



# Biostratigraphic utility of coiling direction in Miocene planktonic foraminiferal genus *Paragloborotalia*

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With 12 figures, 2 plates and 2 tables

**Abstract.** Trochospiral planktonic foraminifera will coil either sinistral (left) or dextral (right). The prevalence of sinistral or dextral coiling can change through the stratigraphic range of morphospecies with a preference in coiling direction. A number of coiling shifts have been applied as secondary marker events through the Recent to late Miocene (~0–7 Ma) biochronology. However, no such events have been applied beyond this age despite a number of species being known to adopt preferential coiling directions. Here we investigate selected Miocene species within the genus *Paragloborotalia*. Previous work in the tropical to subtropical realm has shown that the *mayeri-siakensis* group undergoes a shift from random to sinistrally dominated coiling in the mid Miocene (~15 Ma). We extend the investigation to other Miocene paragloborotaliids in the low (IODP Sites U1337, U1338, ODP Sites 871 and 925), mid (JOIDES-3 hole) and high latitudes (ODP Site 747) in order to assess whether there is global synchronicity and if the change is unique to the *mayeri-siakensis* group. In addition, a number of outcrop samples from the Cipro and Lengua formations in southern Trinidad are quantitatively compared to previously published trends. Our results show that in the low-mid latitudes the coiling shift is at ~15.37 Ma within planktonic foraminiferal Zone M5 within both *Paragloborotalia siakensis* and *Paragloborotalia continuosa*. In the high latitudes the absence of paragloborotaliids through a portion of the mid Miocene interval prevents accurate dating of a shift from early forms showing random coiling to later paragloborotaliids adopting a sinistral preference. We also find two coiling changes in the genus *Globorotalia* at high latitude Site 747, from random to sinistral in the mid Miocene (15.14 Ma) and sinistral to dextral (10.02 Ma) in the late Miocene. We propose the recognition of a coiling change in *Paragloborotalia* as a secondary bioevent in the mid Miocene at 15.37 Ma, and a useful means for the recognition of the base of the Langhian. The coiling shift as a biostratigraphic marker is likely to be particularly useful in regions where the currently applied bioevents, namely the *Praeorbulina-Orbulina* lineage, is rare or poorly represented.

**Key words.** planktonic foraminifera, *Paragloborotalia*, coiling, biostratigraphy, Miocene, Langhian

## 1. Introduction

The sequential addition of chambers during the growth of planktonic foraminifera exhibiting a trochospiral chamber arrangement means that these forms will coil in a left (sinistral) or right (dextral) direction. Coiling direction can be measured from the earliest to final

chamber in spiral view, or alternatively from the final chamber to earliest chamber of the final whorl in umbilical view (Fig. 1).

Bolli (1950) presented the first detailed study on the potential biostratigraphic utility of coiling direction in planktonic foraminifera based on various aged outcrops in the early to middle Miocene of Trinidad.

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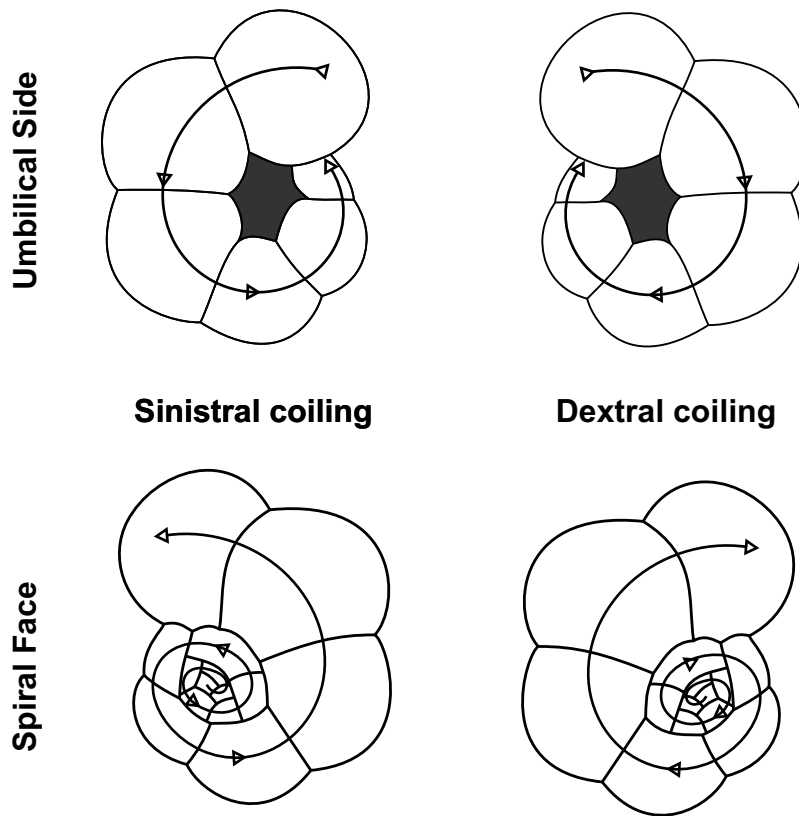
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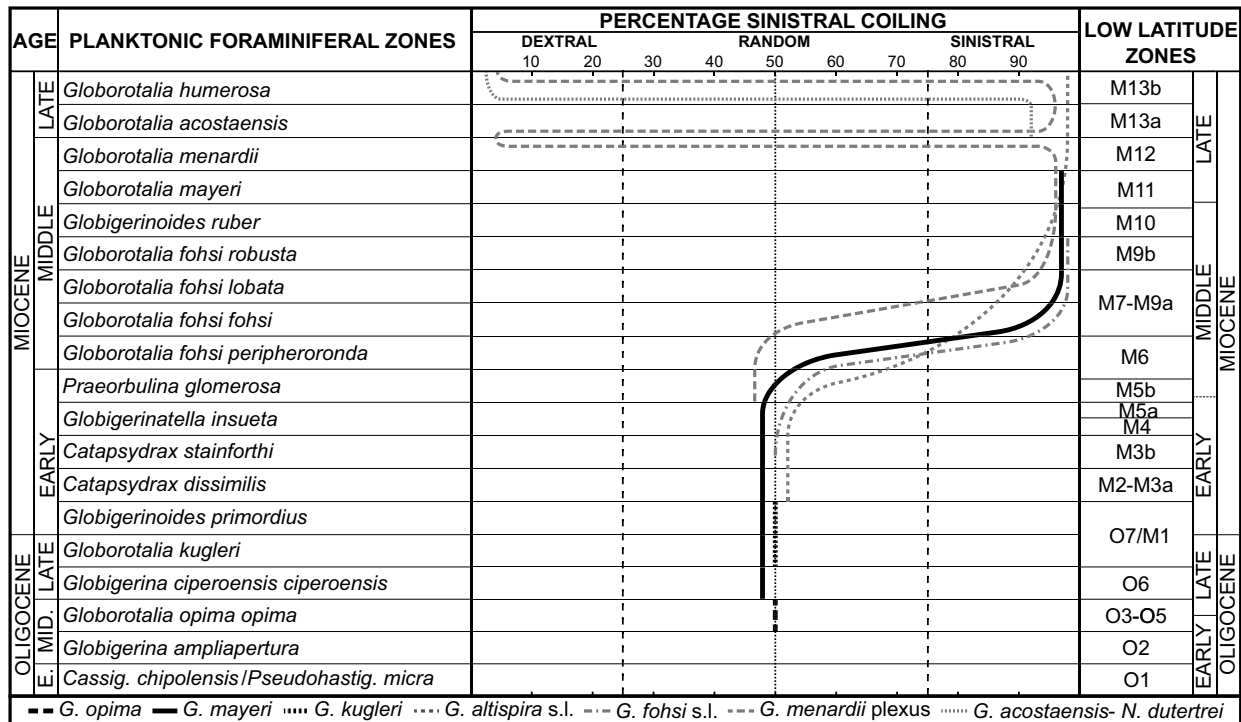


**Fig. 1.** Line drawing of *Paragloborotalia siakensis* showing differences in sinistrally and dextrally coiled specimens when measured from umbilical side (coiling direction from largest to smallest final whorl chamber) and spiral side (coiling directions from earliest chamber to final chamber).

This included the *Fohsella fohsi* and *Globorotalia menardii* lineages, with both showing a period of initial random coiling before adopting preferential coiling higher in their stratigraphic range. The following year, Bolli (1951) illustrated the coiling direction in a number of Oligocene and Miocene taxa, and further expanded this to other species (Bolli 1971, Bolli et al. 1985) which is re-illustrated in Figure 2. In these latter studies coiling changes were recorded in species now recognised within the genus *Paragloborotalia* which is the main genus of interest in this study. Changes in preferential coiling have been applied as secondary bioevents from the late Miocene and younger in the global Cenozoic tropical-subtropical biogeochronological schemes (Wade et al. 2011, King et al. 2020, Raffi et al. 2020) and have also been used to infer palaeoclimatic and palaeoceanographic changes (Ericson 1959, Bandy 1960, Jenkins 1967, Saito 1976). The reasons for preferential coiling have previously been linked to environmental conditions (e. g., Boltovskoy 1971, Naidu and Malmgren 1996) and genetic factors (e. g., Winter and Pearson 2001). Darling et al. (2000, 2004, 2006) found that *Neogloboquadrina incompta* (right-handed coiling) and *Neogloboquadrina pachyderma* (left-handed coiling) represented distinct genotypes rather

than previous interpretations of the two forms being ecophenotypic. Eisenach and Kelly (2006) tested the isotopic ratios of sinistrally and dextrally coiled specimens in the middle Miocene component of the *Fohsella* lineage and found little difference in the stable isotopic values. Conversely in early Eocene morozovellids, Luciani et al. (2021) found differences in carbon isotopic values between sinistral and dextral morphotypes. While investigating the reasons for preferential coiling are not within the scope of this study, based on the above it seems more likely that coiling direction is linked to genetic, rather than climatic or ecophenotypic factors.

Here we investigate the biostratigraphic utility of the coiling changes adopted by the genus *Paragloborotalia*, at varying latitudes primary during the middle Miocene. In addition, we also present coiling results of *Globorotalia* within the southern high latitudes due to the prevalence of this genus within the sub-Antarctic realm. The middle Miocene (15.99–11.65 Ma, Raffi et al. 2020) represented a large-scale change in the Earth's climate. A period of initial warmth culminated in the Miocene Climatic Optimum (MCO), before switching to a prolonged cooling trending associated with the Miocene Climatic Transition (MCT) at 13.90 Ma (Westerhold et al. 2020).



**Fig. 2.** Re-illustration of Bolli et al. (1985, fig. 2) coiling trends in species now recognised as *Paragloborotalia* namely “*Globorotalia*” *mayeri* (includes *P. mayeri* and *P. siakensis*), “*Globorotalia*” *kugleri* (includes *P. kugleri* and *P. pseudo-kugleri*) and “*Globorotalia*” *opima*. Also shown are coiling trends of other notable species including *G. altispira* s. l. (= *Dentoglobigerina altispira* s. l.), *G. fohsi* s. l. (= *Fohsella fohsi* s. l.), *G. menardii* plexus and *G. acostaensis* – *N. dutertrei* (= *Neogloboquadrina acostaensis*). The “Low Latitude Zones” are from King et al. (2020).

*Paragloborotalia* is a cosmopolitan genus ranging from the middle Eocene to late Miocene but reached peak diversity within the early to middle Miocene. The genus is characterised by a low trochospiral test generally consisting of 4 to 6 chambers, a low arched umbilical-extraumbilical aperture and coarsely cancellate *sacculifer*-type wall texture (Leckie et al. 2018). While not the focus of this study, there are a number of outstanding taxonomic issues within the genus. This is primarily related to the taxonomic status of *Paragloborotalia mayeri* (Cushman 1939) and *Paragloborotalia siakensis* (LeRoy 1939), which have been considered synonymous (e. g., Stainforth et al. 1975, Bolli and Saunders 1982) and distinct morphotypes (e. g., Blow 1969, Kennett and Srinivasan 1983, Leckie et al. 2018). Here we consider *mayeri* and *siakensis* as distinct morphotypes but have indicated instances where the original authors synonymised, such as Bolli and Saunders (1985).

