F.robusta*	13.13	X	X	X	X	X	X	6	6	100
	B	*F. lobata* [b]	13.20	X	X	-	-	X	X	4	6	67
M9a	B	*F. fohsi*	13.41	*	*	X	X	-	X	3	4	75
M8	B	*F. "praefohsi"*	13.77	*	*	X	-	-	-	1	4	25
M7	B	*F. peripheroacuta* [c]	14.24	X	X	X	X	X	X	6	6	100
M6	B	*O. suturalis*	15.10	X	X	X	X	X	X	6	6	100
M5b	B	*Pr. glomerosa* s.s.	16.27	X	X	X	X	X	X	6	6	100
M5a	B	*Pr. sicana* s.s	16.38	-	-	-	X	-	X	2	6	33
	B	*Tb. bisphericus* [d]	N/A	-	X	X	-	X	-	3	6	50
M4	T	*Cs. dissimilis*	17.54	X	X	X	X	X	X	6	6	100
	B	*Gt. insueta* s.s.	17.59	X	X	X	X	X	X	6	6	100
M3	B	*Globigerinatella* sp.	19.30	-	-	-	-	-	-	0	6	0
M2	T	*Pg. kugleri*	21.12	X		X	X	X	X	5	5	100
M1b	B	*Gq. dehiscens*	22.44	-		X	X	-	-	2	5	40

M1a	B	*Pg. kugleri*	22.96	*		-	-	-	-	0	4	0
O7	B	*Pg. pseudokugleri* [e]	25.4	X		X	X	X	X	5	5	100
O6	T	*Pg. opima*	27.3	X		X	X	X	X	5	5	100
O5	Tc	*Ch. cubensis*	28.3	-		-	-	-	-	0	5	0
O4	B	*Cr. angulisuturalis*	29.5	X		X	X	X	X	5	5	100
O3	T	*Tr. ampliapertura*	30.4	X		-	-	X	-	2	5	40

Table 3. Primary and secondary bioevents from Wade et al. (2011) and their given age in millions of years (Ma) compared to the recalibration of this study. Primary bioevents are shown in bold. The Age Diff. column shows the differences in age between Wade et al. (2011) and the recalibrations of this study. Abbreviations: W11 = Wade et al. (2011), TS = This Study, At. = Atlantic, I-P = Indo-Pacifc, Pa = Pacific, ran. = random, dex = dextral, sin = sinistral.

Zone		Datum	Age (W11)	Age (TS)	Age Diff.	Bioevent Ref.	Calib. Ref.
	T	*Globorotalia flexulosa*	0.07	0.07	0.00	[a]	[1]
	T	*Globigerinoides ruber* (pink) (I-P)	0.12	0.12	0.00	[b]	[2]
	B	*Globigerinella calida*	0.22	0.22	0.00	[c]	[3]
	B	*Globorotalia flexulosa*	0.40	0.40	0.00	[a]	[1]
	B	*Globorotalia hirsuta*	0.45	0.45	0.00	[d]	[3]
PT1b	**T**	***Globorotalia tosaensis***	**0.61**	**0.61**	0.00	[e]	[4]
	B	*Globorotalia hessi*	0.74	0.74	0.00	[c]	[3]
	X	*Pulleniatina spp.* (ran to dex) (Pa.)	0.79	0.79	0.00	[f]	[5]
	T	*Globigerinoides obliquus*	1.30	1.30	0.00	[g]	[6]
	T	*Globoturborotalita apertura*	1.64	1.64	0.00	[g]	[6]
PT1a	**T**	***Globigerinoidesella fistulosa***	**1.88**	**1.88**	0.00	[g]	[6]
	B	*Globorotalia truncatulinodoes*	1.93	1.92	0.01	[g]	[6]
	T	*Globigerinoides extremus*	1.98	1.97	0.01	[g]	[6]
	B	*Pulleniatina finalis*	2.04	2.05	-0.01	[g]	[6]
	T	*Globorotalia exilis* (At.)	2.09	2.08	0.01	[g]	[6]
	B	*Pulleniatina reapp.* (At.)	2.26	2.25	0.01	[g]	[6]
	T	*Globoturborotalita woodi*	2.30	2.30	0.00	[g]	[6]
	T	*Globorotalia pertenius*	2.30	2.30	0.00	[g]	[6]
PL6 (I-P)	**T**	***Globorotalia pseudomiocenica* (I-P)**	**2.30**	**2.32**	-0.02	[h]	[3]
PL6 (At.)	**T**	***Globorotalia miocenica* (At.)**	**2.39**	**2.37**	0.02	[g]	[6]
	T	*Globorotalia limbata*	2.39	2.37	0.02	[g]	[6]
	T	*Globoturborotalita decoraperta*	2.75	2.74	0.01	[g]	[6]
	T	*Globorotalia multicamerata*	2.98	2.97	0.01	[g]	[6]
PL5 (At.)	**T**	***Dentoglobigerina altispira* (At.)**	**3.13**	**3.00**	0.13	[g]	[6]
PL4 (At.)	**T**	***Sphaeroidinellopsis seminulina* (At.)**	**3.16**	**3.05**	0.11	[g]	[6]
	B	*Globigerinoidesella fistulosa*	3.33	3.33	0.00	[i]	[3]
	B	*Globorotalia tosaensis*	3.35	3.35	0.00	[i]	[3]
	T	*Pulleniatina disappearance*	3.41	3.40	0.01	[g]	[6]
PL5 (Pa.)	**T**	***Dentoglobigerina altispira* (Pa.)**	**3.47**	**3.47**	0.00	[e]	[3]
	B	*Globorotalia pertenuis*	3.52	3.51	0.01	[g]	[6]
PL4 (Pa.)	**T**	***Sphaeroidinellopsis seminulina* (Pa.)**	**3.59**	**3.59**	0.00	[e]	[3]
	T	*Pulleniatina primalis*	3.66	3.66	0.00	[j]	[3]
	B	*Globorotalia miocenica* (At.)	3.77	3.72	0.05	[g]	[6]
	T	*Globorotalia plesiotumida*	3.77	3.72	0.05	[g]	[6]
PL3	**T**	***Globorotalia margaritae***	**3.85**	**3.83**	0.02	[g]	[6]
	X	*Pulleniatina spp.* (sin to dex)	4.08	4.06	0.02	[g]	[6]
	T	*Pulleniatina spectabilis* (Pa.)	4.21	4.21	0.00	[i]	[3]
	B	*Globorotalia crassaformis* s.l.	4.31	4.30	0.01	[g]	[6]
PL2	**T**	***Globoturborotalita nepenthes***	**4.36**	**4.38**	-0.02	[g]	[6]
	B	*Globorotalia exilis*	4.45	4.39	0.06	[g]	[6]

	T	*Sphaeroidinellopsis kochi*	4.53	4.49	0.04	[g]	[6]
	T	*Globorotalia cibaoensis*	4.61	4.61	0.00	[k]	[3]
	B	*Sphaeroidinella dehiscens* s.l.	5.53	5.54	-0.01	[g]	[6]
PL1 (Pa.)	**B**	***Globorotalia tumida* (Pa.)**	**5.57**	**5.57**	0.00	[e]	[3]/[7]
PL1 (At.)	**B**	***Globorotalia tumida* (At.)**	**5.72**	**5.82**	-0.10	[g]	[6]
	B	*Turborotalia humilis*	5.81	5.82	-0.01	[g]	[6]
	T	*Globoquadrina dehiscens*	5.92	5.91	0.01	[l]	[3]/[7]
	B	*Globorotalia margaritae*	6.08	6.09	-0.01	[g]	[6]
	T	*Globorotalia lenguaensis*	6.13	6.14	-0.01	[m]	[7]
	B	*Globigerinoides conglobatus*	6.20	6.21	-0.01	[g]	[6]
	X	*Neogloboquadrina acostaensis* (sin to dex)	6.36	6.34	0.02	[n]	[7]
	B	*Pulleniatina primalis*	6.60	6.57	0.03	[l]	[7]
	X	*Neogloboquadrina acostaensis* (dex to sin)	6.77	6.76	0.01	[n]	[7]
M13b	**B**	***Globorotalia plesiotumida***	**8.58**	**8.77**	-0.19	[g]	[6]
	B	*Globigerinoides extremus*	8.93	8.83	0.10	[g]	[6]
	B	*Globorotalia cibaoensis*	9.44	9.44	0.00	[g]	[6]
	B	*Globorotalia juanai*	9.69	9.78	-0.09	[g]	[6]
M13a	**B**	***Neogloboquadrina acostaensis***	**9.83**	**9.81**	0.02	[g]	[6]
M12	**T**	***Paragloborotalia siakensis***	**10.46**	**10.53**	-0.07	[o]	[6]
	B	*Globorotalia limbata*	10.64	10.63	0.01	[g]	[6]
	T	*Cassigerinella chipolensis*	10.89	10.91	-0.02	[o]	[6]
	B	*Globoturborotalita apertura*	11.18	11.24	-0.06	[g]	[6]
	B	*Globoturborotalita decoraperta*	11.49	11.51	-0.02	[g]	[6]
	T	*Globigerinoides subquadratus*	11.54	11.57	-0.03	[o]	[6]
M11	**B**	***Globoturborotalita nepenthes***	**11.63**	**11.67**	-0.04	[o]	[6]
M10	**T**	***Fohsella fohsi* s.l.**	**11.79**	**11.81**	-0.02	[g]	[6]
	B	*Globorotalia lenguaensis*	12.84	12.86	-0.02	[g]	[6]
	B	*Sphaeroidinellopsis subdehiscens*	13.02	13.04	-0.02	[o]	[6]
M9b	**B**	***Fohsella robusta***	**13.13**	**13.13**	0.00	[g]	[6]
	B	*Fohsella lobata*	-	13.20	-	[p]	
	T	*Riveroinella martinezpicoi*	13.27	13.30	-0.03	[o]	[6]
M9a	**B**	***Fohsella fohsi***	**13.41**	**13.43**	-0.02	[g]	[6]
	T	*Globorotalia praescitula*	13.73	13.77	-0.04	[o]	[6]
M8	**B**	***Fohsella 'praefohsi'***	**13.77**	**13.78**	-0.01	[q]	[6]
	T	*Fohsella peripheroronda*	13.80	13.81	-0.01	[q]	[6]
	T	*Clavatorella bermudezi*	13.82	13.82	0.00	[q]	[6]
	T	*Globorotalia archaeomenardii*	13.87	13.86	0.01	[q]	[6]
M7	B	*Fohsella peripheroacuta*	14.24	14.01	0.23	[o]	[6]
	B	*Globorotalia praemenardii*	14.38	14.32	0.06	[q]	[8]
	T	*Globigerinatella insueta*	14.66	14.60	0.06	[q]	[8]
	B	*Clavatorella bermudezi*	15.73	14.63	1.10	[o]	[9]
M6	B	*Orbulina suturalis*	15.10	15.12	-0.02	[q]	[8]
	B	*Praeorbulina circularis*	15.96	15.98	-0.02	[r]	[9]
	B	*Globorotalia archaeomenardii*	16.26	16.14	0.12	[q]	[8]
M5b	**B**	***Praeorbulina glomerosa* s.s.**	**16.27**	**16.14**	0.13	[q]	[8]
	B	*Praeorbulina curva*	16.28	16.29	-0.01	[r]	[9]
M5a	**B**	***Praeorbulina sicana* s.s.**	**16.38**	**16.39**	-0.01	[r]	[9]
M4	**T**	***Catapsydrax dissimilis***	**17.54**	**17.51**	0.03	[q]	[8]
M3b	**B**	***Globigerinatella insueta* s.s.**	**17.59**	**17.57**	0.02	[q]	[8]
	B	*Globorotalia praescitula*	18.26	18.26	0.00	[r]	[3]
	T	*Dentoglobigerina binaiensis*	19.09	19.26	-0.17	[q]	[8]
M3a	**B**	***Globigerinatella sp.***	**19.30**	**19.31**	-0.01	[q]	[8]
	B	*Globigerinoides altiaperturus*	20.03	20.03	0.00	[s]	[3]
M2	**T**	***Paragloborotalia kugleri***	**21.12**	**21.03**	0.09	[q]	[8]

	T	*Paragloborotalia pseudokugleri*	21.31	21.22	0.09	[q]	[8]
M1b	**B**	***Globoquadrina dehiscens***	**22.44**	**22.50**	-0.06	[l]	[10]
	T	*Ciperoella ciperoensis*	22.90	22.81	0.09	[q]	[8]
	B	*Trilobatus trilobus* s.l.	22.96	22.88	0.08	[q]	[8]
M1a	**B**	***Paragloborotalia kugleri***	**22.96**	**22.99**	-0.03	[q]	[8]

Bioevent reference
[a] Joyce et al. (1990); **[b]** Thompson et al. (1979); **[c]** Chaproniere et al. (1994); **[d]** Pujol and Duprat (1983);
[e] Shipboard Scientific Party (1992); **[f]** Pearson (1995); **[g]** Chaisson and Pearson (1997); **[h]** Berggren et al. (1995);
[i] Hays et al. (1969) **[j]** Keigwin (1982); **[k]** Poore et al. (1984); **[l]** Berggren et al. (1985);
[m] Chaproniere and Nishi (1994); **[n]** Srinivasan and Shina (1992); **[o]** Turco et al. (2002); **[p]** This study;
[q] Pearson and Chaisson (1997); **[r]** Miller et al. (1985); **[s]** Berggren et al. (1983)

Calibration reference
[1] Joyce et al. (1990); **[2]** Thompson et al. (1979); **[3]** Ogg et al. (2016); **[4]** Shackleton et al. (1995);
[5] Wade et al. (2011); **[6]** Wilkens et al. (2017); **[7]** Drury et al. (2017); **[8]** Shackleton et al. (1999);
[9] Kochhann et al. (2017); **[10]** Beddow et al. (2018)