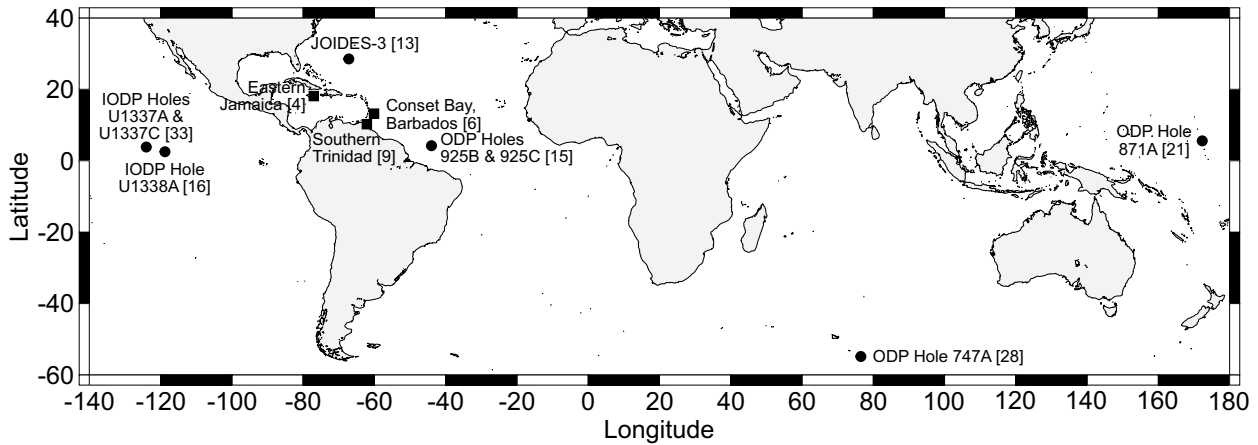
Longer term coiling trends within *Paragloborotalia* have focused on the *mayeri*–*siakensis* lineage and have been investigated by Bolli (1971), Bolli et al. (1985, see also Fig. 2), Winter and Pearson (2001) and Fox

(2014) who all find a switch from random to sinistrally dominated coiling within the middle Miocene. Taking this into account we have further investigated the changes within *mayeri*–*siakensis*, due to the prevalence of this lineage within the mid to low latitudes, as well as extending to other members of the genus namely *P. continua*, *P. incognita*, *P. pseudocontinua* and *P. semivera*. The primary focus of this study is to test the biostratigraphic utility of the coiling change within the middle Miocene. This may provide a useful means of recognising the base of the Langhian, which at present lacks a Global Boundary Stratotype Section and Point (GSSP).

## 2. Material and methods

### 2.1. Study sites

A total of nine sites spanning the low-mid (28° N to 2.5° N) to high latitudes (54° S) were studied (Fig. 3, Table 1). Material was mostly from ocean drilling sites, namely JOIDES-3, ODP Site 747, ODP Site



**Fig. 3.** Map showing study sites. The square brackets indicate the number of samples in which coiling was recorded. Ocean drilling sites are represented by a circular symbol while outcrop samples are shown with squares. Map produced using the marmap package in R (Pante and Simon-Bouhet 2013).

871, ODP Site 925, Integrated Ocean Drilling Program (IODP) Site U1337 and IODP Site U1338. The average sampling resolution for the ocean drilling sites is given in Table 1 and was predominantly determined by the factors such as the availability of material and presence of other stratigraphies (e. g. magneto- and cyclostratigraphy). In addition, we studied outcrop material from eastern Jamaica (Buff Bay and San San Bay), southern Trinidad (Cipero and Lengua formations) and Barbados (Conset Bay). This material is from the collections within the Natural History Museum (London) predominantly collected during the middle of the 20<sup>th</sup> Century for oil and gas exploration purposes. Therefore, while a general location is known, the precise locality and associated information (e. g., outcrop thickness, sample techniques) is not and so no depth scale is possible for the outcrop samples. Due to this, the Jamaican and Barbadian samples are effectively a floating stratigraphy so only a biozone assignment is given. A range of samples from different zones in Trinidad were studied so an age error is given for each sample based on biozone ages given in King et al. (2020, table 3).

## 2.2. Coiling measurements

The species of interest varied depending on the study site (Table 1) and was predominantly based on the prevalence of a given species at each location. In the majority of the sites, *Paragloborotalia siakensis* was the main species of interest. Additionally, coiling was recorded in *Paragloborotalia continua* at IODP Site

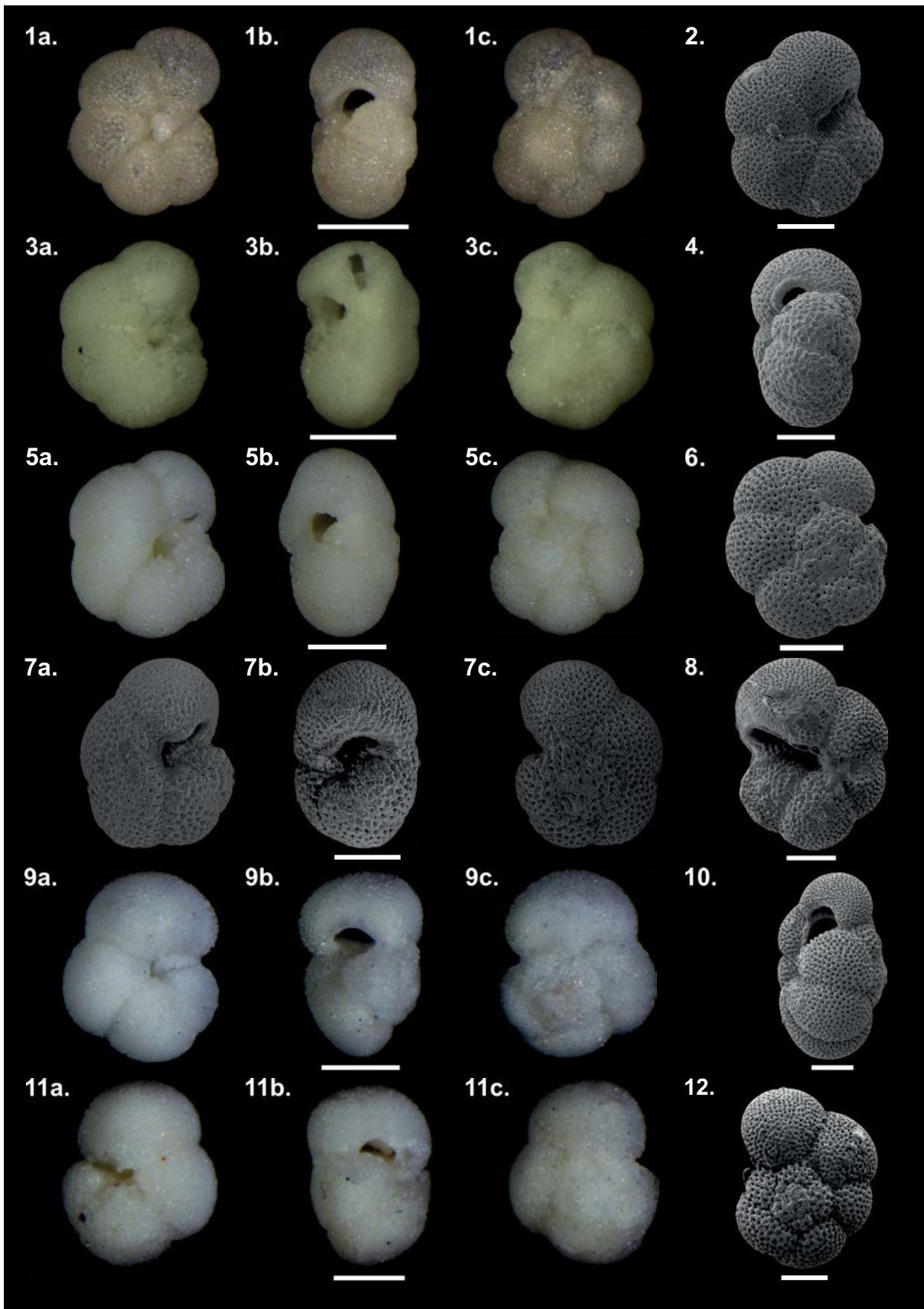
U1338, and *Paragloborotalia kugleri* and *Paragloborotalia pseudokugleri* in southern Trinidad. For ODP Site 747 the sporadic occurrences of *P. siakensis* does not allow this species to be used. Instead, the dominant paragloborotaliids, namely *P. incognita*, *P. pseudocontinua* and *P. semivera* were used for the early Miocene (17.31–21.47 Ma) and *P. continua* for the middle to late Miocene (13.42–6.47 Ma). In addition, the coiling in *Globorotalia* spp. (*G. zealandica*, *G. praescitula* and *G. scitula*) was also recorded as this genus was dominant through a number of intervals in the studied record. The taxonomic concepts for the genera and species followed Leckie et al. (2018) for *Paragloborotalia* and predominantly Cifelli and Scott (1986) and Scott et al. (1990) for *Globorotalia*. Plates 1 and 2 present light microscope and scanning electron microscope images for the species of interest.

The direction of coiling was measured in spiral view with at least 50 specimens being studied per sample following Norris and Nishi (2001), who suggested that at least 50 specimens are required for statistical significance. The number of sinistral specimens per sample was then divided by the total number of specimens counted, and then multiplied by 100 to give the percent of sinistral forms. A 95 % confidence interval was added for each sample using the Modified Wald Method (e. g., Agresti and Coull 1998), following the application of this method for producing coiling error bars in *Pulleniatina* (Pearson and Penny 2021).

In the absence of other studies clearly outlining a threshold that must be exceeded to recognise a dominance in coiling, we suggest the percentage of sinis-

Table 1. Key information for the study sites analysed. Notes: \* As these are from discrete outcrop samples, no sense of depth is possible, the age refers to the top and base ages for the relevant biozone. Abbreviations: EEP – Eastern Equatorial Pacific; E. Jamaica – Eastern Jamaica; S. Barbados – Southern Barbados; S. Trinidad – Southern Trinidad; Bio. Ref. – Biostratigraphic reference; Age Ref. – Age Reference. Species Abbreviations: *Paragloborotalia* species: *sia* – *siakensis*; *inc* – *incognita*; *pcon* – *pseudocontinosa*; *con* – *continua* *Globorotalia* species: *zea* – *zealandica*; *psci* – *praescitula*; *sci* – *scitula*. References: [a] Blow (1969) [b] Berggren (1992) [c] Pearson (1995) [d] King (2019) [e] Fox and Wade (2013) [f] Expedition 320/321 Scientists (2010a) [g] Berggren (1993) [h] This Study [i] King et al. (2020) [j] Backman et al. (2016) [k] Holbourn et al. (2014) [l] Tian et al. (2013, 2018) [m] Kochhann et al. (2016)