Figures

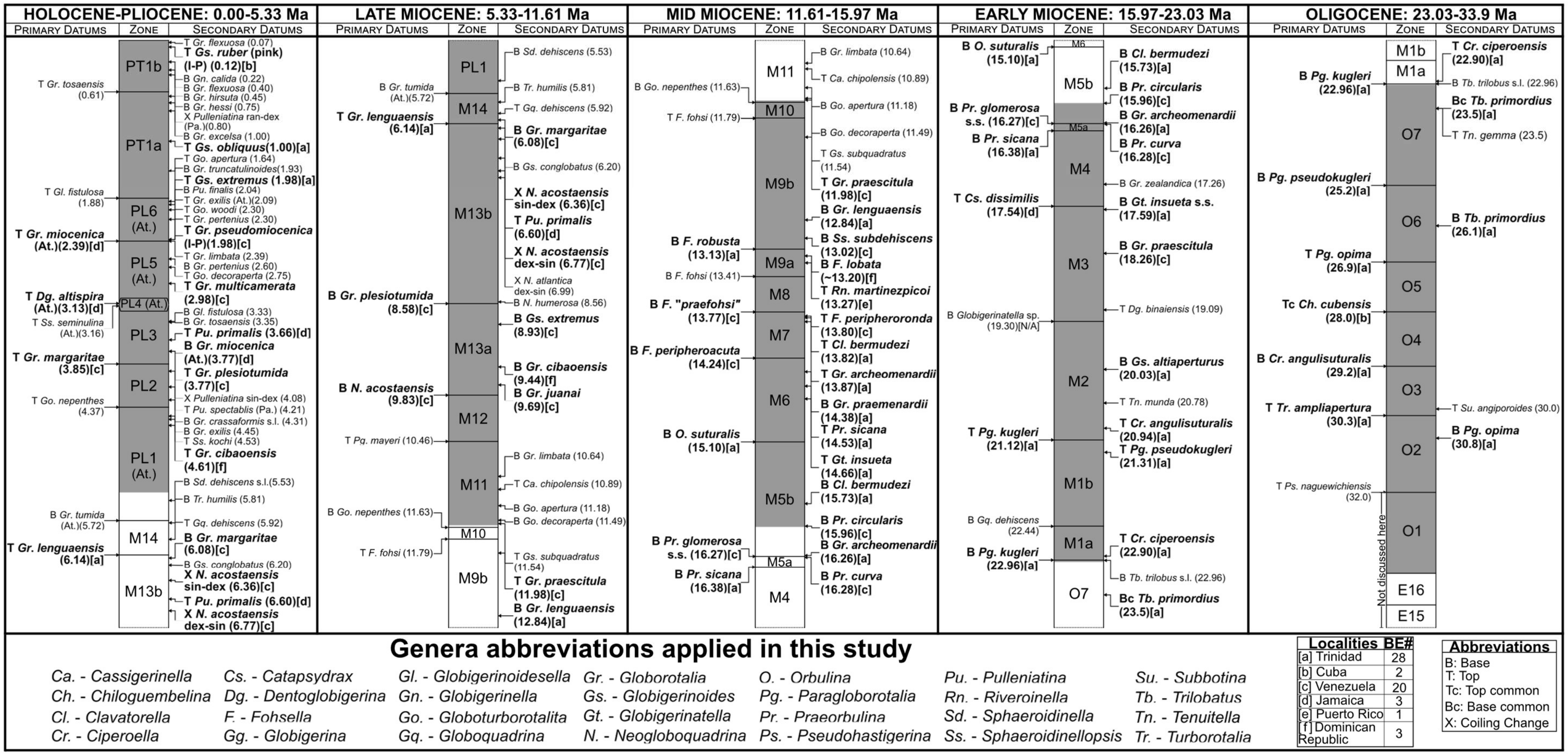


Figure 1. Primary and secondary datums applied in Wade et al. (2011) based on species described from the Caribbean region. The alphanumeric zones are for the Atlantic region. BE# respectively refers to the bioevents recognised based on the original country in which the species was described.

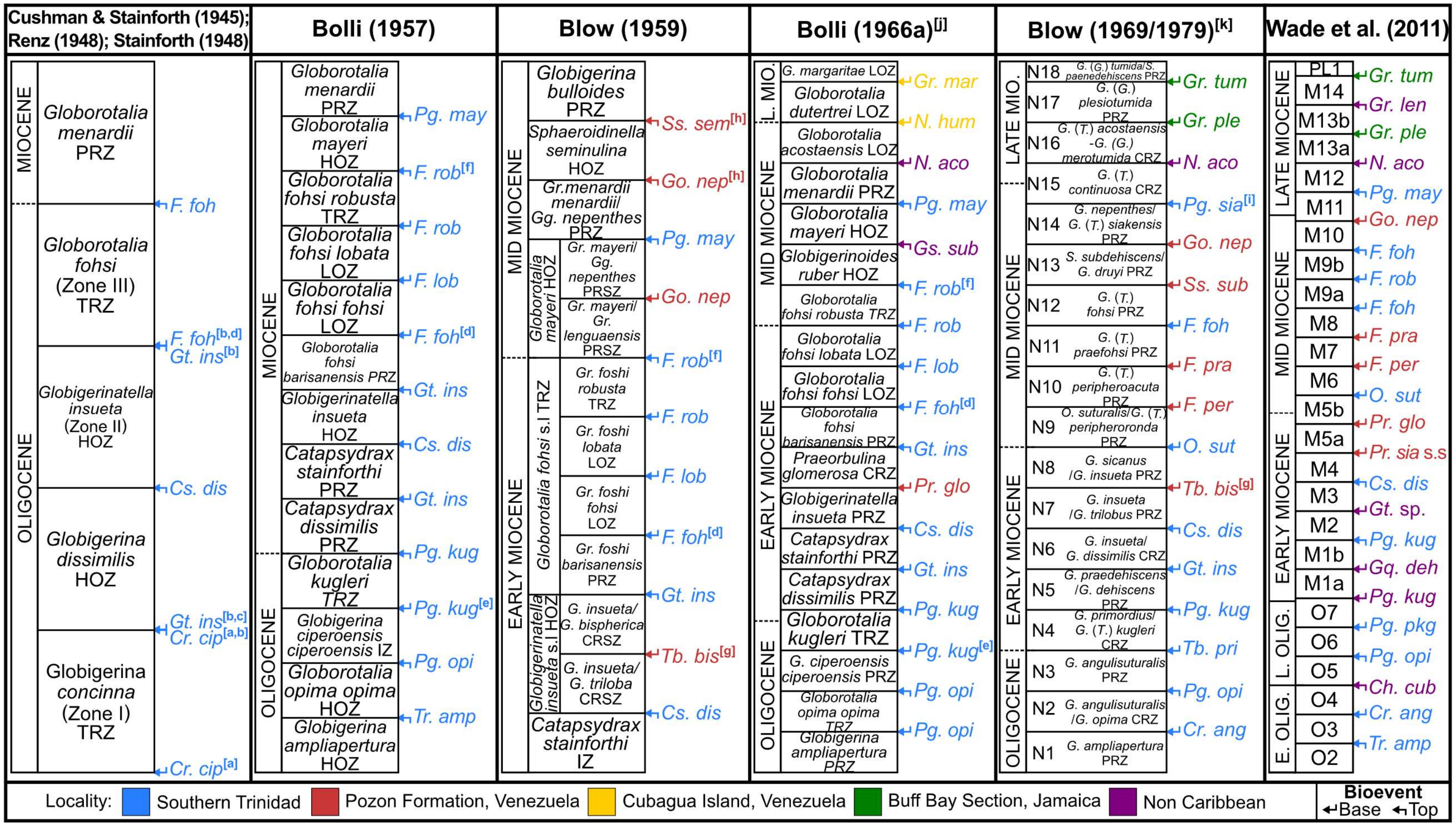


Figure 2. Key Caribbean centric schemes detailing the area where each bioevent was first recognised. Notes: [a] Top and Base *Globigerina concinna* were initially applied as bioevents but this species was misidentified and replaced with the then newly described *Ciperoella ciperoensis* by Bolli (1954). [b] Bioevents now known to be diachronous. [c] Prior to the recognition of the *Catapsydrax dissimilis* Zone,

Cushman and Stainforth (1945) employed Base *Gt. insueta* to mark the base of Zone II (*Gt. insueta* Zone). [d] Author(s) included *F. peripheroacuta* and *F. "praefohsi"* within their concept of *F. fohsi*. [e] Author(s) included *Pg. pseudokugleri* within their concept of *Pg. kugleri.* [f] Top of the *Fohsi* lineage (currently calibrated on Top *F. fohsi*). [g] Blow (1969) later amended this zone to Base *Gs. sicana* and considered the two synonymous. [h] Localised extinction events, not able to be correlated globally. [i] Due to ongoing taxonomic controversary between *Pg. mayeri* and *Pg. siakensis* and some authors considering the forms synonymous, the datums are considered to be synchronous. [j] Partly based on Bolli and Bermudez (1965) in the upper Miocene interval. [k] Primarily based on datums from Banner and Blow (1965a).

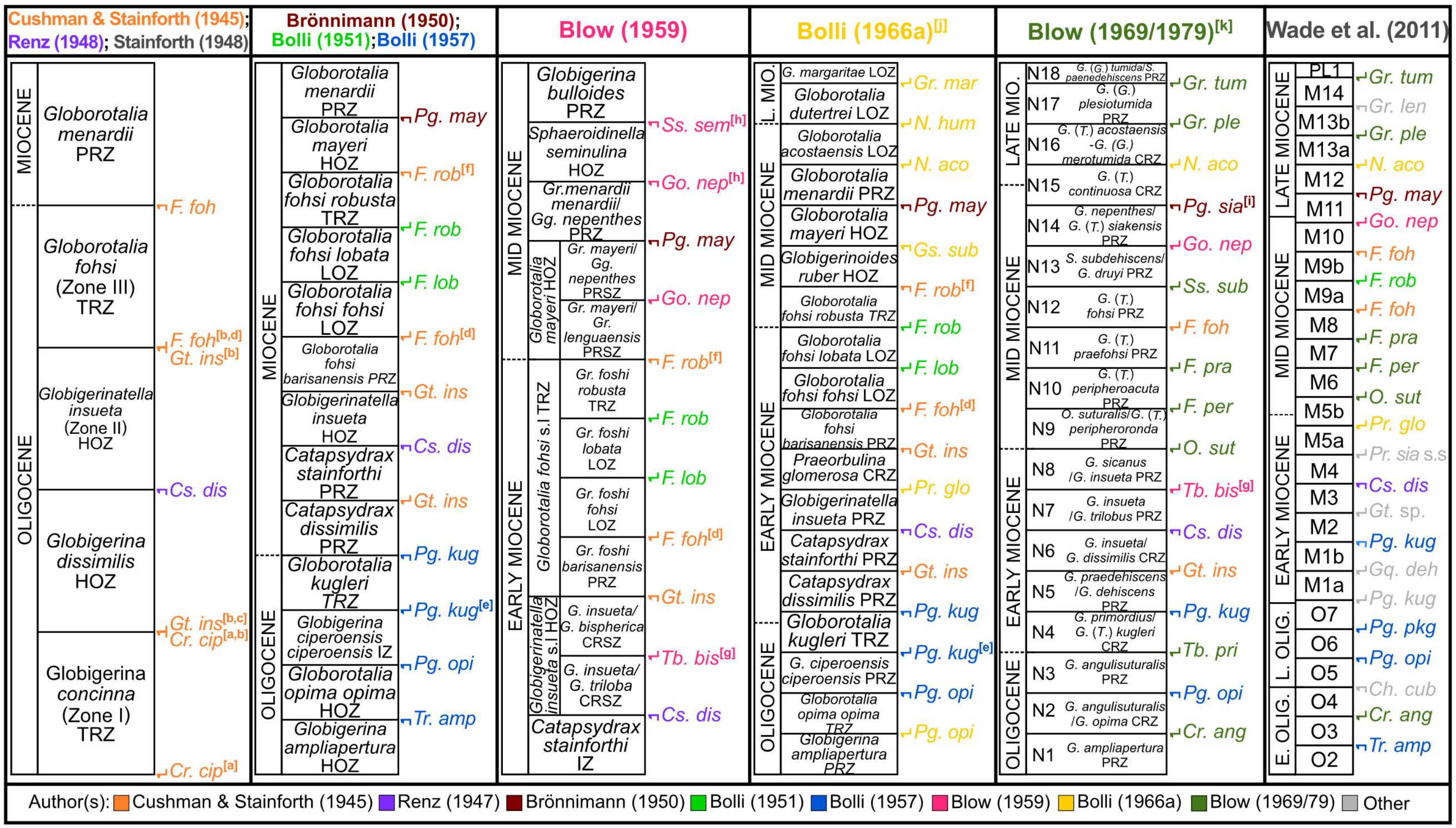


Figure 3. Key Caribbean centric schemes detailing authors who first applied a given bioevent. See Figure 2 caption for figure notes.

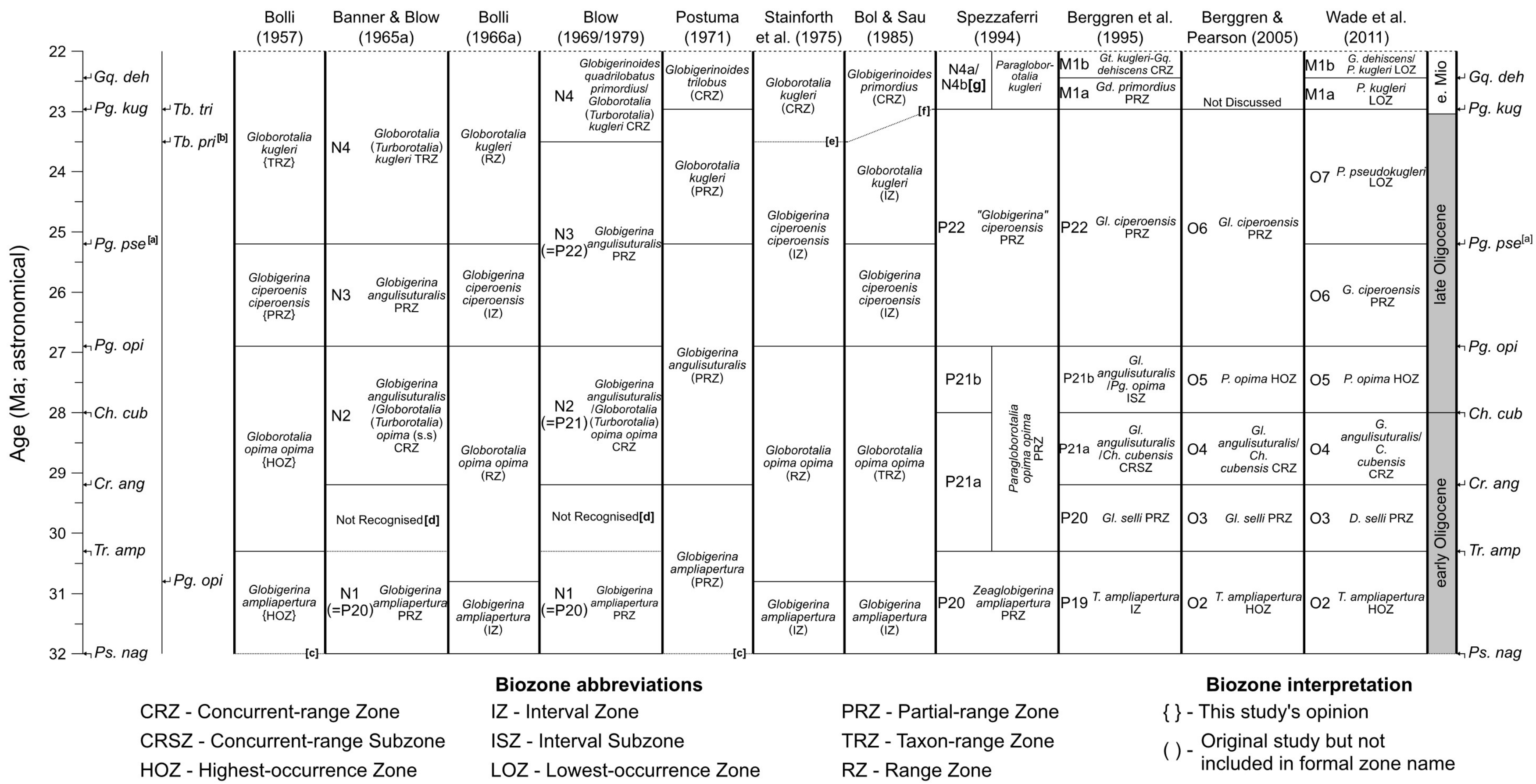


Figure 4. Comparison of key Caribbean centric zonal schemes for the Oligocene interval calibrated to the datums and geological timescale of Wade et al. (2011; table 4). Bol & Sau (1985) = Bolli and Saunders (1985). The shaded grey box on geological epochs illustrates the relevant interval. Notes: [a] Author considered *Pg. pseudokugleri* within their concept of *Pg. kugleri*. [b] Base common *Tb. primordius.* [c] Base not

observed. [d] *Tr. ampliapertura* and *Cr. angulisuturalis* are suggested to have overlapping ranges meaning Zone O3 is not recognised in these schemes. [e] Authors do not specify which species is applied in their zonal description, the level here is based on their range chart. [f] Base is diachronous. [g] Subzone N4a (Base *Pg. kugleri*) and Subzone N4b (Base *Tb. trilobus*) considered synchronous bioevents.

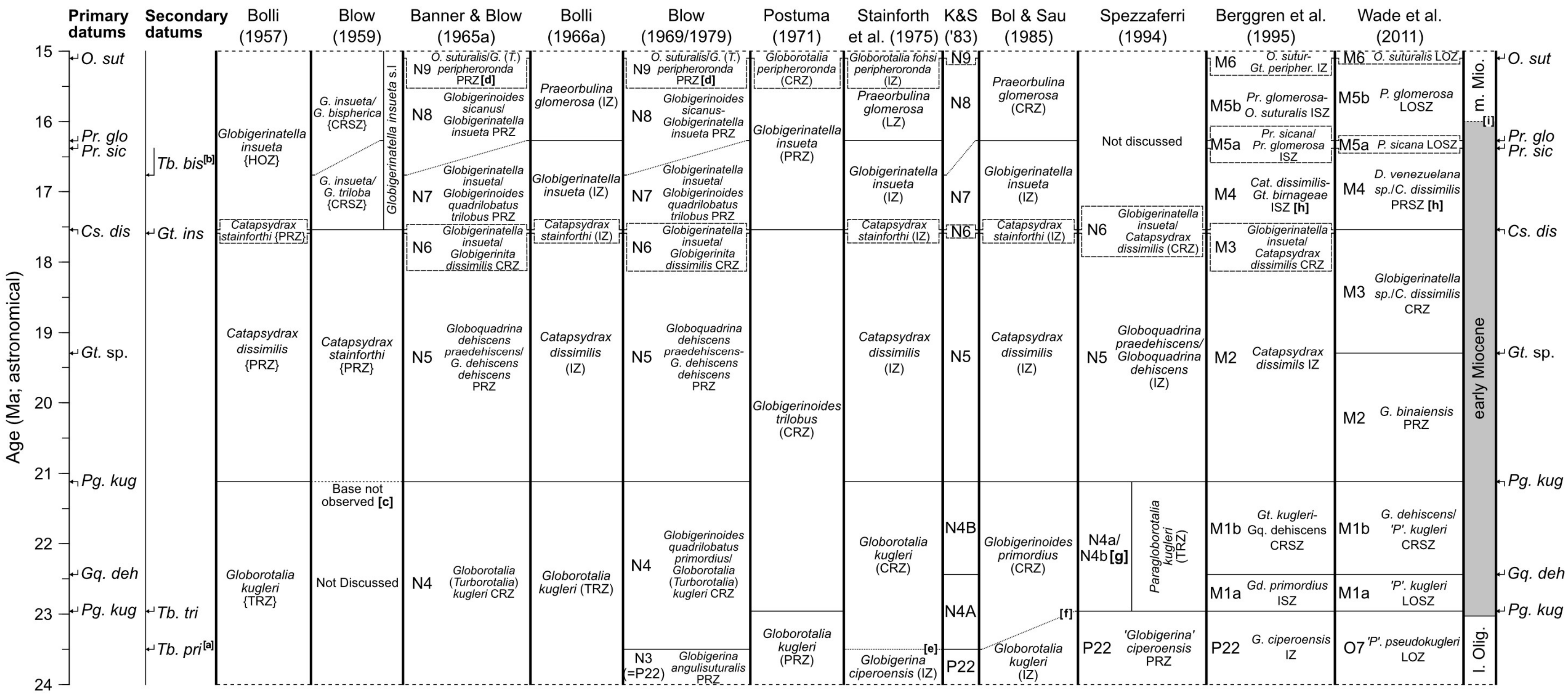


Figure 5. Comparison of key Caribbean centric zonal schemes for the early Miocene interval calibrated to the datums and geological timescale of Wade et al. (2011; table 3). K&S ('83) = Kennett and Srinivasan (1983), Bol & Sau (1985) = Bolli and Saunders (1985). Notes: [a] Base common *Tb. primordius.* [b] Base of *Tb. primordius* currently poorly constrained. [c] The exact position of the base of the Pozon Formation within the *Cs. dissimilis* biozone is unknown. [d] The full formal name of Zone N9 is the *Orbulina suturalis-Globorotalia* (*Turborotalia*) *peripheroronda* PRZ. [e] Authors do not specify which species is applied in their zonal description, the level here is based on their range chart.

[f] Base is diachronous. [g] Zone N4a (Base *Pg. kugleri*) and Zone N4b (Base *Tb. trilobus* s.l.) now considered synchronous datums. [h] Base of *Pg. birnageae* is no longer recognised as a bioevent, meaning Subzone M4b is no longer recognised. [i] Base of the Langhian (=base of mid Miocene) is currently unratified.

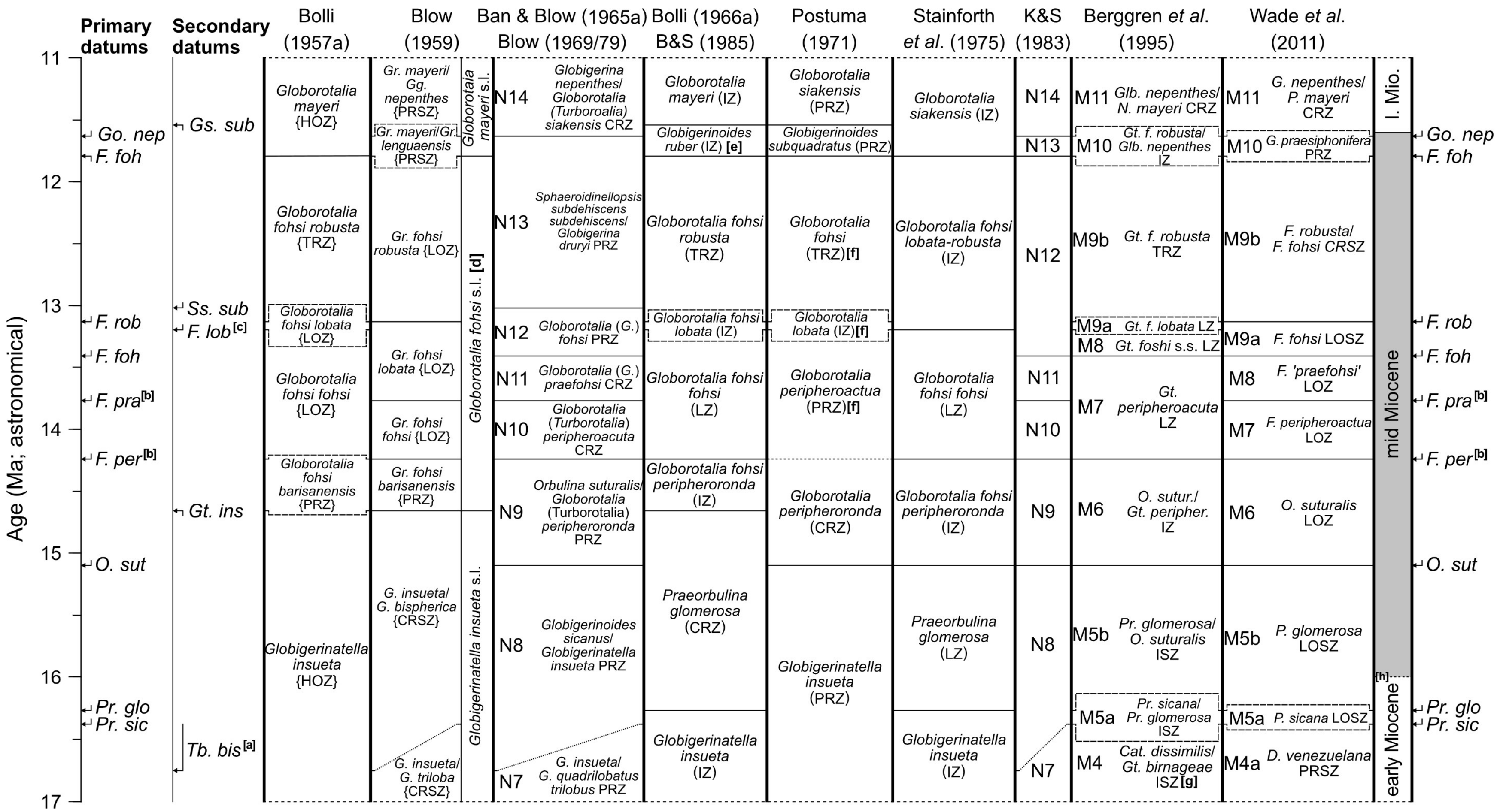


Figure 6. Comparison of key Caribbean centric zonal schemes for the mid Miocene interval calibrated to the datums and geological timescale from Wade et al. (2011; table 3). Ban & Blow (1965) = Banner and Blow (1965a), B&S (1985) = Bolli and Saunders (1985), K&S (1983) =

Kennett and Srinivasan (1983). Notes: [a] Base of *Tb. primordius* currently poorly constrained [b] Some authors include *F. peripheroacuta* and *F. praefohsi* in their concept of *F. fohsi*. [c] Base of *F. lobata* estimated based on figure 5 in Wade et al. (2011). [d] Correlations of the Blow's (1959) *Fohsella* zones are based on the correlations and concepts presented in figure 18 of Blow (1969). [e] Bolli applied the top Miocene occurrence of *Gs. ruber* from a core in Java (Bolli, 1966b) this is consistent with the level of Top *Gs. subquadratus.* [f] Species concepts of *Fohsella* group unclear; Chart 3 in Postuma (1971) suggests zonations correlate to those of Bolli (1966a). [g] Base of *P. birnageae* is no longer recognised as a bioevent, meaning Subzone M4b is no longer recognised. [h] Base of the Langhian (=base of mid Miocene) is not yet ratified.