Study Site	Latitude	Longitude	No. of Samples	Depth/Sample ID	Average Resolution	Age (Ma)	Zone/Subzone	Species	Bio. Ref.	Age Ref.
Ocean Drilling Sites	JOIDES 3 (Blake Plateau)	28.500	-66.517	14	105.1–266.0 ft (32.03–81.08 m)	11.48 ft (3.5 m)	M11 to M5	sia	[a]	[i]
	ODP Hole 747A (Kergulen Plateau)	-54.811	76.794	19	37.51–121.61 mbsf	2.91 m	G. <i>scitula</i> to P. <i>incognita</i> (M13b–M2)	inc, sem, pcon, con, zea, psci, sci	[b]	[b]
	ODP Hole 871A (Limalok Guyot)	5.557	172.344	21	28.59–104.6 mbsf	7.36 m	M9b to M3a	sia	[c]	[i]
	ODP Hole 925B (Ceara Rise)	4.204	-43.489	9	291.60–298.86 med	0.54 m	M11	sia	[d]	[j]
	ODP Hole 925C (Ceara Rise)	4.204	-43.489	6	290.42–292.46 med	0.12 m	M11	sia	[d]	[j]
	IODP Hole U1338A (EEP)	2.508	-117.97	16	277.93–453.83 m CCSF-A	4.51 m	M6 to M3–M4	sia, con	[e]	[j]
	IODP Hole U1337A (EEP)	3.833	-123.206	12	336.81–347.09 m CCSF-A	0.53 m	M6 to M5a	sia	[f]	[l]
	IODP Hole U1337C (EEP)	3.833	-123.206	21	336.21–347.36 m CCSF-A	0.53 m	M6 to M5a	sia	[f]	[m]
	IODP Hole U1337D (EEP)	3.833	-123.206	21	336.21–347.36 m CCSF-A	0.53 m	M6 to M5a	sia	[f]	[m]
	IODP Hole U1337E (EEP)	3.833	-123.206	21	336.21–347.36 m CCSF-A	0.53 m	M6 to M5a	sia	[f]	[m]
Outcrop Sections	San San Bay (E. Jamaica)	18.173	-76.392	3	ER143/2 to ER143/4	N/A	M11	sia	[g]	[i]
	Buff Bay (E. Jamaica)	18.231	-76.652	1	ER146/32	N/A	M11	sia	[g]	[i]
	Conset Bay (S. Barbados)	13.176	-59.463	6	BN34 to BN29	N/A	M7	sia	[h]	[i]
	Lengua Area (S. Trinidad)	10.238	-61.361	2	KR23422 to KR23425	N/A	M12 to M11	sia	[i]	[i]
	Cipero Coast (S. Trinidad)	10.270	-61.473	4	K9397 Rz108 JS32, Bo354	N/A	M3b M5 M9	sia	[i]	[i]
	Mosquito Creek (S. Trinidad)	10.247	-61.501	1	Blow's Co-type	N/A	M1b	sia, kug, pkug	[i]	[i]
	Golconda Estate (S. Trinidad)	10.247	-61.433	1	Bo185a	N/A	M9a	sia	[i]	[i]
	San Fernando Bypass Road (S. Trinidad)	10.275	-61.451	1	Bo267	N/A	M3a–M2	sia	[i]	[i]
	Hermitage Quarry (S. Trinidad)	10.233	-61.462	1	Bo202	N/A	M6	sia	[i]	[i]



**Plate 1.** Representative specimens of the paragloborotaliids measured for coiling direction in this study. **1–8, 10, 12.** *Paragloborotalia siakensis*. **9, 11.** *Paragloborotalia incognita*. **1a–c.** *Paragloborotalia siakensis*. Sample 144-871A-8H-1, 59–61 cm, 65.10 mbsf (mid Miocene Subzone M5b) (NHMUK PM PF 75253). **2, 4.** *Paragloborotalia siakensis*. Sample 321-U1337A-45XCC, 463.77 m CCSF-A (early Miocene Subzone M1a) (NHMUK PM PF 75254 and 75256 respectively). **3a–c.** *Paragloborotalia siakensis*. Sample ER143-2, Montpelier Formation, San San Bay Section, eastern Jamaica (late Miocene Zone M11) (NHMUK PM PF 75255). **5a–c.** *Paragloborotalia siakensis*. Sample JOIDES-3, 157.6 ft (mid Miocene Zone M8) (NHMUK PM PF 75257). **6.** *Paragloborotalia siakensis*. Sample 321-U1338A-41X-CC (early Miocene Subzone M5a) (NHMUK PM PF 75258). **7a–c.** *Paragloborotalia siakensis*. Sample KR23422, Lengua Formation, Cunjal Road outcrop, southern Trinidad (late Miocene Zone M11) (NHMUK PM PF 75259). **8.** *Paragloborotalia siakensis*. Sample 154-925B-29H-4, 36–38 cm, 295.05 m CCSF-A (late Miocene Zone M11) (NHMUK PM PF 75260). **9a–c, 11a–c.** *Paragloborotalia incognita*. Sample 120-747A-9H-6, 100–102 cm, 82.61 mbsf (mid Miocene *Globorotalia miozea* Zone = Subzone M5b) (NHMUK PM PF 75261 and 75263 respectively). **10.** *Paragloborotalia siakensis*. Sample 154-925B-29H-3, 13–15 cm, 293.32 m CCSF-A (late Miocene Zone M11) (NHMUK PM PF 75262). **12.** *Paragloborotalia siakensis*. Sample 925D-28H-2, 83–84 cm, 290.25 m CCSF-A (late Miocene Zone M11) (NHMUK PM PF 75264). All scale bars are 100  $\mu\text{m}$ . Biozones refer to those in King et al. (2020).

trally or dextrally coiled specimens must exceed 75 % of the total specimens to be considered the dominant coiling direction.

### 2.3. Abundance counts

Both semi-quantitative and quantitative abundance counts were applied to test the link between species abundance and coiling direction in all the ocean drilling sites except ODP Site 871. The biostratigraphy and species abundances for Site 871 were detailed in Pearson (1995), with the samples we examined either being from similar depths, or the same depth, and so follow very similar abundance trends. Fully quantitative records were used for Site U1338 and ODP Site 747, where each residue was split using a sample splitter until approximately 300 specimens of planktonic foraminifera were present with typically the >125  $\mu\text{m}$  size fraction being analysed. The number of specimens of the species/genus of interest were then divided by 300 in order to obtain a relative abundance.

Semi-quantitative methods were applied to Site U1337 and JOIDES-3, with the residue again split and a single picking tray analysed. The criteria for defining abundance was adapted from that typically used in ocean drilling (e. g., Expedition 320/321 Scientists 2010a) whereby:

- Dominant (>30 % of the planktonic foraminiferal assemblage)
- Common (>10 % to <30 %)
- Few (>5 % to <10 %)
- Rare (>1 % to <5 %)
- Present (<1 %)
- Absent

## 3. Results

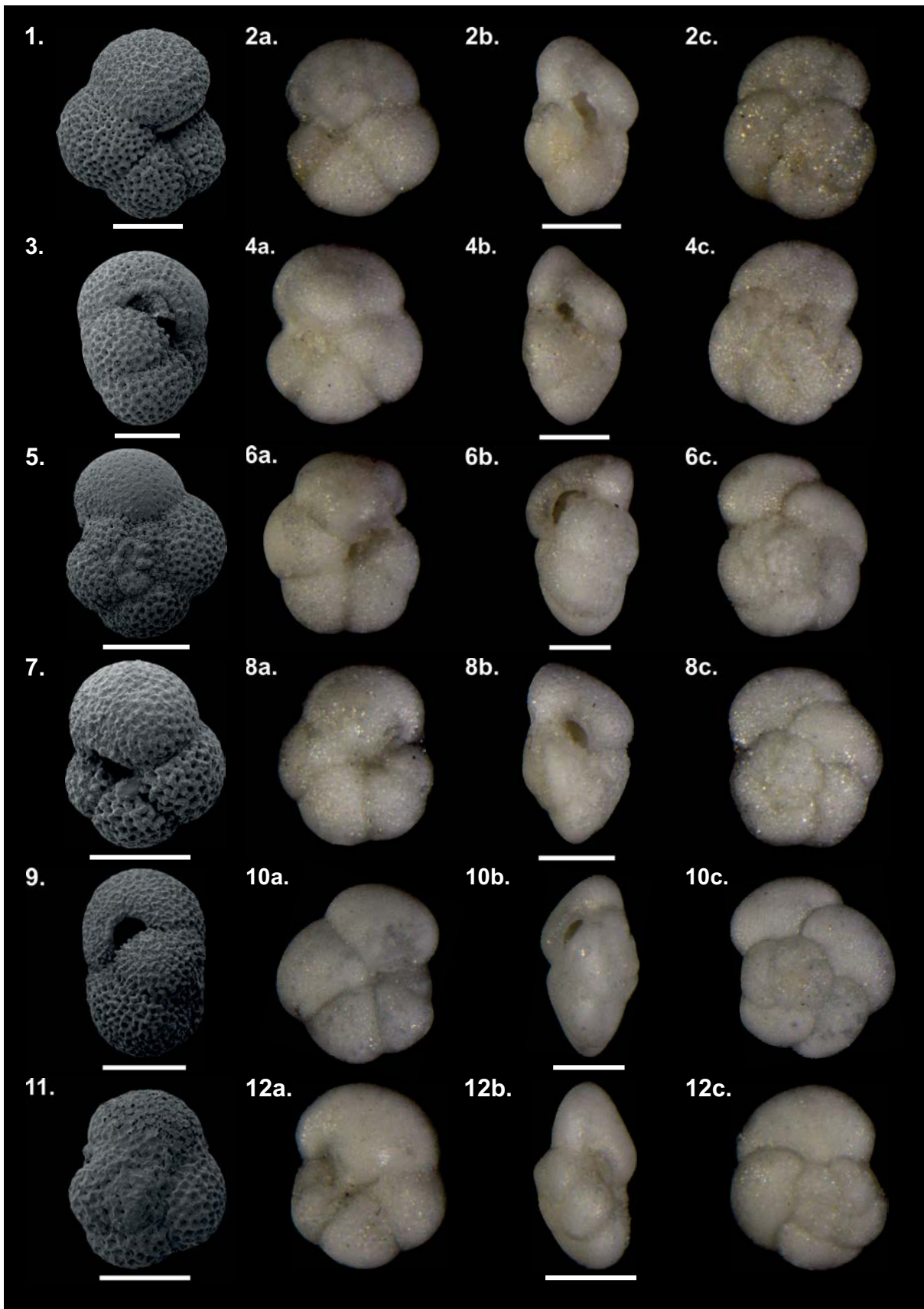
Coiling directions, and where appropriate the abundance records, are shown in Figs 4–11, with raw data presented in Supplementary Table S1 (see electronic supplement). The majority of the sites are plotted relative to depth, with a secondary axis showing the age. Sites U1337 (Fig. 4) and U1338 (Fig. 5) have two age axes due to conflicting age interpretations. The Trinidad record (Fig. 7) is plotted relative to age, while the records from eastern Jamaica and Conset Bay (Fig. 8) contain only the sample IDs.

### 3.1. Site U1337

At Eastern Equatorial Pacific Site U1337 (Fig. 4), random coiling is seen for *P. siakensis* in the 10 most downhole samples (~344–347.50 m CCSF-A). A switch to sinistrally dominated coiling occurs at  $343.75 \pm 0.2$  m CCSF-A (between samples U1337A, 34X-4, 84–86 cm and U1337A, 34X-4, 124–126 cm) within the mid part of Subzone M5b and is maintained through the rest of the studied samples. The age of the coiling change is at  $15.242 \pm 0.008$  Ma using the Tian et al. (2013, 2018) age model or  $15.368 \pm 0.007$  Ma using the Kochann et al. (2016) age model. Through the coiling change there is a minor increase in the abundance of *P. siakensis* from Few to Common, although the species is a consistent component throughout the studied interval and represents the most abundant paragloborotaliid.

### 3.2. Site U1338

The coiling ratios of both *P. siakensis* and *P. continuosa* in Hole U1338A (eastern equatorial Pacific) are





**Plate 2.** Representative specimens of the paragloborotaliids (1, 3, 5, 7, 9, 11) and globorotaliids (2, 4, 6, 8, 10, 12) measured for coiling direction in this study. **1, 3, 5, 7, 9, 11.** *Paragloborotalia continuosa*. **2, 4.** *Globorotalia zealandica*. **6, 8.** *Globorotalia praescitula*. **10, 12.** *Globorotalia scitula*. **1, 11.** *Paragloborotalia continuosa*. Sample 120-747A-5H-7, 50–52 cm, 46.61 mbsf (late Miocene *Globorotalia scitula* Zone = Zone M12). **2a–c, 4a–c.** *Globorotalia zealandica*. Sample 120-747A-10H-1, 63–65 cm, 85.64 mbsf (early Miocene *Globorotalia praescitula* Zone = Subzone M5a) (NHMUK PM PF 75265 and 75267 respectively). **3, 7.** *Paragloborotalia continuosa*. Sample 120-747A-6H-2, 110–112 cm, 49.61 mbsf (late Miocene *Neogloboquadrina nympha* Zone = Zone M12) (NHMUK PM PF 75266 and 75270 respectively). **5, 9.** *Paragloborotalia continuosa*. Sample 120-747A-4H-7, 50–52 cm, 37.51 mbsf (late Miocene *Globorotalia scitula* Zone = Subzone M13a) (NHMUK PM PF 75268 and 75272 respectively). **6a–c.** *Globorotalia praescitula*. Sample 120-747A-10H-1, 63–65 cm, 85.64 mbsf (early Miocene *Globorotalia praescitula* Zone = Subzone M5a) (NHMUK PM PF 75269). **8a–c.** *Globorotalia praescitula*. Sample 120-747A-9H-2, 96–98 cm, 76.56 mbsf (mid Miocene *Globorotalia miozea* Zone = Zone M6) (NHMUK PM PF 75271). **10a–c.** *Globorotalia scitula*. Sample 120-747A-6H-2, 110–112 cm, 49.61 mbsf (late Miocene *Neogloboquadrina nympha* Zone = Zone M12) (NHMUK PM PF 75273). **12a–c.** *Globorotalia scitula*. Sample 120747A-4H-7, 50–52 cm, 37.51 mbsf (late Miocene *Globorotalia scitula* Zone = Subzone M13a) (NHMUK PM PF 75274). All scale bars are 100  $\mu\text{m}$ . Biozones refer to those in King et al. (2020).

shown in Figure 5. The change to a sinistral coiling direction occurred synchronously at  $404.77 \pm 1.24$  m CCSF-A (between samples 40X-1, 115–117 cm and 40X-3, 27–29 cm) within the lower part of Subzone M5b. The age of the coiling change is  $15.024 \pm 0.034$  Ma or  $14.891 \pm 0.03$  Ma based on the age models of Backman et al. (2016) and Holbourn et al. (2014) respectively. The coiling direction of *P. continuosa* is not given in the uppermost two samples, due to insufficient specimens for the 50 specimen threshold. Like U1337, there are no obvious links between coiling direction and the abundance of either morphospecies.