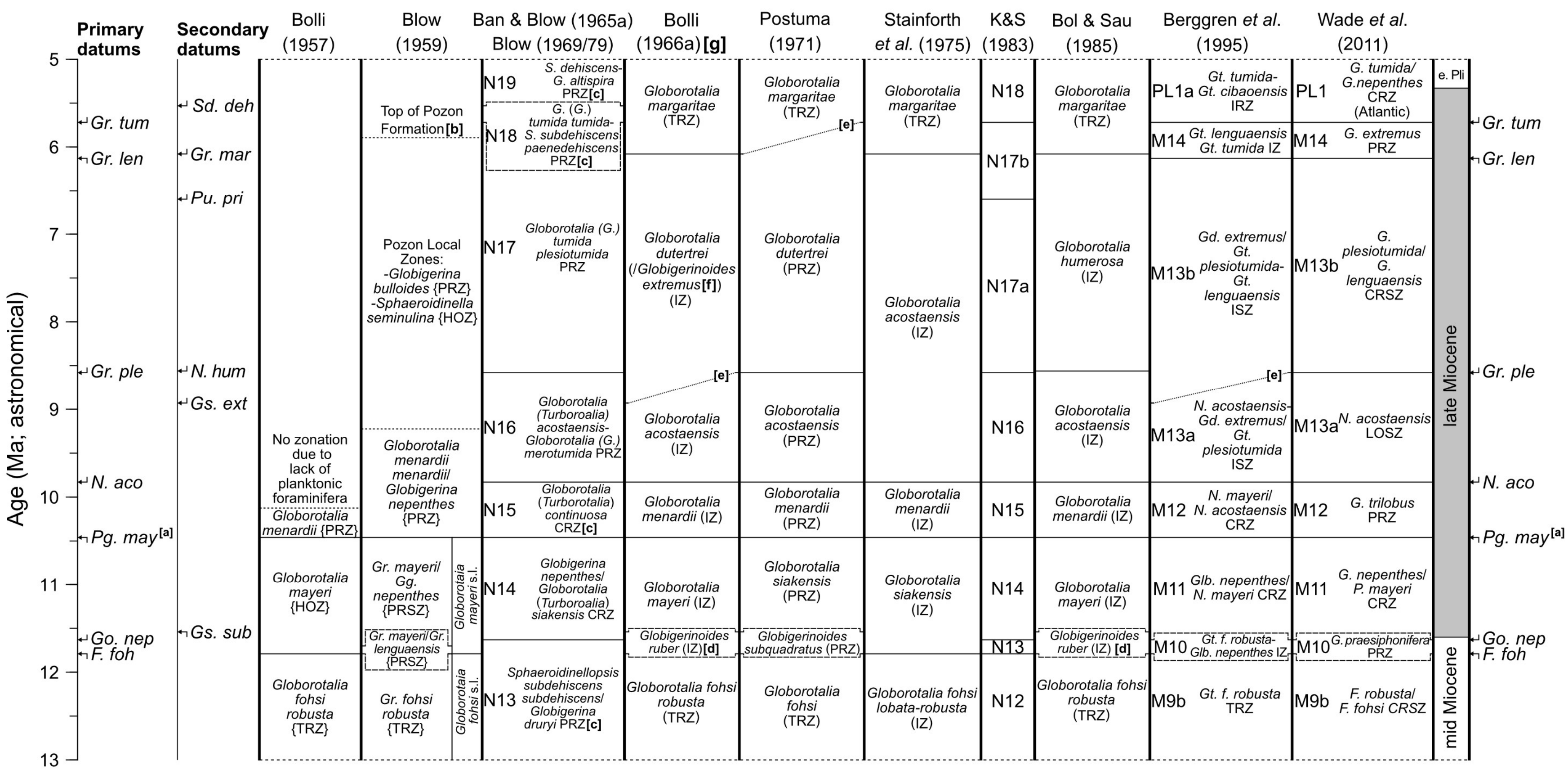


Figure 7. Comparison of key Caribbean centric zonal schemes for the late Miocene interval calibrated to the datums from Wade et al. (2011; table 3). Ban & Blow (1965) = Banner and Blow (1965a), K&S (1983) = Kennett and Srinivasan (1983), Bol & Sau (1985) = Bolli and Saunders (1985). Notes: [a] Due to ongoing taxonomic controversy, both the Top *Pg. mayeri* and *Pg. siakensis* are considered within this bioevent. [b] Top position of Pozon Formation inferred from Figure 17 of Blow (1969). [c] Blow's (1969; 1979 formal names applied here. These differ in

Banner and Blow (1965a); N13: *Sphaeroidinellopsis subdehiscens-Globigerina* n.sp.aff. nepenthes, N15: *Globorotalia (Turborotalia) continuosa* PRZ, N18: *Globorotalia* (*G.*) *tumida tumida-Sphaeroidinellopsis subdehiscens* PRZ, N19: *Sphaeroidinella dehiscens* (s.s.)/*Globoquadrina altispira* (s.s.) PRZ. [d] Bolli applied the top Miocene occurrence of *Gs. ruber* from a core in Java (Bolli, 1966b) this is consistent with the level of Top *Gs. subquadratus.* [e] Base now considered to be diachronous. [f] Bolli and Bermudez (1965) defined this zone based on Base *G. dutertrei* and/or Base *G. extremus*, but Bolli (1966a) simplified this to Base *G. dutertrei* only, which the author later recognised as Base *N. humerosa*. [g] Based partly on Bolli and Bermudez (1965).

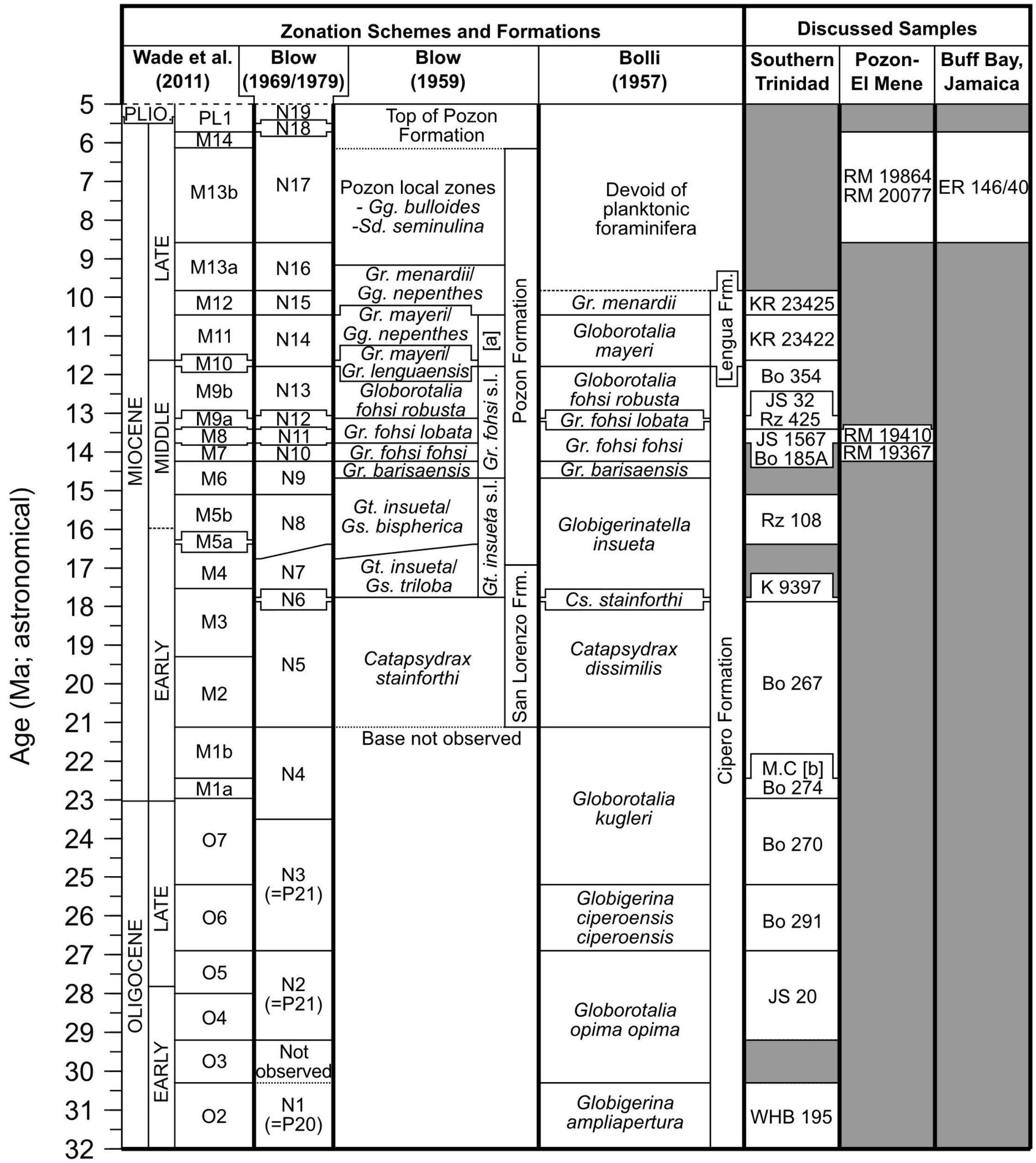


Figure 8. Zonal schemes of Bolli (1957), Blow (1959), Blow (1969, 1979) and Wade et al. (2011) relative to the stratigraphic position of the samples for the residues and slides that we re-studied from southern Trinidad, the Pozon-El Mene Road Section (northeast Venezuela) and Buff Bay (eastern Jamaica). The formations listed next to Bolli (1957) and Blow (1959) are from southern Trinidad and the Pozon El-Mene section respectively. Notes: [a] *Globorotalia mayeri* Zone. [b] Mosquito Creek co-type *kugleri* locality.

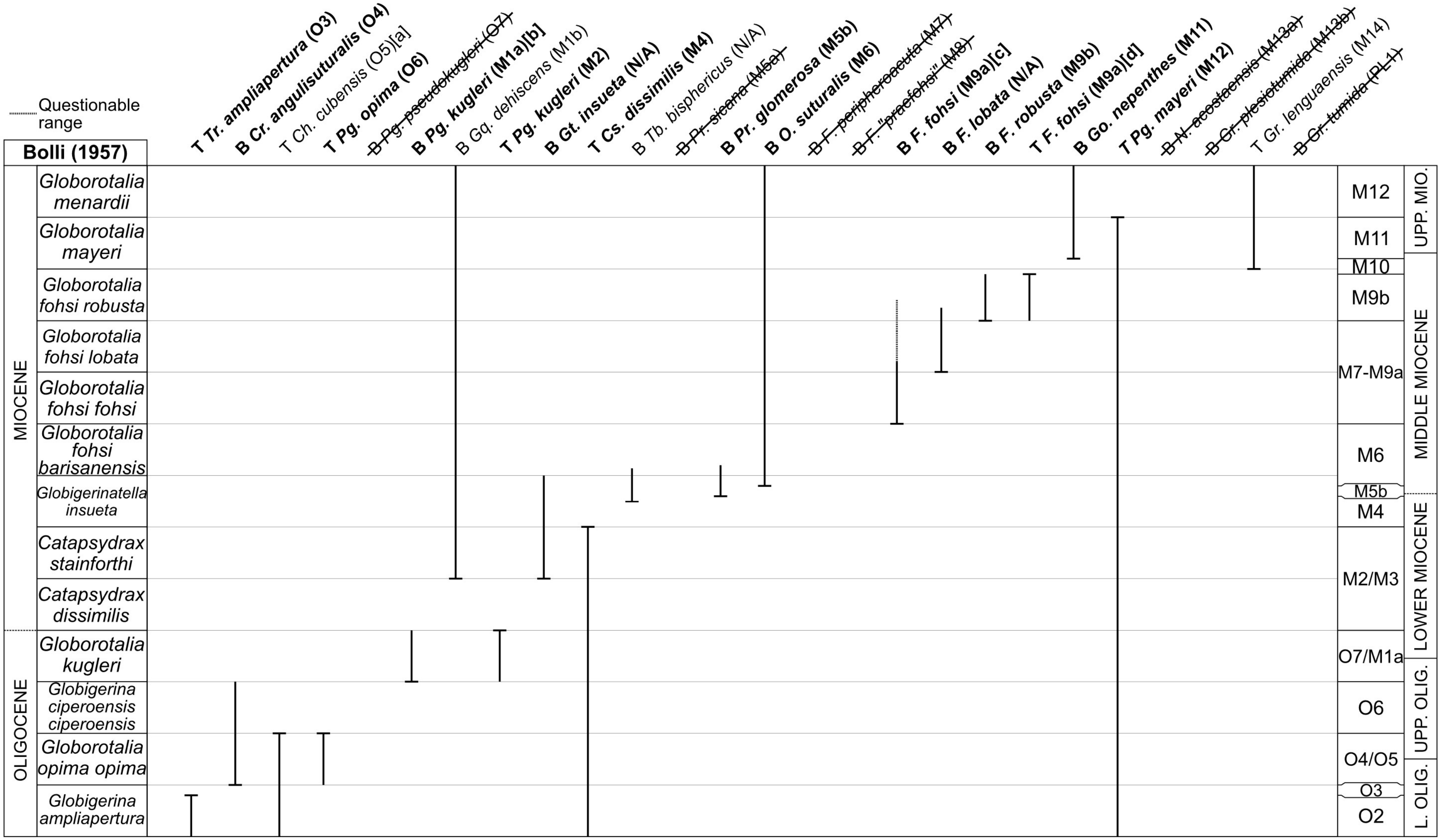
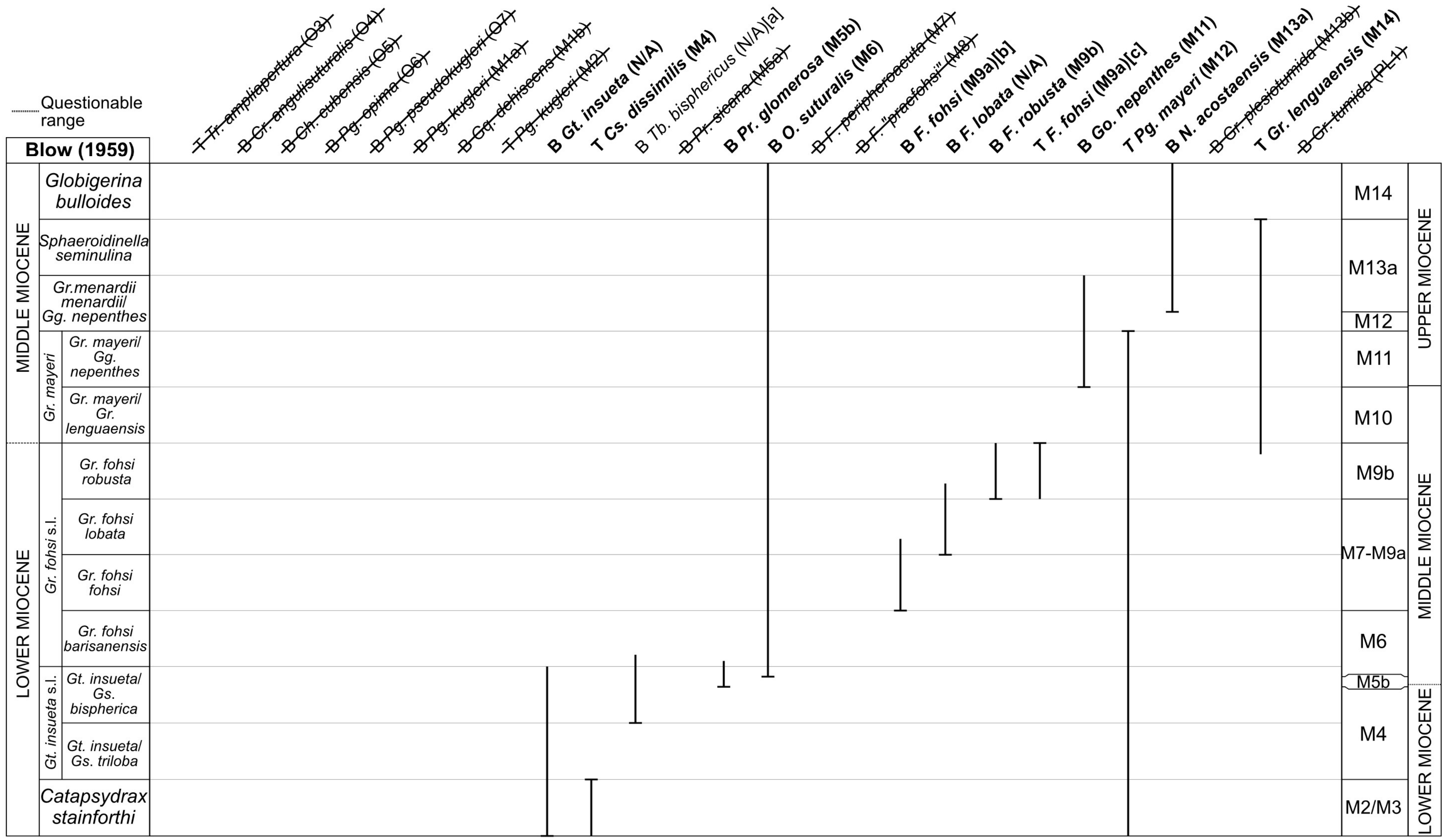
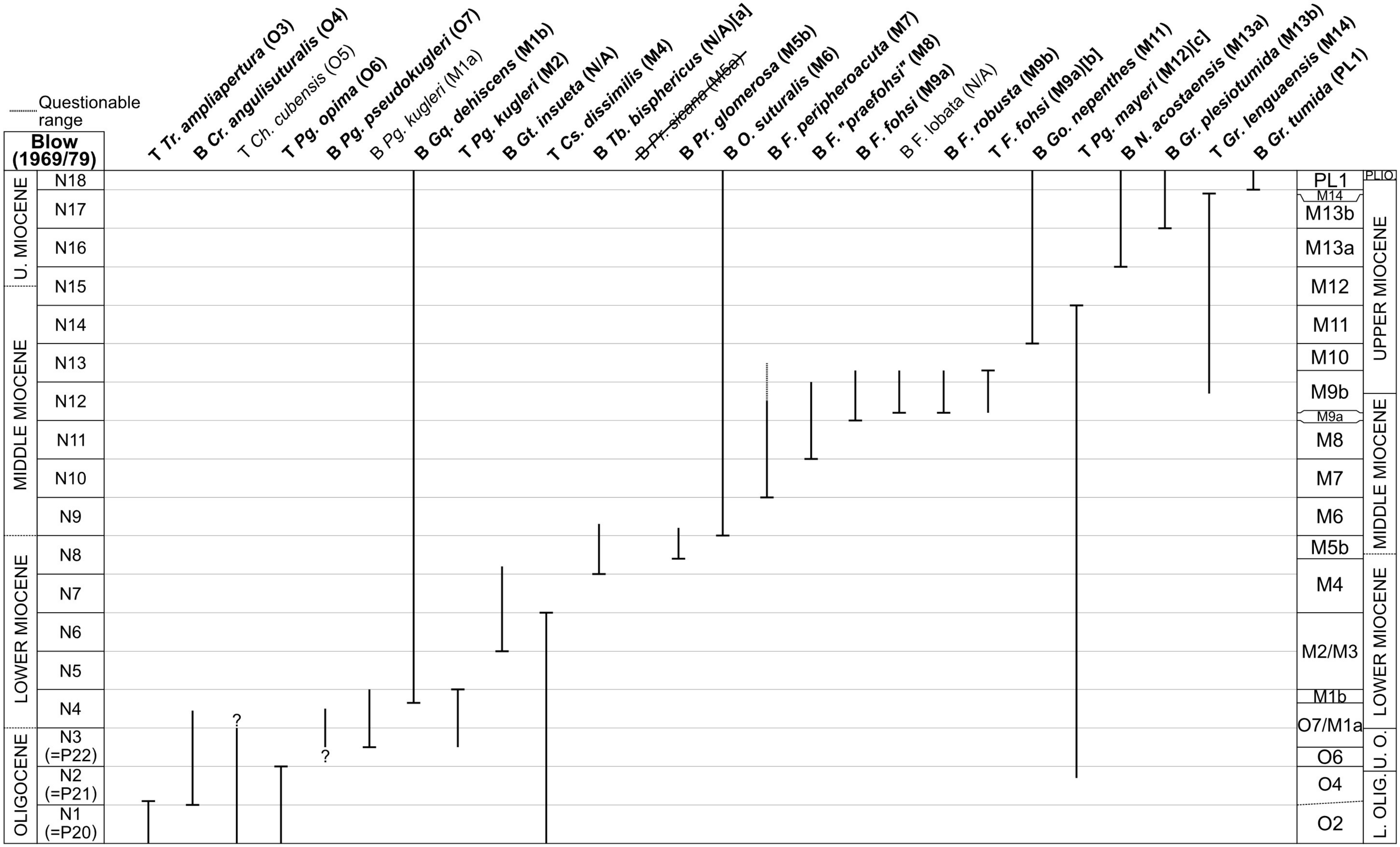

Questionable range
Bolli (1957)
T Tr. ampliapertura (O3)
B Cr. angulisuturalis (O4)
T Ch. cubensis (O5)[a]
T Pg. opima (O6)
B Pg. pseudokugleri (O7)
B Pg. kugleri (M1a)[b]
B Gq. dehiscens (M1b)
T Pg. kugleri (M2)
B Gt. insueta (N/A)
T Cs. dissimilis (M4)
B Tb. bisphericus (N/A)
B Pr. sicana (M5a)
B Pr. glomerosa (M5b)
B O. suturalis (M6)
B F. peripheroacuta (M7)
B F. "praefohsi" (M8)
B F. fohsi (M9a)[c]
B F. lobata (N/A)
B F. robusta (M9b)
T F. fohsi (M9a)[d]
B Go. nepenthes (M11)
T Pg. mayeri (M12)
B N. acostaensis (M13a)
B Gr. plesiotumida (M13b)
T Gr. lenguaensis (M14)
B Gr. tumida (PL1)
MIOCENE
OLIGOCENE
Globorotalia menardii
Globorotalia mayeri
Globorotalia fohsi robusta
Globorotalia fohsi lobata
Globorotalia fohsi fohsi
Globorotalia fohsi barisanensis
Globigerinatella insueta
Catapsydrax stainforthi
Catapsydrax dissimilis
Globorotalia kugleri
Globigerina ciperoensis ciperoensis
Globorotalia opima opima
Globigerina ampliapertura
M12
M11
M10
M9b
M7-M9a
M6
M5b
M4
M2/M3
O7/M1a
O6
O4/O5
O3
O2
UPP. MIO.
MIDDLE MIOCENE
LOWER MIOCENE
UPP. OLIG.
L. OLIG.

Figure 9. Zonal scheme and ranges from Bolli (1957; figure 18) and interpreted zonal scheme based on Wade et al. (2011). The species in bold were in a position consistent to their biostratigraphic application, while those not in bold were inconsistent. The species with a text strike through were not found by the original author or were included in their concept of another species. The species name is based upon the original authors opinion.Notes: [a] Range of *Ch. cubensis* from Beckmann (1957; figure 16). [b] *Pg. pseudokugleri* is included within the author's concept of *Pg. kugleri*. [c] *F. peripheroacuta* and *F. praefohsi* are included within the author's concept of *F. fohsi*. [d] Level of Top *F. robusta*.



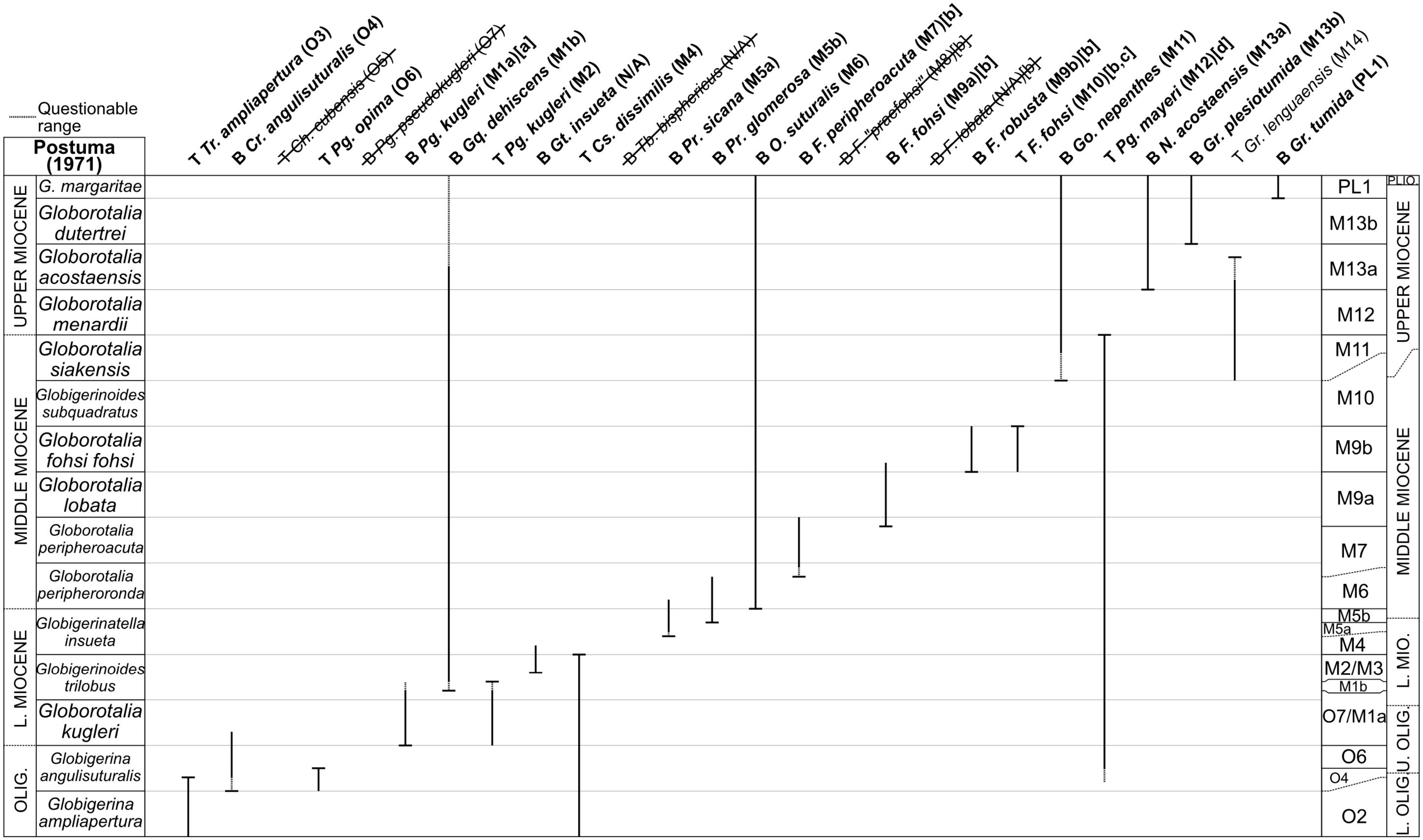
Questionable range
Blow (1959)
T Tr. ampliapertura (O3)
B Gr. angulisuturalis (O4)
B Ch. cubensis (O5)
B Pg. opima (O6)
B Pg. pseudokugleri (O7)
B Pg. kugleri (M1a)
B Gq. dehiscens (M1b)
T Pg. kugleri (M2)
B Gt. insueta (N/A)
T Cs. dissimilis (M4)
B Tb. bisphericus (N/A)[a]
B Pr. sicana (M5a)
B Pr. glomerosa (M5b)
B O. suturalis (M6)
B F. peripheroacuta (M7)
B F. "praefohsi" (M8)
B F. fohsi (M9a)[b]
B F. lobata (N/A)
B F. robusta (M9b)
T F. fohsi (M9a)[c]
B Go. nepenthes (M11)
T Pg. mayeri (M12)
B N. acostaensis (M13a)
B Gr. plesiotumida (M13b)
T Gr. lenguaensis (M14)
B Gr. tumida (PL1)
MIDDLE MIOCENE
LOWER MIOCENE
Globigerina bulloides
Sphaeroidinella seminulina
Gr.menardii menardii/ Gg. nepenthes
Gr. mayeri
Gr. mayeri/ Gg. nepenthes
Gr. mayeri/ Gr. lenguaensis
Gr. fohsi s.l.
Gr. fohsi robusta
Gr. fohsi lobata
Gr. fohsi fohsi
Gr. fohsi barisanensis
Gt. insueta s.l.
Gt. insueta/ Gs. bispherica
Gt. insueta/ Gs. triloba
Catapsydrax stainforthi
M14
M13a
M12
M11
M10
M9b
M7-M9a
M6
M5b
M4
M2/M3
UPPER MIOCENE
MIDDLE MIOCENE
LOWER MIOCENE

Figure 10. Zonal scheme and ranges from Blow (1959; chart 3) and interpreted zonal scheme based on Wade et al. (2011). The species in bold were in a position consistent to their biostratigraphic application, while those not in bold were inconsistent. The species with a text strike through were not found by the original author or were included in their concept of another species. The species name is based upon the original authors opinion. Notes: [a] Blow originally applied Base *Tr. bisphericus* in zone recognition but later included this species within his concept of *Gs. sicanus*. [b] *F. peripheroacuta* and *F. praefohsi* are included within the author's concept of *F. fohsi*. [c] Level of Top *F. robusta*.