### 3.3. Site 871

The record of *P. siakensis* for Hole 871A (western equatorial Pacific; Fig. 6) shows a general random coiling trend in the nine downhole samples (68.34–104.60 mbsf), however the sample at 86.25 mbsf shows a preference for sinistral coiling,

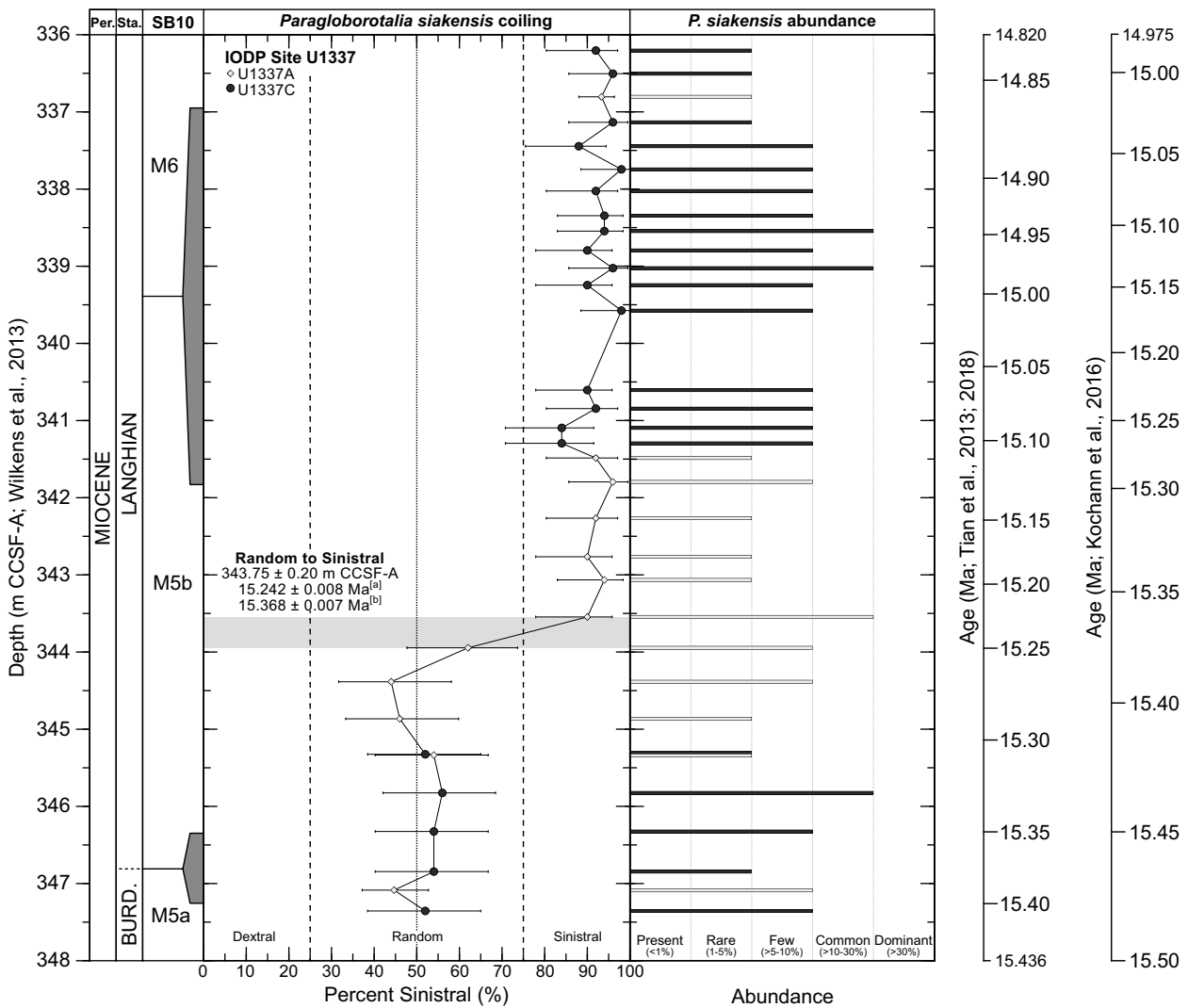
although the next uphole sample at 81.00 mbsf again shows random coiling. A permanent switch to a sinistral coiling dominance occurs at  $66.72 \pm 1.63$  mbsf (between samples 8H-1, 59–61 cm and 8H-3, 83–85 cm) within Subzone M5b. This section appears fairly condensed with 66.72 mbsf suggesting an age of 16.03 Ma for the coiling change, with the lower and upper bounds at 16.11 Ma and 15.36 Ma respectively. Mixing and slumping is also an issue at ODP Site 871 (Pearson 1995), and so this may also have an impact on the biostratigraphic interpretations.

### 3.4. Southern Trinidad

Figure 7 shows the coiling record for *Paragloborotalia* in southern Trinidad. As each studied sample was from a discrete outcrop section, no sense of depth can be given, and instead the midpoint age of each sample is plotted along with the associated error. *Paragloborotalia siakensis* was found in all samples and a continuous coiling trend was deduced. The coiling in *P. kugleri* and *P. pseudokugleri* was given for the lowermost sample namely Blow's *Globorotalia kugleri* Co-type locality in Mosquito Creek, to the south of the Ciperó Coast section. This was the only sample studied in which all three morphotypes were found to co-occur, with all species showing a random coiling trend. The record for *P. siakensis* maintains random coiling up until sample Rz 108, with the shift to a sinistral coiling preference occurring in the next sample (Bo 202) within Subzone M5b at  $15.20 \pm 1.19$  Ma. This sinistral coiling preference is then maintained through the four subsequent samples, up until Top *P. siakensis* in sample KR 23422.

### 3.5. Eastern Jamaica and Southern Barbados

Figure 8 shows the *P. siakensis* records from the Zone M11 interval of the San San Bay and Buff Bay sections in eastern Jamaica and the M7 Biozone of the Conset Bay Section in southern Barbados. A sinistral coiling preference is shown throughout the studied interval with the extinction level for *P. siakensis* in Jamaica recorded in sample ER143/4. This indicates a strong sinistral preference is maintained up until the last occurrence of the species. No ages are assigned to these records as they are essentially floating stratigraphies from discrete outcrop samples.