Questionable range
Blow (1969/79)
T Tr. ampliapertura (O3)
B Cr. angulisuturalis (O4)
T Ch. cubensis (O5)
T Pg. opima (O6)
B Pg. pseudokugleri (O7)
B Pg. kugleri (M1a)
B Gq. dehiscens (M1b)
T Pg. kugleri (M2)
B Gt. insueta (N/A)
T Cs. dissimilis (M4)
B Tb. bisphericus (N/A)[a]
B Pr. sicana (M5a)
B Pr. glomerosa (M5b)
B O. suturalis (M6)
B F. peripheroacuta (M7)
B F. "praefohsi" (M8)
B F. fohsi (M9a)
B F. lobata (N/A)
B F. robusta (M9b)
T F. fohsi (M9a)[b]
B Go. nepenthes (M11)
T Pg. mayeri (M12)[c]
B N. acostaensis (M13a)
B Gr. plesiotumida (M13b)
T Gr. lenguaensis (M14)
B Gr. tumida (PL1)
U. MIOCENE
MIDDLE MIOCENE
LOWER MIOCENE
OLIGOCENE
N18
N17
N16
N15
N14
N13
N12
N11
N10
N9
N8
N7
N6
N5
N4
N3 (=P22)
N2 (=P21)
N1 (=P20)
?
?
PL1
M14
M13b
M13a
M12
M11
M10
M9b
M9a
M8
M7
M6
M5b
M4
M2/M3
M1b
O7/M1a
O6
O4
O2
PLIO
UPPER MIOCENE
MIDDLE MIOCENE
LOWER MIOCENE
U. O.
L. OLIG.

Figure 11. Zonal scheme and ranges from Blow (1969/1979; figures 1-13) and interpreted zonal scheme based on Wade et al. (2011). The species in bold were in a position consistent to their biostratigraphic application, while those not in bold were inconsistent. The species with a text strike through were not found by the original author or were included in their concept of another species. The species name is based upon the original authors opinion. Notes: [a] Included *Tb. bisphericus* within his concept of *"Tb." sicanus* [b] Level of Top *F. robusta*. [c] Level of Top *Pg. siakensis.*



Questionable range
Postuma (1971)
T Tr. ampliapertura (O3)
B Cr. angulisuturalis (O4)
T Ch. cubensis (O5)
T Pg. opima (O6)
B Pg. pseudokugleri (O7)
B Pg. kugleri (M1a)[a]
B Gq. dehiscens (M1b)
T Pg. kugleri (M2)
B Gt. insueta (N/A)
T Cs. dissimilis (M4)
B Tb. bisphericus (N/A)
B Pr. sicana (M5a)
B Pr. glomerosa (M5b)
B O. suturalis (M6)
B F. peripheroacuta (M7)[b]
B F. "praefohsi" (M8)[b]
B F. fohsi (M9a)[b]
B F. lobata (N/A)[b]
B F. robusta (M9b)[b]
T F. fohsi (M10)[b,c]
B Go. nepenthes (M11)
T Pg. mayeri (M12)[d]
B N. acostaensis (M13a)
B Gr. plesiotumida (M13b)
T Gr. lenguaensis (M14)
B Gr. tumida (PL1)
UPPER MIOCENE
MIDDLE MIOCENE
L. MIOCENE
OLIG.
G. margaritae
Globorotalia dutertrei
Globorotalia acostaensis
Globorotalia menardii
Globorotalia siakensis
Globigerinoides subquadratus
Globorotalia fohsi fohsi
Globorotalia lobata
Globorotalia peripheroacuta
Globorotalia peripheroronda
Globigerinatella insueta
Globigerinoides trilobus
Globorotalia kugleri
Globigerina angulisuturalis
Globigerina ampliapertura
PL1
M13b
M13a
M12
M11
M10
M9b
M9a
M7
M6
M5b
M5a
M4
M2/M3
M1b
O7/M1a
O6
O4
O2
PLIO.
UPPER MIOCENE
MIDDLE MIOCENE
L. MIO.
U. OLIG.
L. OLIG.

Figure 12. Zonal scheme and ranges from Postuma (1971; chart 3) and interpreted zonal scheme based on Wade et al. (2011). The species in bold were in a position consistent to their biostratigraphic application, while those not in bold were inconsistent. The species with a text strike through were not found by the original author or were included in their concept of another species. The species name is based upon the original authors opinion. Notes: [a] *Pg. pseudokugleri* is included within the author's concept of *Pg. kugleri*. [b] Postuma has a confusing concept on the fohsellids, the ranges here are based on personal interpretations. [c] Level of Top *F. robusta*. [d] Level of Top *Pg. siakensis*.

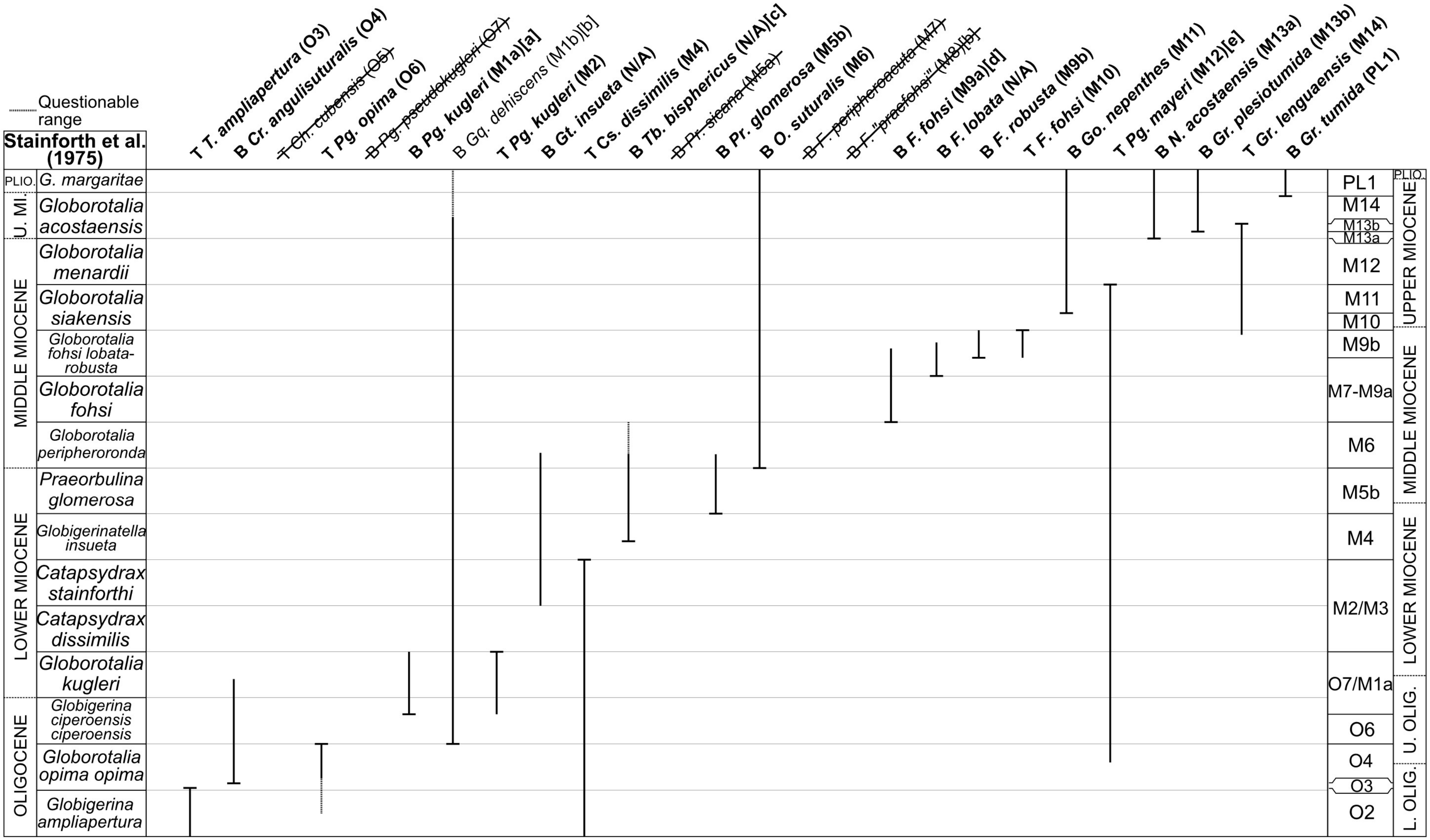
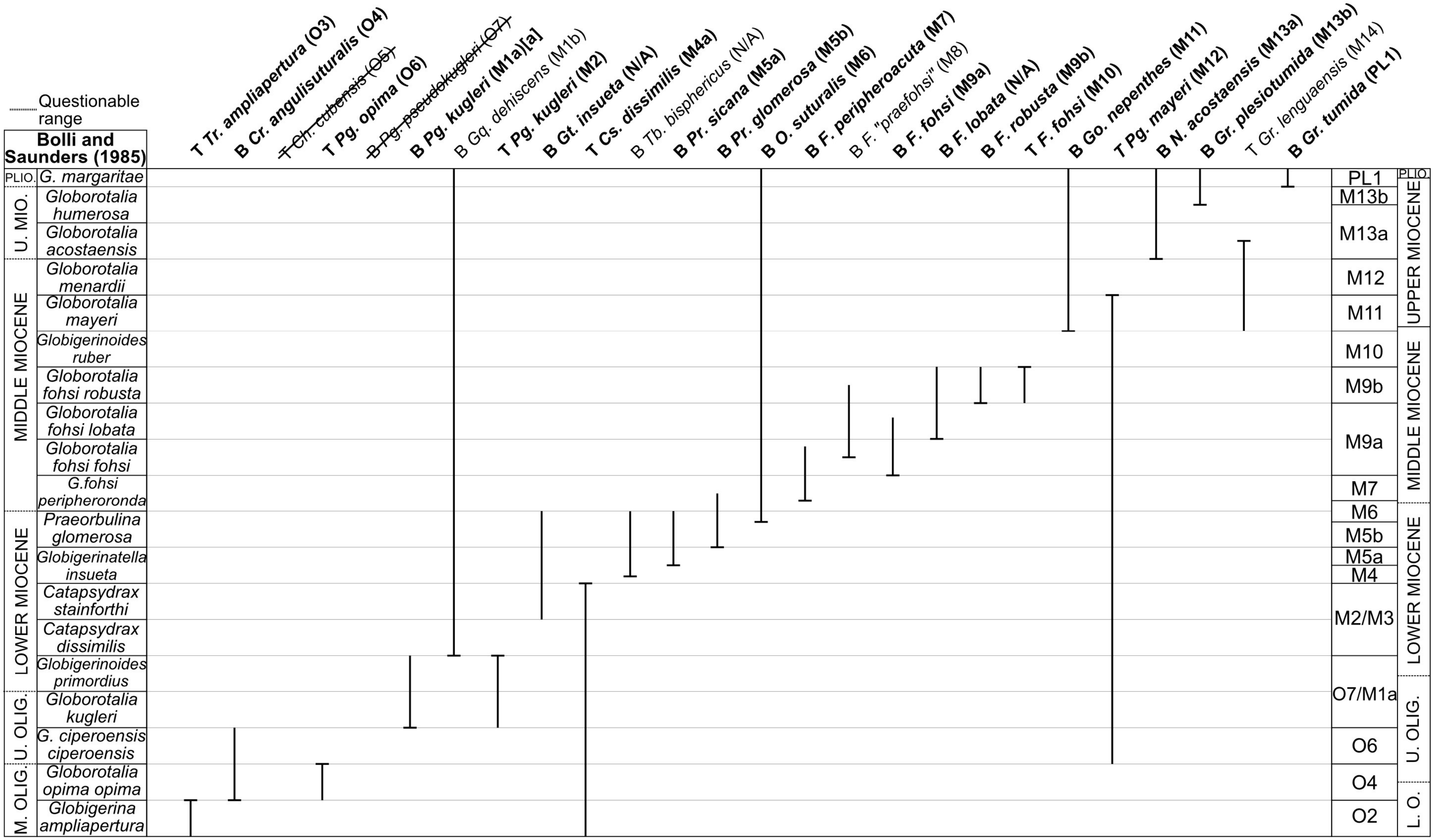

Questionable range
Stainforth et al. (1975)
T T. ampliapertura (O3)
B Cr. angulisuturalis (O4)
T Ch. cubensis (O5)
T Pg. opima (O6)
B Pg. pseudokugleri (O7)
B Pg. kugleri (M1a)[a]
B Gq. dehiscens (M1b)[b]
T Pg. kugleri (M2)
B Gt. insueta (N/A)
T Cs. dissimilis (M4)
B Tb. bisphericus (N/A)[c]
B Pr. sicana (M5a)
B Pr. glomerosa (M5b)
B O. suturalis (M6)
B F. peripheroacuta (M7)
B F. "praefohsi" (M8)[b]
B F. fohsi (M9a)[d]
B F. lobata (N/A)
B F. robusta (M9b)
T F. fohsi (M10)
B Go. nepenthes (M11)
T Pg. mayeri (M12)[e]
B N. acostaensis (M13a)
B Gr. plesiotumida (M13b)
T Gr. lenguaensis (M14)
B Gr. tumida (PL1)
PLIO.
G. margaritae
U. MI.
Globorotalia acostaensis
MIDDLE MIOCENE
Globorotalia menardii
Globorotalia siakensis
Globorotalia fohsi lobata-robusta
Globorotalia fohsi
Globorotalia peripheroronda
LOWER MIOCENE
Praeorbulina glomerosa
Globigerinatella insueta
Catapsydrax stainforthi
Catapsydrax dissimilis
Globorotalia kugleri
OLIGOCENE
Globigerina ciperoensis ciperoensis
Globorotalia opima opima
Globigerina ampliapertura
PL1
M14
M13b
M13a
M12
M11
M10
M9b
M7-M9a
M6
M5b
M4
M2/M3
O7/M1a
O6
O4
O3
O2
PLIO.
UPPER MIOCENE
MIDDLE MIOCENE
LOWER MIOCENE
U. OLIG.
L. OLIG.