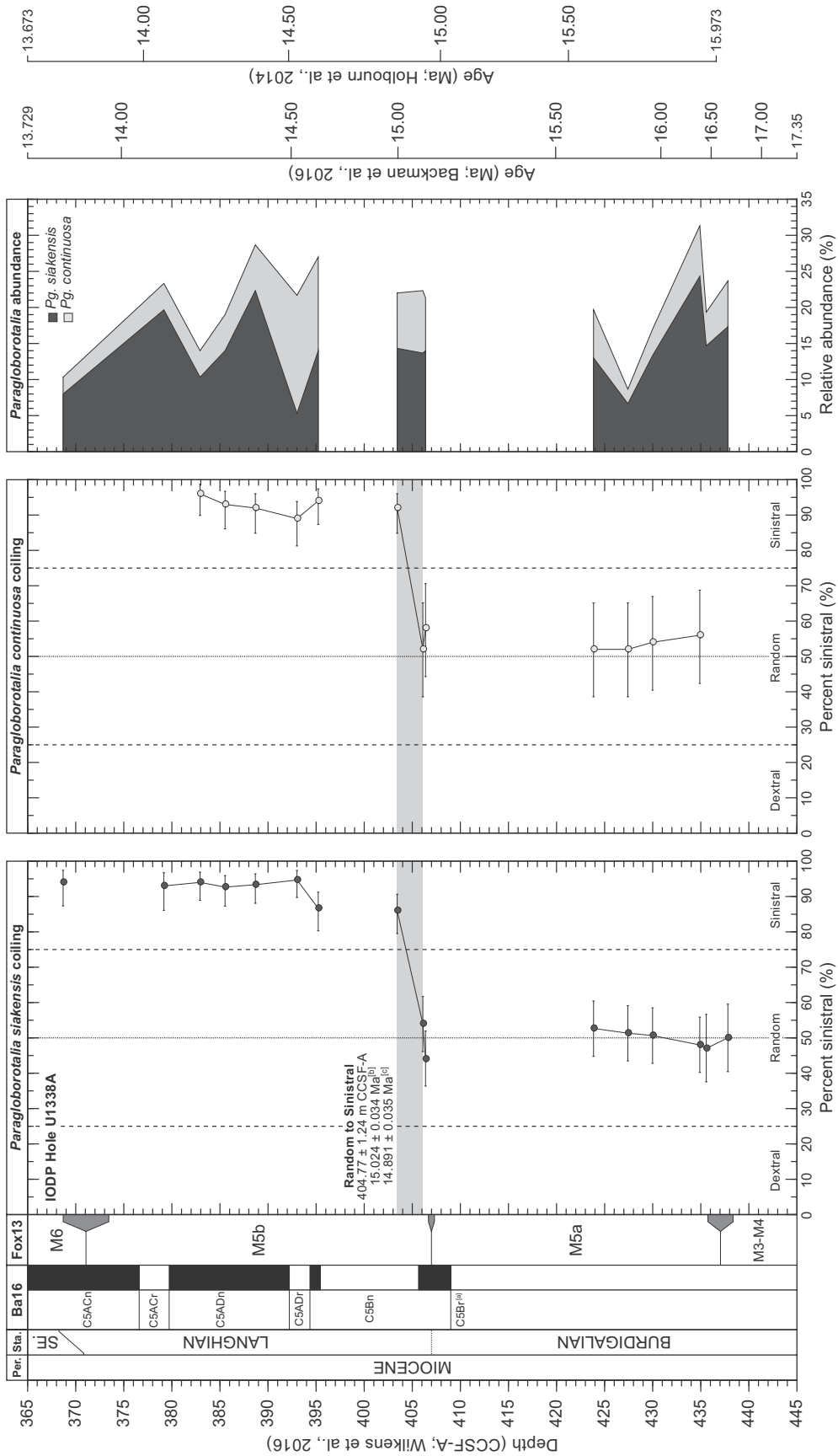


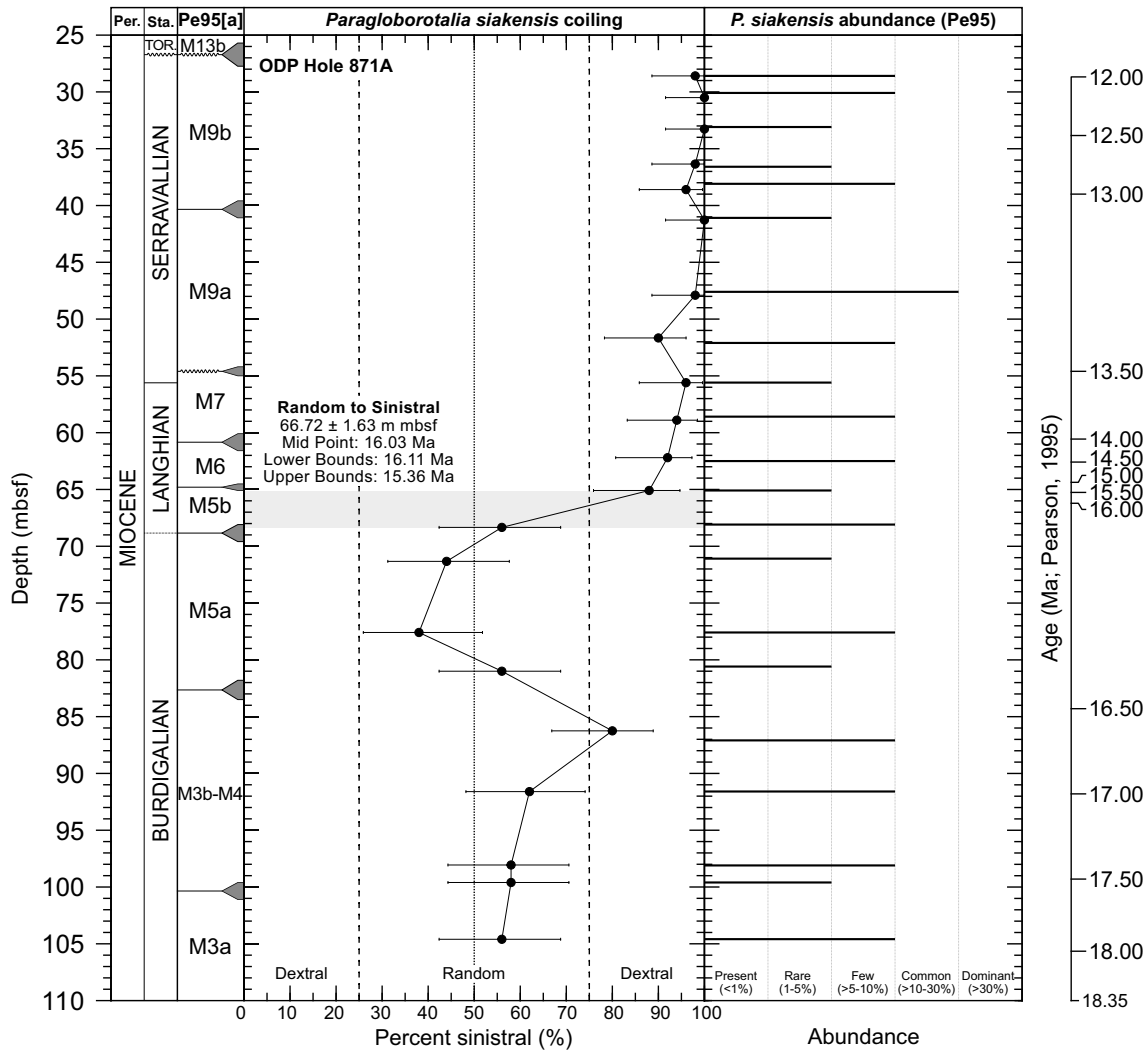
**Fig. 4.** Direction of coiling and semi-quantitative abundance of *Paragloborotalia siakensis* in IODP Holes U1337A and U1337C. The grey box shows the upper and lower bounds for the change from random to sinistral coiling. The samples are calibrated to the depth scale of Wilkens et al. (2013) and relative to the cyclostratigraphic timescales of Tian et al. (2013, 2018) and Kochann et al. (2016). Biostratigraphy is based on Expedition 320/321 Scientists (2010b) (SB10) with the grey shaded triangles in this column showing the upper and lower error for the biozones. Notes: Timing of coiling change based on: [a] Tian et al. (2013, 2018) and [b] Kochann et al. (2016).

### 3.6. Site 925

Like eastern Jamaica (Fig. 8), the record from Site 925 in the western equatorial Atlantic Ocean (Fig. 9) captures the coiling direction through the extinction level of *P. siakensis* albeit at a higher resolution and with a chronostratigraphy. A strong sinistral preference is seen throughout the interval up until the extinction

**Fig. 5.** Direction of coiling and relative abundance for *Paragloborotalia siakensis* (dark grey) and *Paragloborotalia continuosa* (light grey) from IODP Hole U1338A. The grey box shows the upper and lower bounds for the change from random to sinistral coiling. The samples are calibrated to the depth scale of Wilkens et al. (2013) and relative to the magnetostratigraphic timescale of Backman et al. (2016) (Ba16) and cyclostratigraphic timescale of Holbourn et al. (2014). Biostratigraphy is based on Fox and Wade (2013) (Fox13) with the grey shaded triangles in this column showing the upper and lower error for the biozones. Notes: [a] Base of Chron C5Br not given; Timing of coiling change based on: [b] Backman et al. (2016) and [c] Holbourn et al. (2014).





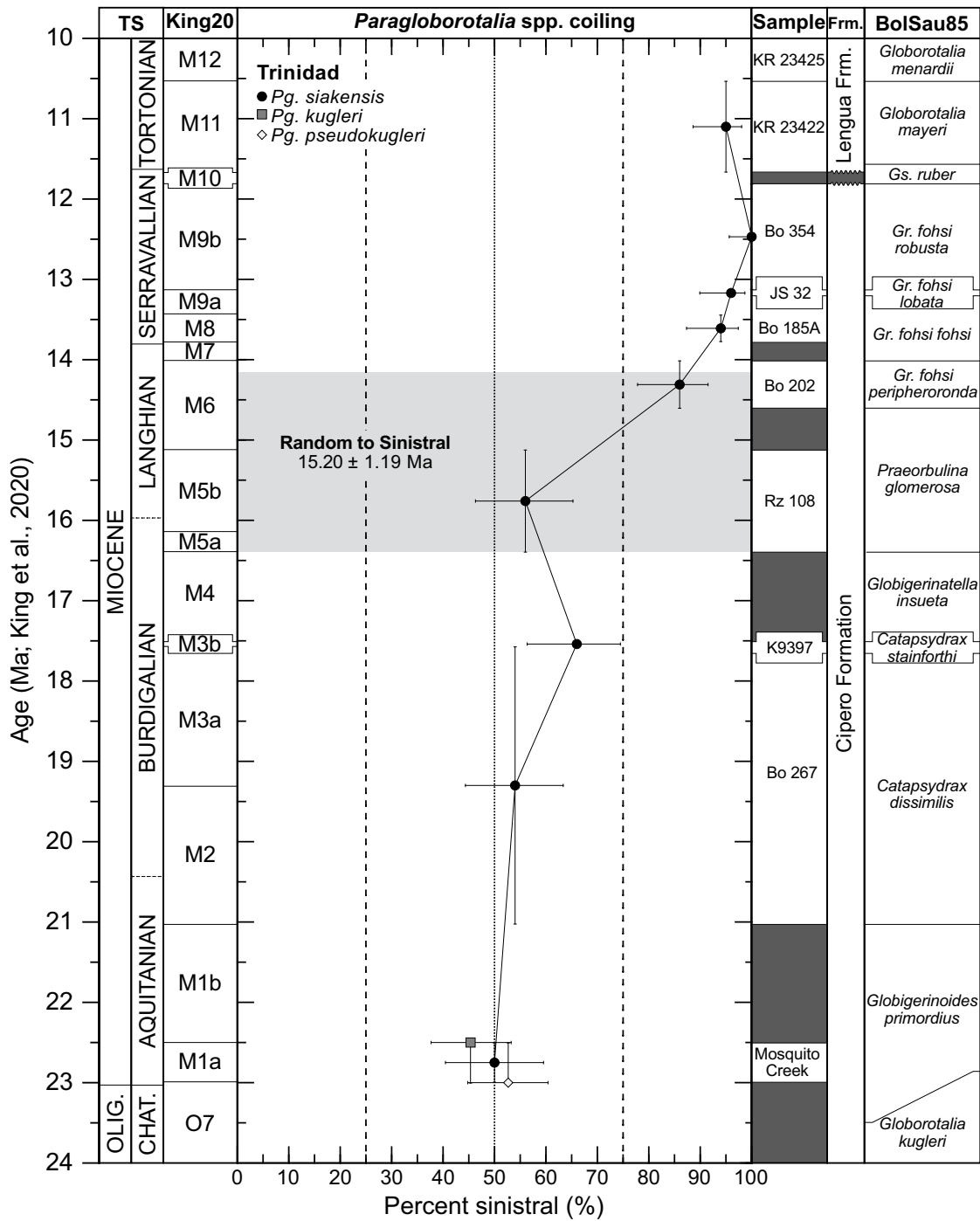
**Fig. 6.** Direction of coiling and relative abundance in *Paragloborotalia siakensis* from ODP Hole 871A. The grey box shows the upper and lower bounds for the change from random to sinistral coiling. Biostratigraphy and relative abundance records are based on Pearson (1995) (Pe95) calibrated to King et al. (2020). The grey shaded triangles in the biozone column shows the upper and lower error for the biozones. The age is given as upper and lower bounds due to the apparent condensed sequence between ~64–67 mbsf. Inferred unconformities are denoted by the wavy line in the biozone column. Notes: [a] Pearson (1995) originally applied a modified version of the biostratigraphic scheme of Kennett and Srinivasan (1983). We have updated to King et al. (2020) based upon the range charts provided in Pearson (1995, tables 1 and 2).

level at  $290.47 \pm 0.05$  mcd (between 925C-28H-6, 24–25 cm and 925C-28H-6, 14–15 cm) equivalent to  $10.605 \pm 0.001$  Ma. It is worth noting that a notable decline in the relative abundance of *P. siakensis* is found prior to the extinction of the species.

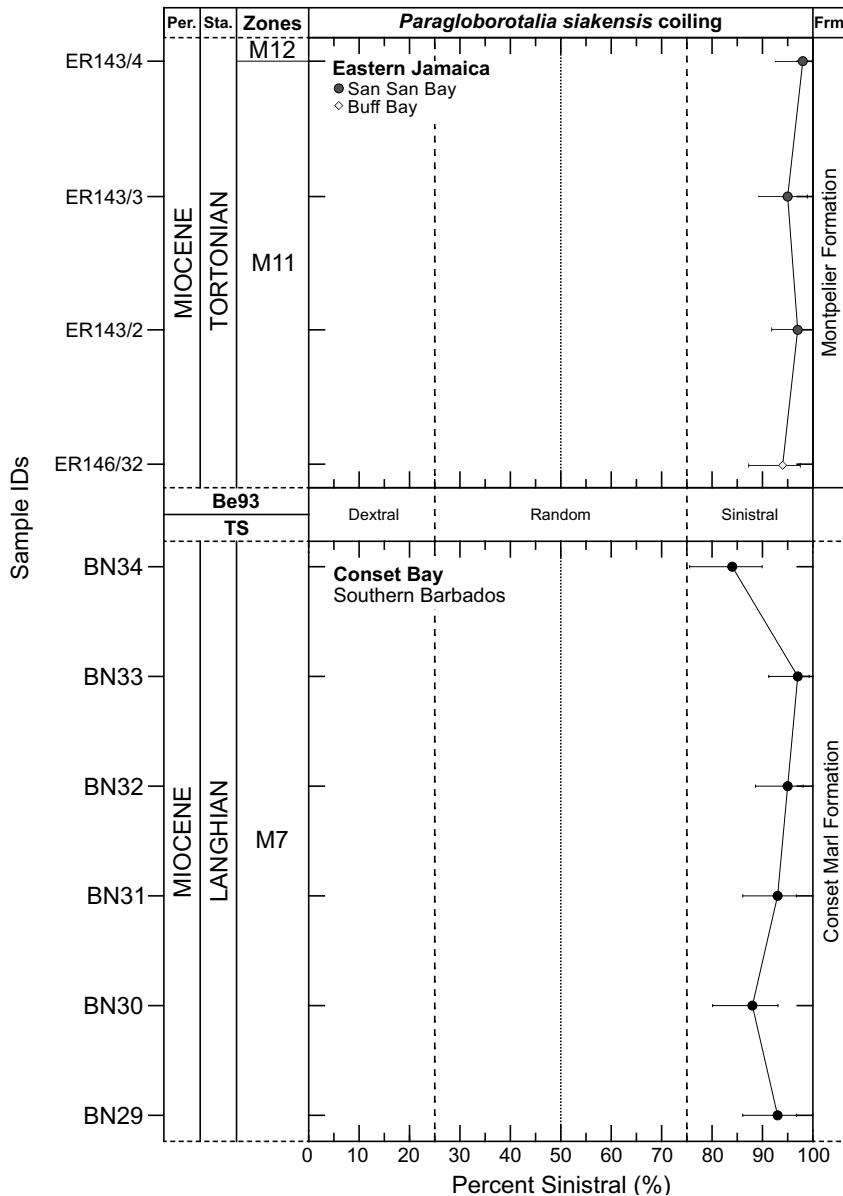
### 3.7. JOIDES 3

The JOIDES-3 samples from the western North Atlantic Ocean (Fig. 10) show a slightly more gradational

coiling change compared to the previous sites. The percentage of sinistral forms of *P. siakensis* in the sample just prior to the observed coiling change at 243 ft (73.15 m) is at the very upper limits of random coiling (~74%). The coiling change itself occurs at  $238.0 \pm 5.0$  ft ( $72.54 \pm 1.54$  m) within the upper part of the undifferentiated Zone M5, with an age of  $15.35 \pm 0.17$  Ma. As with the records from Trinidad, Jamaica and ODP Site 925 (Figs 7–9), *P. siakensis* maintains a sinistral coiling preference up until its last uphole



**Fig. 7.** Direction of coiling in *Paragloborotalia siakensis* (black), *P. kugleri* (dark grey) and *P. pseudokugleri* (light grey) in samples from southern Trinidad. The grey box shows the upper and lower bounds for the change from random to sinistral coiling. A depth scale is not given due to the samples being from discrete outcrop sections. The biostratigraphic interpretation is based on King et al. (2020) (King20). Sample IDs and formations come from Bolli (1957). The biostratigraphic scheme of Bolli and Saunders (1985) (BolSau85) is also shown as a means of comparison between this figure and the schematic trends shown in Figure 2.