Figure 13. Zonal scheme and ranges from Stainforth et al. (1975; figures 16, 19) and interpreted zonal scheme based on Wade et al. (2011). The species in bold were in a position consistent to their biostratigraphic application, while those not in bold were inconsistent. The species with a text strike through were not found by the original author or were included in their concept of another species. The species name is based upon the original authors opinion. Notes: [a] *Pg. pseudokugleri* is included within the author's concept of *Pg. kugleri*. [b] The authors only recognised a *Gq. dehiscens* group and did not differentiate between species, thus Subzone M1b cannot be recognised. [c] *F. peripheroacuta* and *F. praefohsi* are included within the author's concept of *F. fohsi.* [d] Level of Top *F. robusta*. [e] Level of Top *Pg. siakensis*.



Questionable range
Bolli and Saunders (1985)
T Tr. ampliapertura (O3)
B Cr. angulisuturalis (O4)
T Ch. cubensis (O5)
T Pg. opima (O6)
B Pg. pseudokugleri (O7)
B Pg. kugleri (M1a)[a]
B Gq. dehiscens (M1b)
T Pg. kugleri (M2)
B Gt. insueta (N/A)
T Cs. dissimilis (M4a)
B Tb. bisphericus (N/A)
B Pr. sicana (M5a)
B Pr. glomerosa (M5b)
B O. suturalis (M6)
B F. peripheroacuta (M7)
B F. "praefohsi" (M8)
B F. fohsi (M9a)
B F. lobata (N/A)
B F. robusta (M9b)
T F. fohsi (M10)
B Go. nepenthes (M11)
T Pg. mayeri (M12)
B N. acostaensis (M13a)
B Gr. plesiotumida (M13b)
T Gr. lenguaensis (M14)
B Gr. tumida (PL1)
PLIO.
G. margaritae
U. MIO.
Globorotalia humerosa
Globorotalia acostaensis
MIDDLE MIOCENE
Globorotalia menardii
Globorotalia mayeri
Globigerinoides ruber
Globorotalia fohsi robusta
Globorotalia fohsi lobata
Globorotalia fohsi fohsi
G.fohsi peripheroronda
LOWER MIOCENE
Praeorbulina glomerosa
Globigerinatella insueta
Catapsydrax stainforthi
Catapsydrax dissimilis
Globigerinoides primordius
U. OLIG.
Globorotalia kugleri
G. ciperoensis ciperoensis
M. OLIG.
Globorotalia opima opima
Globigerina ampliapertura
PL1
M13b
M13a
M12
M11
M10
M9b
M9a
M7
M6
M5b
M5a
M4
M2/M3
O7/M1a
O6
O4
O2
PLIO.
UPPER MIOCENE
MIDDLE MIOCENE
LOWER MIOCENE
U. OLIG.
L. O.

Figure 14. Zonal scheme and ranges from Bolli and Saunders (1985; figures 6-7, 9-12) and interpreted zonal scheme based on Wade et al. (2011). The species in bold were in a position consistent to their biostratigraphic application, while those not in bold were inconsistent. The species with a text strike through were not found by the original author or were included in their concept of another species. The species name is based upon the original authors opinion. Notes: [a] *Pg. pseudokugleri* is included within the author's concept of *Pg. kugleri*.

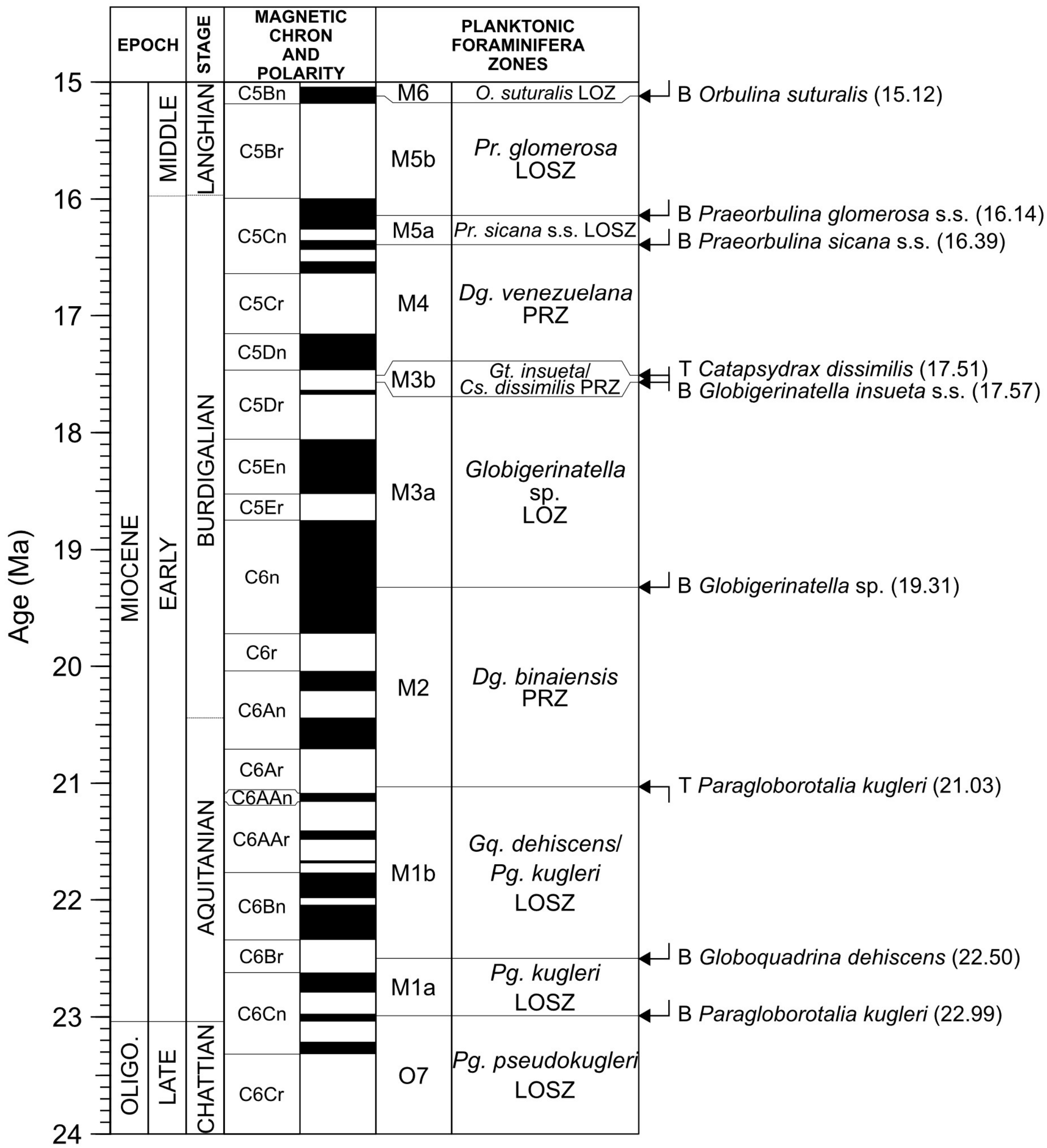


Figure 15. Primary planktonic foraminiferal bioevents for the early Miocene against the geomagnetic polarity scale of Beddow et al. (2018) from the bottom of the figure to Base Subchron C6Bn.1n, Ogg et al. (2016) for Top Subchron C6Bn.1n to Top C5En and Kochhann et al. (2016) from Base Subchron C5Dr.1n to the top of the figure.

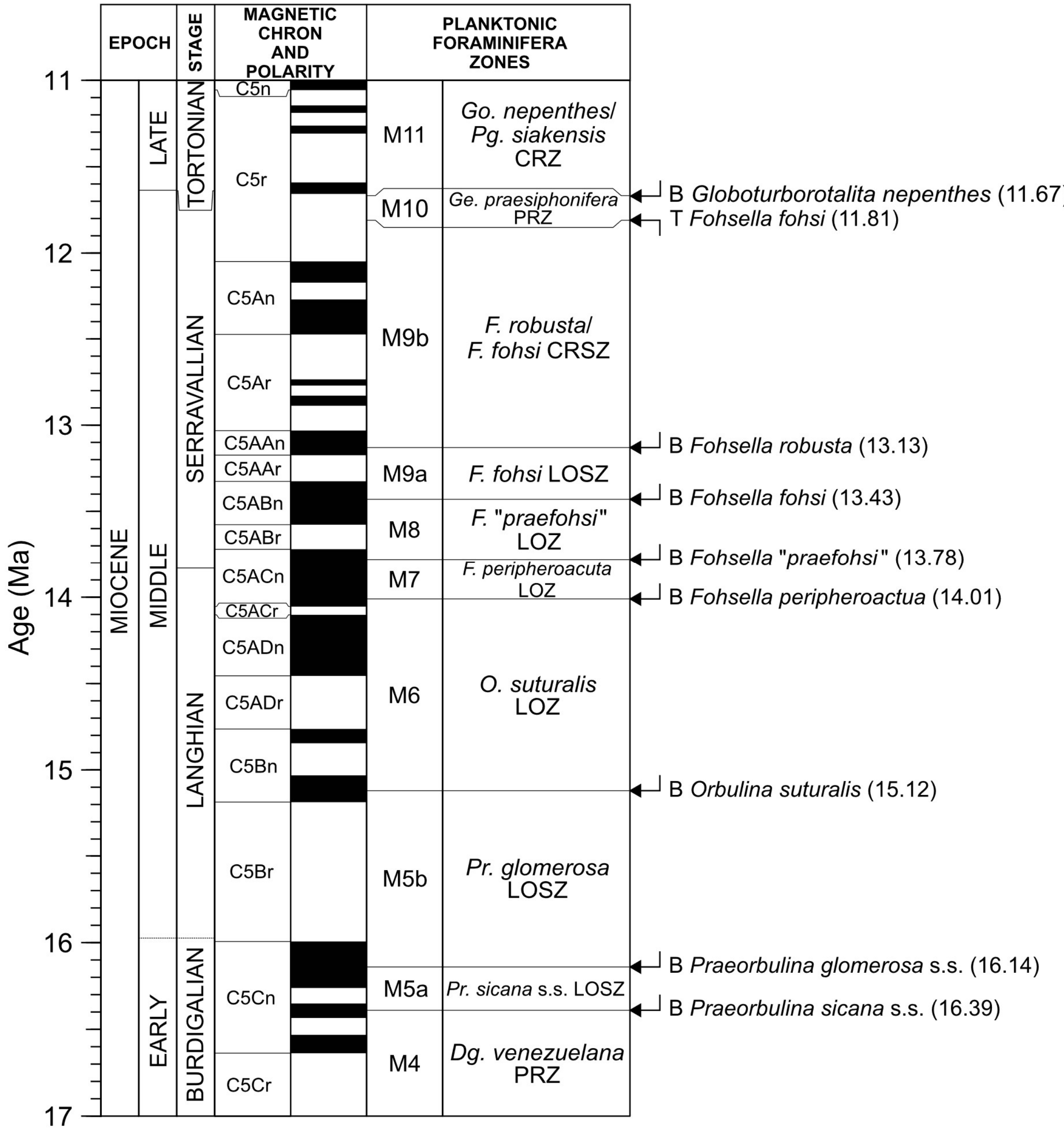


Figure 16. Primary planktonic foraminiferal bioevents for the mid Miocene against the geomagnetic polarity scale of Ogg et al. (2016) from the bottom of the figure to Top C5En, Kochhann et al. (2016) from Base Subchron C5Dr.1n to Base C5AAn and Ogg et al. (2016)n from Top C5AAn to the top of the figure.