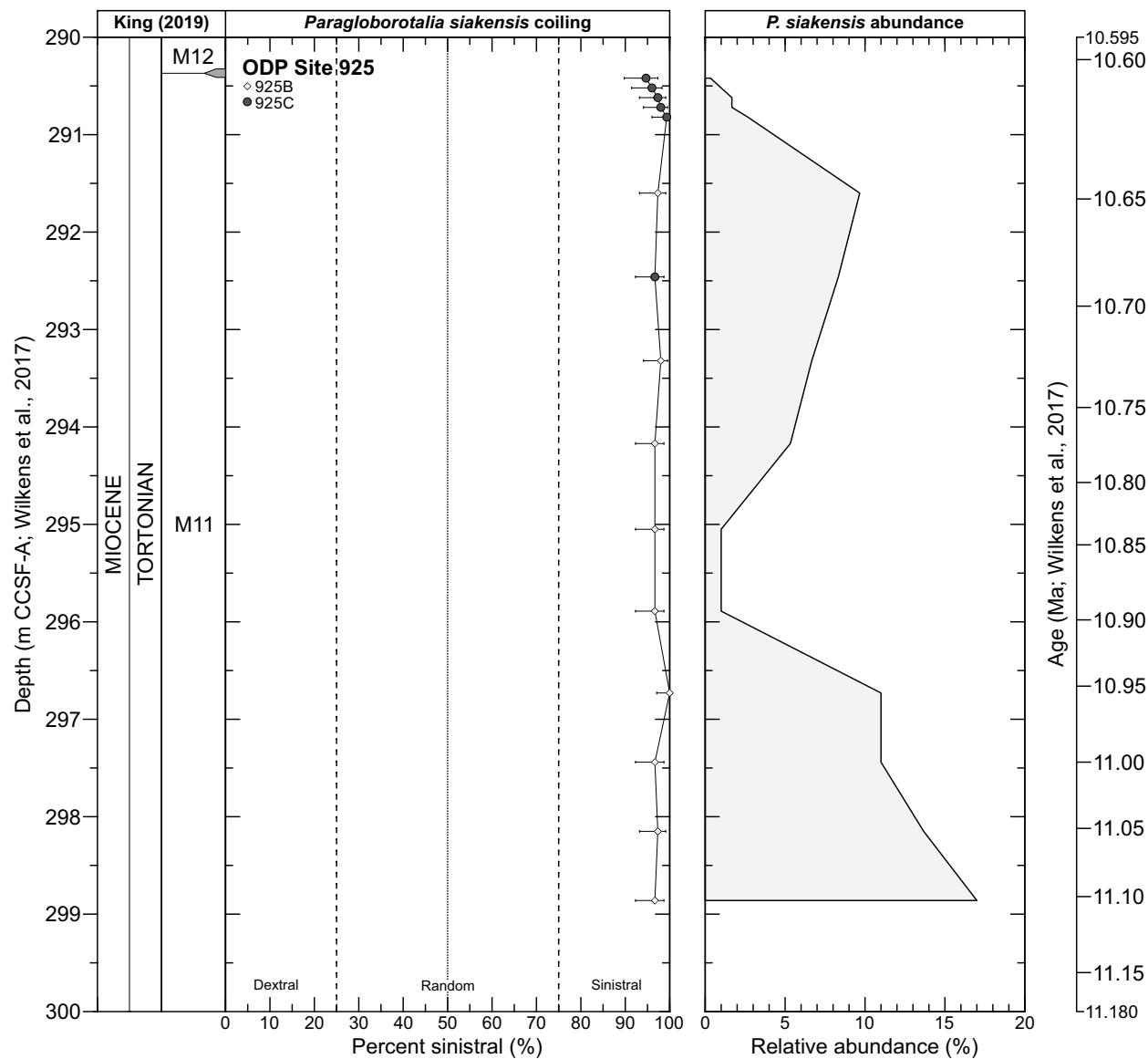
**Fig. 8.** Direction of coiling in *Paragloborotalia siakensis* from Conset Bay (southern Barbados), and the San San and Buff Bay sections (eastern Jamaica). A depth scale is not given due to the samples being from discrete outcrop sections. Biostratigraphy is based on personal observations (TS) for Barbados, and Berggren (1993) (Be93) for eastern Jamaica. Stratigraphic formations are from Blow (1969, 1979) for Barbados, and Robinson (1969) for Jamaica.

occurrence at 105.1 ft (32.03 m). There appears to be no link with the abundance record and the coiling change seen at this site.

### 3.8. Site 747

The coiling directions of *Paragloborotalia* and *Globorotalia* in ODP Hole 747A (southern Indian Ocean) are shown in Figure 11. The disparity in the

stratigraphic ranges between the last appearance of *P. incognita*, *P. semivera* and *P. pseudocontinuosus* (94.61 mbsf; 17.31 Ma) and first appearance of *P. continuosus* (67.61 mbsf; 13.43 Ma) within Site 747 means the exact level of the coiling change is not documented, nor if there is any link between coiling direction and abundance. The records do clearly illustrate that a coiling change occurs at some level through the record between 67.61–94.61 mbsf, due to *P. continuosus* only

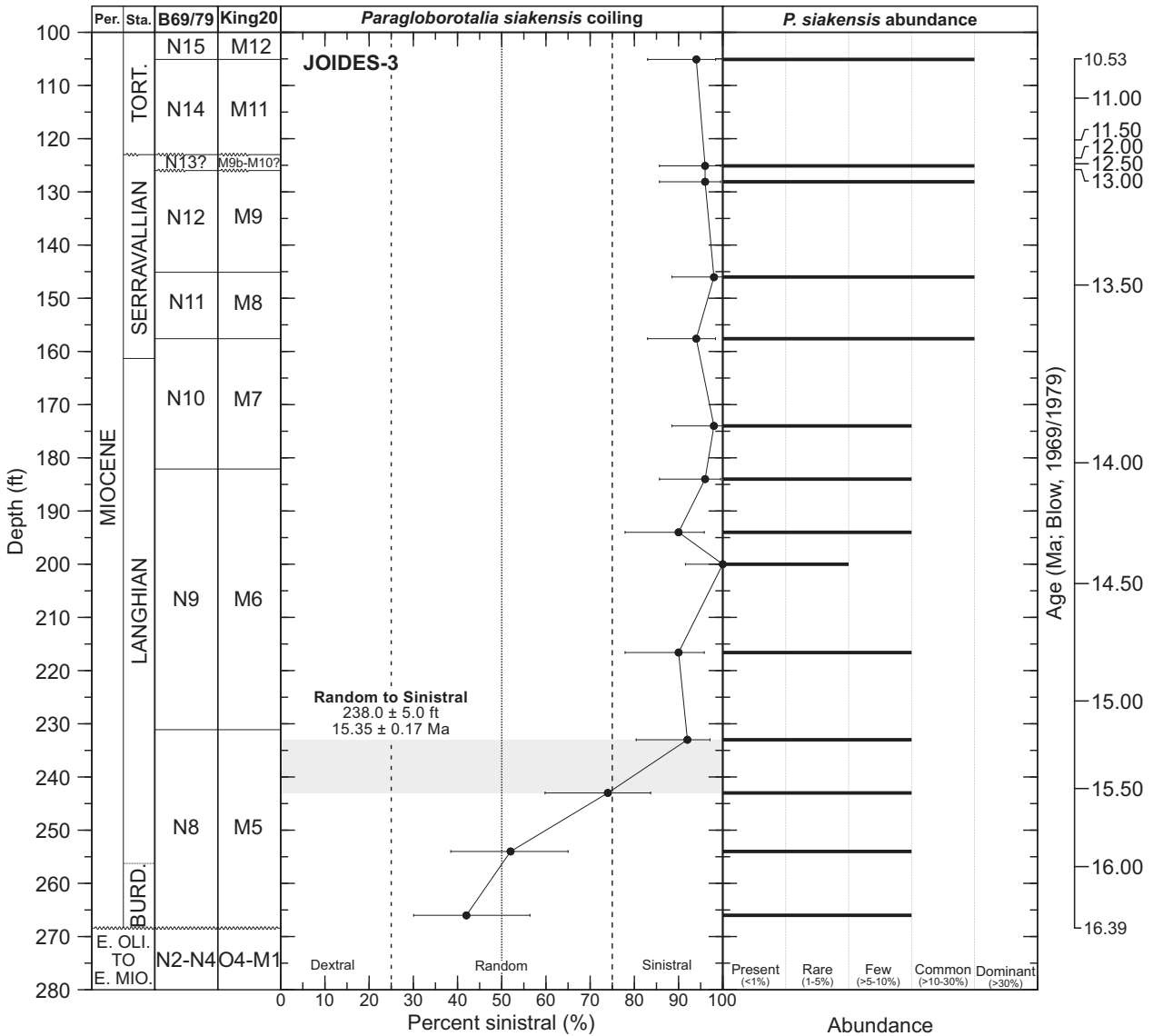


**Fig. 9.** Direction of coiling and relative abundance of *Paragloborotalia siakensis* in ODP Holes 925B and 925C. The grey box shows the upper and lower bounds for the change from random to sinistral coiling. Biostratigraphy is based on King (2019), with the grey triangle in the biozone column showing the upper and lower errors for the biozones. The samples are calibrated to the Wilkens et al. (2017) depth and age scale.

showing sinistral dominance. Conversely random coiling is observed downhole within the earlier paragloborotaliids (*P. incognita*, *P. semivera* and *P. pseudocontinuosus*).

*Globorotalia* first appear at 100.61 mbsf (11H-5, 10–12 cm) and the increase in abundance of this genus appears to be somewhat coincidental with the decline of the early paragloborotaliids. Unlike *Paragloborotalia*, globorotaliids are found in abundance in nearly

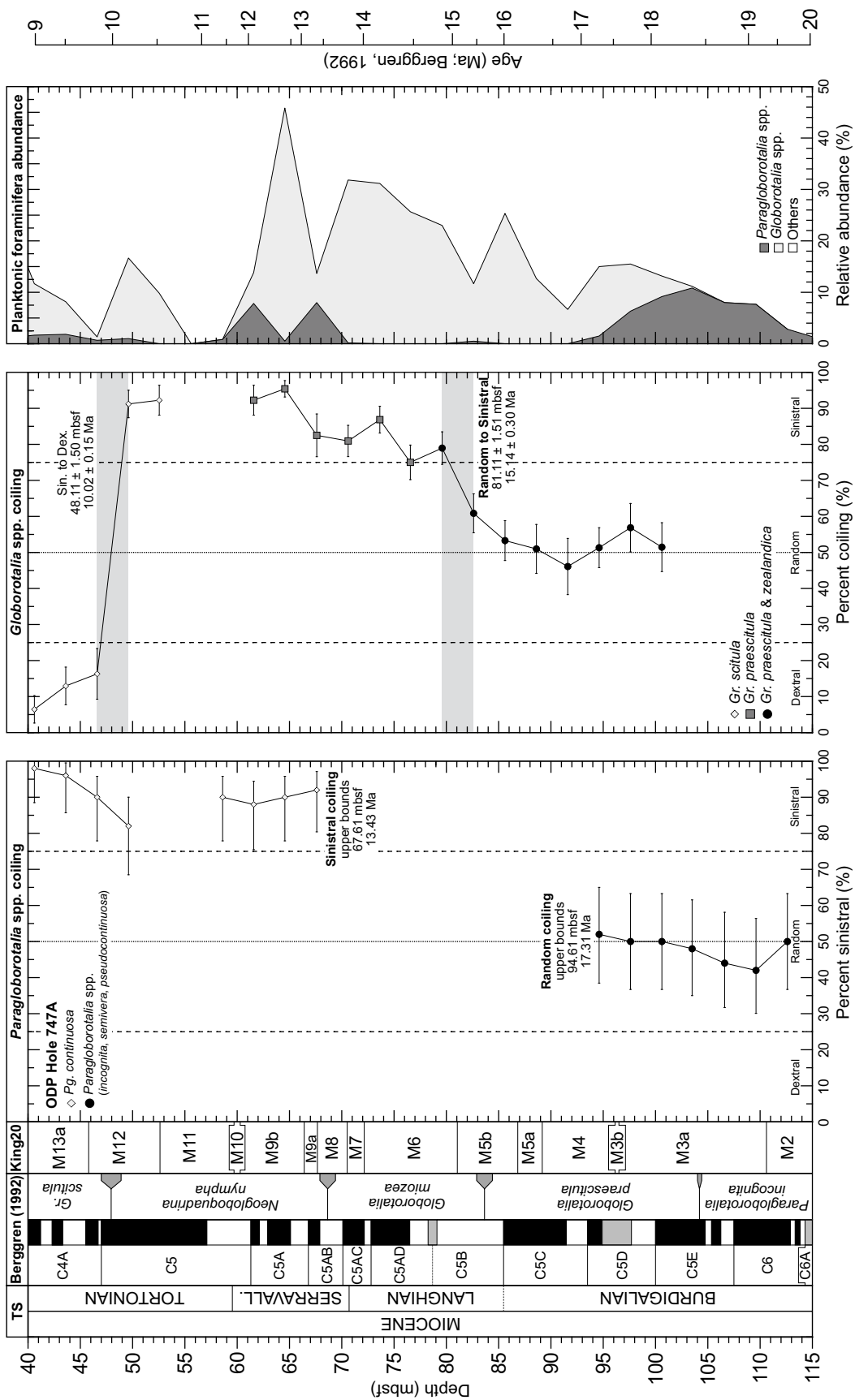
every sample throughout the sampled interval, although are absent between 52.55–61.58 mbsf (samples 6H-6, 100–112 cm and 7H-2, 60–62 cm). The early *Globorotalia* assemblages (79.60–100.61 mbsf) are dominated by *Globorotalia praescitula* and *Globorotalia zealandica*, with this assemblage showing a change from random to sinistral coiling at  $81.11 \pm 1.51$  mbsf ( $15.14 \pm 0.30$  Ma; between 9H-4, 100–102 cm to 9H-6, 100–102 cm). Above this inter-



**Fig. 10.** Direction of coiling and semi-quantitative abundance of *Paragloborotalia siakensis* in the JOIDES-3 borehole. The grey box shows the upper and lower bounds for the change from random to sinistral coiling. The biozones are based on the biostratigraphy of Blow (1969, 1979) (B69/79), which are calibrated to those in King et al. (2020) (King20) to produce the age.

**Fig. 11.** Direction of coiling and relative abundance of *Paragloborotalia* spp. (*P. continua*, *P. incognita*, *P. semi-vera* and *P. pseudocontinua*) and *Globorotalia* spp. (*G. scitula*, *G. praescitula* and *G. zealandica*) in ODP Hole 747A. The grey box on the *Globorotalia* shows the upper and lower bounds for the two coiling changes observed, while no box is given for *Paragloborotalia*, due to the lack of paragloborotaliids between ~67–94 mbsf. High latitude biozones and magnetostratigraphy are from Berggren et al. (1992). Chron ages are calibrated to King et al. (2020) (King20), with the low latitude biozones being calibrated directly from the magnetostratigraphy. The grey triangles in the Berggren et al. (1992) biozone column show the upper and lower errors for the biozones.





val, the globorotaliids are dominated by *G. praescitula* (51.58–76.55 mbsf), which maintains a preference for sinistral coiling. *Globorotalia scitula* was the most common species of the genus in the upper part of the studied interval (34.61–52.55 mbsf) and initially maintained a sinistral coiling direction (49.61–52.55 mbsf). Another coiling switch from sinistral to dextral dominated coiling is at  $48.11 \pm 1.50$  mbsf ( $10.02 \pm 0.15$  Ma; between 5H-7, 10–12 cm to 6H-2, 100–112 cm), with dextral coiling maintained in the remaining samples.

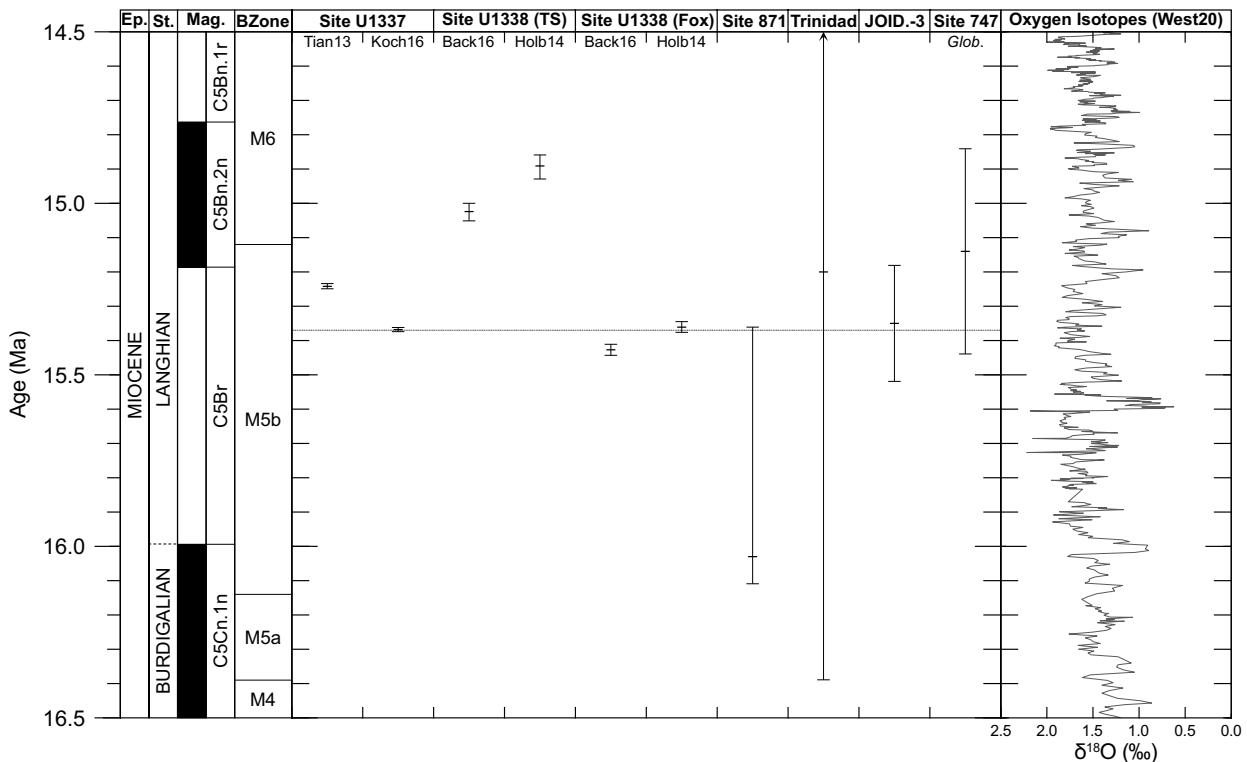
## 4. Discussion

### 4.1. The biostratigraphic utility of *Paragloborotalia* coiling direction

The long-term records of *P. siakensis* coiling show a change from a random to sinistral coiling preference in the eastern (Figs 4 and 5) and western equatorial Pacific Ocean (Fig. 6), southern Trinidad (Fig. 7)

and the western North Atlantic Ocean (Fig. 11). In addition, the record from IODP Site U1338 shows a synchronous change in coiling between *P. siakensis* and *P. continuosa* (Fig. 5). While a coiling change was recorded in *Paragloborotalia* in the sub-Antarctic Realm (ODP Site 747), the discrepancy in stratigraphic range of the paragloborotaliids means a precise level was not constrained (Fig. 11). A summary of the timing for the coiling change is shown in Table 2 and Figure 12. While Fig. 12 provides the stable isotope ( $\delta^{18}\text{O}$ ) record from Westerhold et al. (2020), and Figs 4–5 and 9–11 provided abundance changes, neither climate nor species abundance appears to have a clear control on the timing of the coiling changes, and so these are not discussed further.

In Winter and Pearsons (2001) study of the western equatorial Pacific and Atlantic oceans (ODP Sites 871 and 925 respectively) the authors found a coiling switch in *Paragloborotalia mayeri* (including *siakensis* as a junior synonym) within Zone N8 (~Zone M5) at ~15 Ma. Fox (2014, table 5.2) presented a high-



**Fig. 12.** Timing and age error of *Paragloborotalia* and *Globorotalia* coiling changes in our studied sites and the record of Fox (2014) for Site U1338. The magnetostratigraphy and biozones are based on King et al. (2020), while the base of the Langhian is from Raffi et al. (2020). The oxygen isotope record is the compiled benthic foraminifera ( $\delta^{18}\text{O}$ ) from Westerhold et al. (2020). The dashed line at 15.37 Ma, shows the bioevent age we suggest for the coiling change in *Paragloborotalia*. Abbreviations: Ep. – Epoch; St. – Stage; Mag – Magnetostratigraphy, Bzone – Biozone; Tian13 – Tian et al. (2013, 2018); Koch16 – Kochhann et al. (2016); Back16 – Backman et al. (2016); Holb14 – Holbourn et al. (2014); Glob – *Globorotalia*.

Table 2. Upper, lower and midpoint ages for the coiling switch in the *Paragloborotalia* (and *Globorotalia*, Site 747 only). Ages are based on this study and Fox (2014) for Site U1338. The references in brackets after the sites show which age reference was applied in instances where multiple age models exist.

Site	Lower Age	Midpoint Age	Upper Age
Site U1337 (Tian et al. 2013, 2018)	15.233	15.242	15.250
Site U1337 (Kochhann et al. 2016)	15.361	15.368	15.375
Site U1338 (Backman et al. 2016)	14.999	15.024	15.052
Site U1338 (Holbourn et al. 2014)	14.858	14.891	14.930
Site U1338 [Fox, 2014] (Backman et al. 2016)	15.410	15.427	15.444
Site U1338 [Fox, 2014] (Holbourn et al. 2014)	15.344	15.361	15.377
Site 871	15.36	16.03	16.11
Southern Trinidad	14.01	15.20	16.39
JOIDES-3	15.18	15.35	15.52
Site 747 ( <i>Paragloborotalia</i> )	13.34	N/A	17.31
Site 747 ( <i>Globorotalia</i> )	14.84	15.14	15.44

resolution study of the coiling change in *P. siakensis* at Site U1338 and recorded the change from random to sinistral coiling at  $15.36 \pm 0.033$  Ma. Fox's record followed the original spliced composite depth scale for Site U1338 (Expedition 320/321 Scientists 2010c), so was of a much higher resolution compared to the record produced in this study, which was solely based on Hole U1338A. In our analysis of Hole U1338A, the timing of the coiling change varied depending on the age model applied (Fig. 5). When the depth of the coiling change ( $404.77 \pm 1.24$  m CCSF-A) is correlated to the cyclostratigraphic record of Holbourn et al. (2014) the age is  $14.894 \pm 0.036$  Ma. In contrast, calibrating the same depth to Backman et al. (2016) magnetostratigraphic record yielded an age of  $15.025 \pm 0.026$  Ma within the lower part of Subchron C5Bn.1r. Both of these ages are younger than that suggested by Fox (2014) whose ages were derived from Holbourn et al. (2014). While the depth scale applied in this work (Wilkens et al. 2013) differs from that of Fox (2014) the recalibration of Fox's data to Wilkens et al. (2013) still shows a notable offset with the coiling change at  $417.38 \pm 0.60$  m CCSF-A. The coiling change would be expected to be near synchronous in all the holes from Site U1338. Hole U1338A has lower recovery, in comparison to Holes U1338B and C (Expedition 320/321 Scientists 2010c), and this offset may highlight a potential issue of the spliced depth scale. What is apparent is that the coiling change within both records occurs within Subzone M5b. Although the ages ( $14.891$  Ma and  $15.024$  Ma) derived from our record would fall within Zone M6 based on the tropical-subtropical biogeochronology ( $15.12$  Ma; King et al. 2020, Raffi et al. 2020), the *Orbulina* datum is

diachronous at Site U1338 occurring at  $\sim 14$  Ma (Fox and Wade 2013, Hayashi et al. 2013).