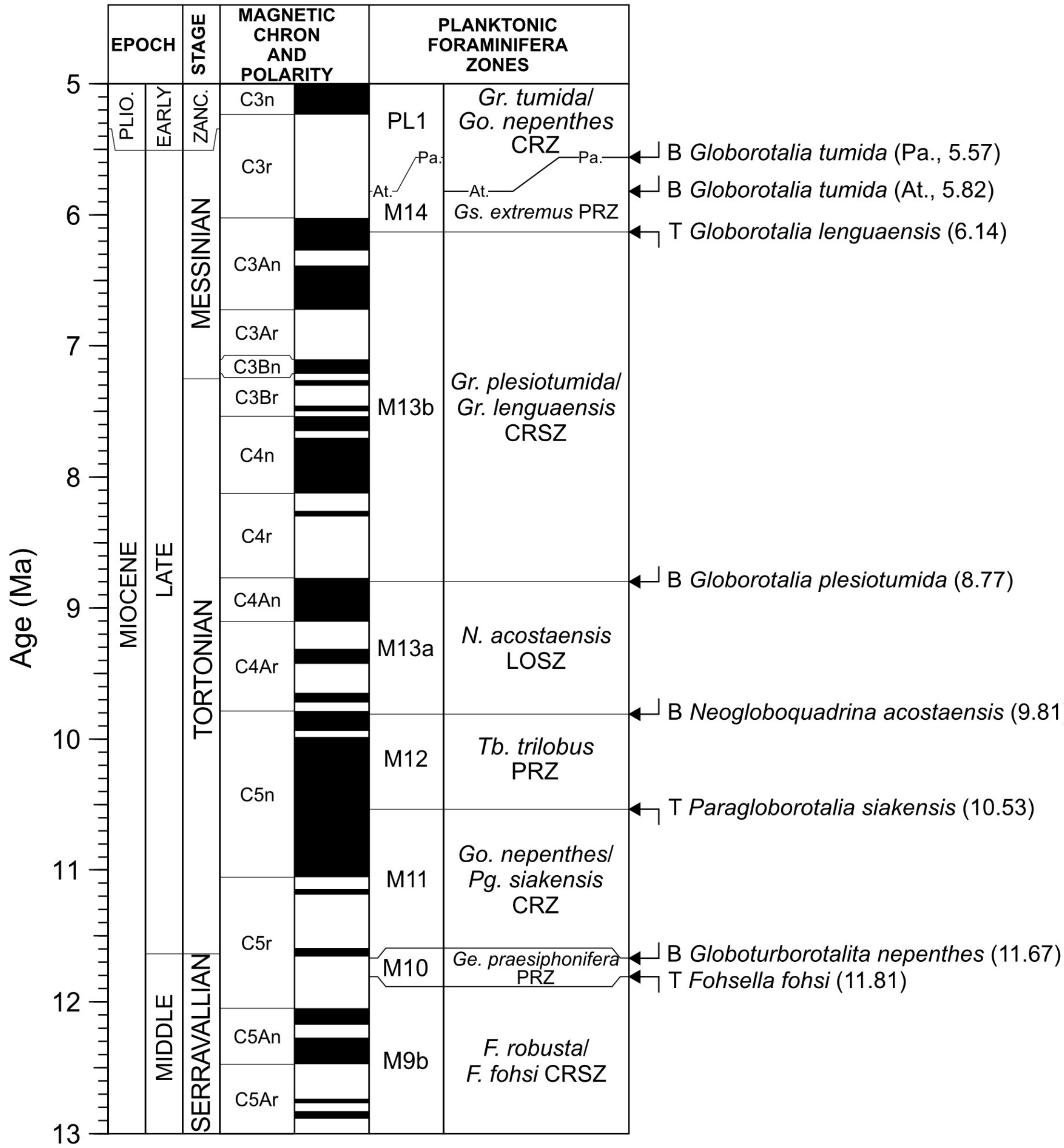


Figure 17. Primary planktonic foraminiferal bioevents for the late Miocene against the geomagnetic polarity scale of Ogg et al. (2016) from the base of the figure to Base Subchron C4r.1n, Drury et al. (2017) from Top Subchron C4r.1n to the top of the figure. Abbreviations: At. – Atlantic; Pa. – Pacific.

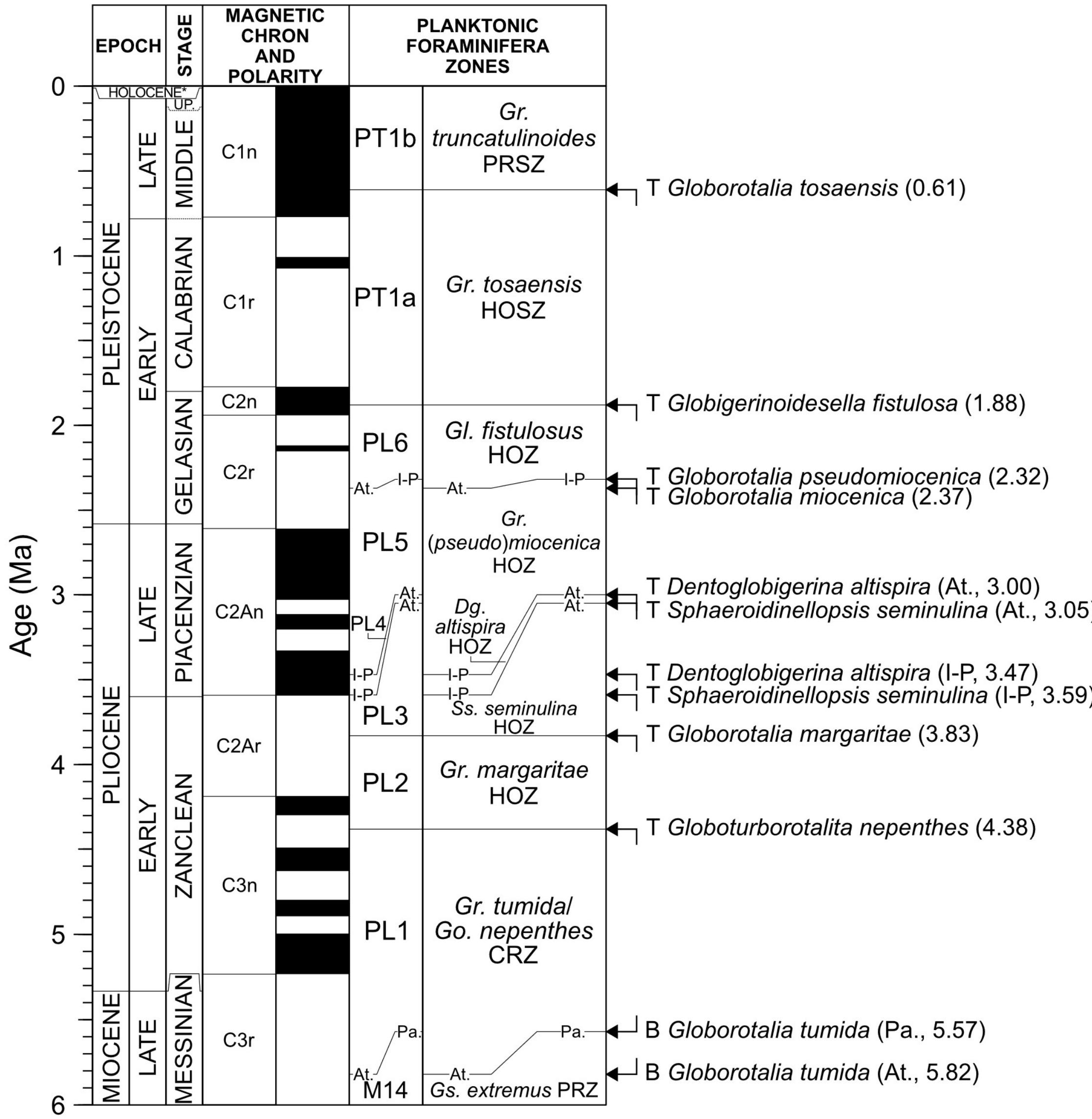


Figure 18. Primary planktonic foraminiferal bioevents for the Pliocene to Recent against the geomagnetic polarity scale of Ogg et al. (2016). Abbreviations: At. – Atlantic; Pa. – Pacific; I-P – Indo-Pacifc. Notes: * Due to the short time interval within the Holocene stages, they are not shown individually in the zonation.

Plates

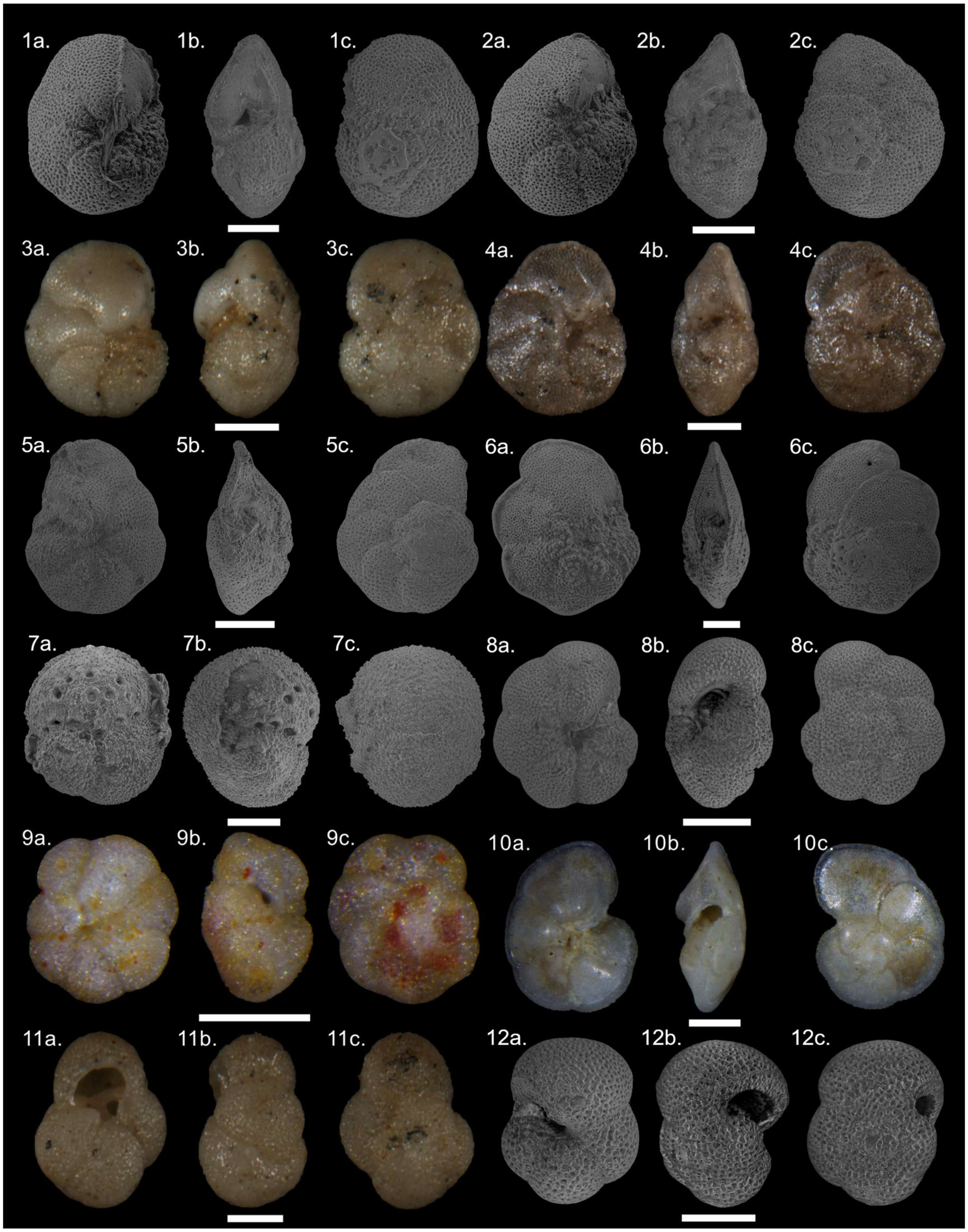


Plate Captions

Plate 1. Selected biostratigraphicially important species from the Caribbean region. Figure 8 details the stratigraphic position of the samples which the specimens were found. All scale

bars are 100 µm. Sample ID localities: NHMUK = Natural History Museum, London, USNM = Smithsonian Museum of Natural History. **1a-c. *Fohsella peripheroacuta.*** From sample JS 1567, mid Miocene Zone M8, Cipero Formation, southern Trinidad (NHMUK PM BP2668; identified by Desai and Banner). **2a-c. *Fohsella "praefohsi".*** From sample JS 1567, mid Miocene Zone M8, Cipero Formation, southern Trinidad (NHMUK PM BP2668; originally identified by Desai and Banner). **3a-c. *Fohsella peripheroacuta*.** From sample Bo 185a, mid Miocene Zone M8, Cipero Formation, southern Trinidad (USNM P5668; originally illustrated as *Globorotalia fohsi fohsi* by Bolli (1957; plate 28, figures 10a-c)). **4a-c. *Fohsella "praefohsi"*.** From Sample Bo 185a, mid Miocene Zone M8, Cipero Formation, southern Trinidad (USNM P5667; originally described as *Globorotalia fohsi fohsi* by Bolli (1957; plate 28, figures 9a-b)). **5a-c. *Fohsella fohsi*.** From sample Bo 185a, mid Miocene Zone M8, Cipero Formation, southern Trinidad. **6a-c. *Fohsella lobata.*** From sample JS 32, mid Miocene Subzone M9a, Cipero Formation, southern Trinidad. **7a-c. *Globigerinatella insueta.*** From sample Rz 108, lower-mid Miocene Zone M5, Cipero Formation, southern Trinidad. **8a-c. *Paragloborotalia pseudokugleri*.** From sample Bo 270, upper Oligocene Zone O7, Cipero Formation, southern Trinidad. **9a-c. *Paragloborotalia kugleri.*** From Blow's co-type *kugleri* Zone, lower Miocene Subzone M1a, Cipero Formation, southern Trinidad. **10a-c. *Globorotalia plesiotumida*.** From sample RM 20077, upper Miocene Subzone M13b, Pozon Formation, northeast Venezuela (NHMUK PM BP2443; originally identified by Blow). **11a-c. *Globoturborotalita nepenthes*.** From sample KR 23422, upper Miocene Zone M12, Lengua Formation, southern Trinidad (USNM P5621; originally illustrated as *Globigerina nepenthes* by Bolli (1957; plate 24, figures 2a-c)). **12a-c. *Turborotalia ampliapertura.*** From sample WHB 195, lower Oligocene Zone O2, Cipero Formation, southern Trinidad (NHMUK PM BP2645; originally identified by Blow).