The Site U1338 coiling shift age of *P. siakensis* from Fox (2014;  $15.36$  Ma) shows good agreement with the timing from the JOIDES-3 ( $15.35$  Ma  $\pm 0.17$  Ma; Fig. 10) within the undifferentiated Zone M5 (Zone N8 of Blow 1969). Likewise, the record from southern Trinidad (Fig. 7) produces an age of  $15.20 \pm 1.19$  Ma (Zone M5-M6), while the upper bound age from ODP Site 871 (Fig. 6) is  $15.36$  Ma (Subzone M5b). For Site 871 the coiling change appears to occur in a highly condensed sequence where sedimentation rate dramatically increases (Pearson 1995, fig. 3), so should be treated with a degree of caution. While each of these ages agree well with Fox (2014), some degree of caution is needed as the ODP Site 871, JOIDES-3 and southern Trinidad records are based solely of biostratigraphic datums and lack other means of age control (e. g. magneto- or cyclostratigraphy). Conversely, our high-resolution record from IODP Site U1337 (Fig. 4) is calibrated relative to two cyclostratigraphic frameworks (Kochhann et al. 2016, Tian et al. 2013, Tian et al. 2018). Like our Site U1338 record, there are conflicting ages depending on the cyclostratigraphy applied, but both fall within Subzone M5b. The age model of Tian et al. (2013, 2018) suggests  $15.242 \pm 0.008$  Ma, while Kochhann et al. (2016) gives an age of  $15.368 \pm 0.007$  Ma. Both of these ages are older than our age from Site U1338, but are much closer to Fox's (2014) Site U1338 record and our records from Trinidad, JOIDES-3 and ODP Site 871.

Our evidence from multiple sites indicates that the *Paragloborotalia* coiling change, most notably *P. siakensis*, can be considered a robust bioevent within the

mid Miocene in the low to mid latitudes of the northern Pacific and Atlantic Oceans. Unfortunately, the fairly sporadic nature of *P. siakensis* in the Mediterranean area, where the species' occurrences form a series of acmes (e. g., Abdul Aziz et al. 2008, Foresi et al. 2011, Turco et al. 2017) means it is unlikely to be useful within this region. Despite this and taking into consideration the datum ages obtained as part of this study and Fox (2014) we propose an age of 15.37 Ma within the upper part of Subzone M5b and Chron C5Br (C5Br 0.75, Subzone M5b 0.8, Zone M5 0.9) to define the “*Paragloborotalia* coiling change” within the tropical to subtropical realm (Fig. 12). This datum may prove to be useful in areas where the *Praeorbulina-Orbulina* lineage is poorly represented, the whole evolutionary lineage is not present, and/or specimens are rare, as is seen in Site U1338 (Fox and Wade 2013, Hayashi et al. 2013) and ODP Sites 925-926 (Chaisson and Pearson 1997, Shackleton et al. 1999).

#### 4.2. The base of the Langhian and the microfossil record

The Langhian and the Burdigalian are the two stages of the Miocene which currently lack a Global Boundary Stratotype Section and Point (GSSP) (Raffi et al. 2020). The historical means of recognising the base of the Langhian in the microfossil record is the *Praeorbulina* datum (Rio et al. 1997) which represents the origination of this genus. Defining the *Praeorbulina* datum has proven difficult as *sicana* (*sicanus* auctorum) the evolutionary intermediate between *Trilobatus bisphericus* and *Praeorbulina curva*, has been assigned to *Praeorbulina* (e. g., Aze et al. 2011, Bolli and Saunders 1985, Kennett and Srinivasan 1983), *Globigerinoides* (e. g., Blow 1969, Stainforth et al. 1975) and *Trilobatus* (Spezzaferri et al. 2015). Additionally, the taxonomic concepts of *sicana/sicanus* have been open to interpretation (e. g., Jenkins et al. 1981, Turco et al. 2011, see also King et al. (2020, section 4.4.) for a more detailed discussion). Indeed, Turco et al. (2011) considered the *Praeorbulina* datum to be unsuitable for recognising the base of the Langhian, as the varied taxonomic concepts among different authors led to different Chron assignments for the origination of *Praeorbulina* (Raffi et al. 2020).

Due to issues identifying the *Praeorbulina* datum, Raffi et al. (2020) suggested that a palaeomagnetic reversal would provide a less ambiguous means of defining base Langhian, highlighting the top or base of Chron C5Br (15.19 Ma and 15.99 Ma respectively;

Fig. 12). While this seems to be a more reliable means of defining the base of the Langhian, identifying a correlation event in the microfossil record is also important. This is because a magnetostratigraphic record is not always readily available at a given study site and biostratigraphy often helps to identify magnetostratigraphic Chrons and Subchrons. Two promising candidate sections for the Langhian GSSP have been identified, the La Vedova Section in Italy (Turco et al. 2017) and St. Peter's Pool Section in Malta (Foresi et al. 2011), Raffi et al. (2020) recognised the importance of linking these Mediterranean Sections to the open ocean benthic foraminiferal records due to the Langhian falling within the Miocene Climatic Optimum (~14–17 Ma, Westerhold et al. 2020; Fig. 12). For this reason, Raffi et al. (2020) suggested that defining an auxiliary boundary stratotype within an ocean drilling core would be advisable and suggested two sites studied here, namely IODP Sites U1337 and U1338, as potential sites. Due to the issues of the *Praeorbulina* datum, the seemingly near synchronous coiling switch in *Paragloborotalia* in the low to low-mid latitudes is a bioevent that can be considered robust as a means of approximating the base of the Langhian. However, more work remains to refine the ages of bioevents after revisiting spliced sections from ocean drilling sites, and investigating the coiling switch at additional sites in other ocean basins. While magnetostratigraphy (the top or base of Chron C5Br) will likely provide the best primary event for defining a Langhian GSSP, the *Paragloborotalia* coiling change can be considered one of the key biostratigraphic correlation events for the Burdigalian-Langhian boundary.

#### 4.3. *Globorotalia* coiling change

Our record from ODP Site 747 (Fig. 11) shows that two coiling changes are apparent in *Globorotalia* over the studied interval. The timing of the change from random to sinistral dominance ( $15.14 \pm 0.30$  Ma) occurs in close proximity to that of the paragloborotaliid coiling change. Unfortunately, globorotaliids were not in a high enough abundance at our low latitude sites to investigate how synchronous the coiling change may be in the tropical-subtropical realm. Our data is in good agreement with Majewski (2010, fig. 3), who shows coiling ratio changes in the *G. zealandica* and *G. praescitula* plexuses between ~12–15 Ma, also from Site 747. Like our record (Fig. 11), the globorotaliids maintain a preference of sinistral coiling through this inter-

val. However, Majewski (2010) finds a brief period of random coiling in both plexuses at ~13.5 Ma before reverting back to a sinistral preference. This short-lived random coiling interval in Majewski (2010), was not apparent in our record, but may be a product of their much higher sampling resolution (~0.3 m) compared to our record (~3 m). We find a second change, namely sinistral to dextral coiling, in *Globorotalia* at  $10.02 \pm 0.15$  Ma (Fig. 11). This second coiling change occurs when there is only a single *Paragloborotalia* species remaining, namely *P. continuosa*, which only occurs sporadically in the late Miocene (Leckie et al. 2018). Therefore, no attempts have been made to assess whether a similar switch from a sinistral to dextral coiling preference is observed within *Paragloborotalia*.

#### 4.4. A quantitative assessment of Bolli's coiling trends

Bolli (1950, 1951) was the first author to recognise coiling changes within planktonic foraminifera and later illustrated changes within *Paragloborotalia* in Trinidad (Bolli 1971, Bolli et al. 1985). As noted by Winter and Pearson (2001), these records (Fig. 2) were schematic, as opposed to fully quantitative. The majority of the samples we studied for our Trinidad record (Fig. 7) were from the outcrop localities that Bolli used in his original (Bolli 1957) and later (Bolli 1966) zonations of southern Trinidad. This allowed the unique opportunity to compare Bolli's schematic trends to our quantitative record. Bolli's record (Fig. 2) shows the random to sinistral coiling change in *mayeri* (including *siakensis* as a junior synonym) occurred within the *Globorotalia fohsi peripheridonda* Zone (equivalent to upper Zone M6), with sinistral coiling maintained up until the extinction of the species. This is well reflected in our record (Fig. 7), with random coiling in sample Rz 108 (*Praeorbulina glomerosa* Zone = Subzone M5b to Zone M6), with the first sample showing sinistral preference being from Bo 202, the type locality for Bolli's (1957) *Globorotalia fohsi peripheridonda* Zone. In addition, the sinistral coiling preference is maintained up until Top *P. siakensis* in Sample KR23422 (*Globorotalia mayeri* Zone = Zone M11). Likewise, the random coiling suggested by Bolli in *Paragloborotalia kugleri* (including *P. pseudokugleri* as a junior synonym) in his *Globorotalia kugleri* and *Globgerigerinoides primordius* Zone (=Zone O7 to Zone M1), was also reflected in our analysis of Blow's Co-type *kugleri* locality

sample (equivalent to Subzone M1a), with random coiling in both *P. kugleri* and *P. pseudokugleri*.

## 5. Conclusions

Here we show the biostratigraphic utility of coiling direction in *Paragloborotalia* during the mid Miocene. Through a quantitative assessment of outcrop samples from southern Trinidad, we were able to show excellent agreement between our records and the schematic coiling diagram first proposed by Hans Bolli in the 1970s. Based on our analysis of a number of low to mid-low latitude sites, we find a near synchronous change in the coiling direction of *P. siakensis* from a random to sinistral coiling preference across the Pacific and Atlantic oceanic basins. The sinistral coiling preference is maintained until the extinction of *P. siakensis* at 10.605 Ma. Based on our study sites the coiling change occurs at 15.37 Ma within Subzone M5b. The age is derived primarily on our record from IODP Site U1337 and falls within the error range of all our study sites capturing the coiling change. In addition, *Paragloborotalia continuosa* also undergoes a synchronous change from random to sinistral coiling at IODP Site U1338, but further investigations are required to constrain whether this is true in other sites and paragloborotaliids. The coiling change represents a useful bioevent for recognising the base of the Langhian, which currently lacks a GSSP, due to issues associated with the *Praeorbulina* and *Orbulina* datums. Therefore the *P. siakensis* coiling change is the best micropalaeontological event if an auxiliary boundary stratotype is implemented for the Langhian, as has been suggested for IODP sites U1337 or U1338. Our high latitude record of *Paragloborotalia* coiling from ODP Site 747 shows that while the early Miocene paraglobrotallids (*P. semivera*, *P. incognita* and *P. pseudocontinuosa*) exhibit random coiling, the middle to late Miocene ranging *P. continuosa* shows a sinistral preference. Unfortunately, due to the discrepancy and lack of overlap in stratigraphic ranges of these species at Site 747, the timing of the coiling cannot be accurately constrained, but nevertheless shows the coiling shift is not just limited to the tropical to subtropical realm.

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