Late Miocene–Early Pliocene planktic foraminiferal biostratigraphy of deep offshore southwestern Niger Delta

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Received: 26 October 2020 / Accepted: 1 February 2021 / Published online: 15 February 2021
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Abstract

The planktic foraminiferal biostratigraphy of the deep offshore southwestern Niger Delta has been studied from three wells (DPW-1, DPW-2 and DPW-3). A total of 418 ditch cutting samples (104 samples from DPW-1, 165 from DPW-2 and 149 from DPW-3) taken at 18-m intervals were subjected to standard micropaleontological processing techniques. In total, 42, 52 and 40 planktic foraminiferal species were identified from DPW-1, DPW-2 and DPW-3, respectively. The identified planktic species allow the delineation of the studied section into four biozones—*Globorotalia acostaensis* (N16), *Globigerinoides obliquus extremus*/*Globorotalia merotumida* (N17), *Globorotalia margaritae primitiva* (N18) and *Globorotalia margaritae evoluta*/*Globigerina nepenthes* (N19) zones, based on the first appearance datums (FADs), last appearance datums (LADs) of the nominate taxa and associated assemblages. The well sections dated Late Miocene to Early Pliocene based on the occurrence of certain diagnostic planktic foraminiferal datums such as FADs *Globorotalia acostaensis*, *Globigerinoides obliquus extremus*, *Globorotalia merotumida/plesiotumida*, *Globorotalia margaritae primitiva* and the LADs *Globigerina nepenthes*, *Globorotalia margaritae primitiva* and *Globorotalia margaritae evoluta*. The Miocene/Pliocene boundary was placed at the FAD *Globorotalia margaritae primitiva*. In the Niger Delta, this boundary is commonly placed at the FADs *Globorotalia margaritae margaritae* and *Globorotalia crassaformis* probably due to nonrecovery of *Globorotalia margaritae primitiva*. However, in this studied section of the deep offshore southwestern Niger Delta, FAD *Globorotalia margaritae primitiva* occurs consistently in the three study wells and is therefore considered an appropriate datum for the placement of the Miocene/Pliocene boundary.

Keywords Planktic foraminifera · Biostratigraphy · Niger Delta · Offshore · Late Miocene · Early Pliocene

1 Introduction

The study area is located in the deep offshore southwestern part of the Niger Delta. The Niger Delta is located in southern Nigeria on the West African coast. It lies between latitudes 03° and 06° N and longitudes 002° and 010° E, southern Nigeria. The Niger Delta is one of the most petroliferous Tertiary Basins of the world. Since the discovery of hydrocarbon in the basin in the 1950s, it has continued to attract the attention of researchers from both the academia and the oil industry. Many studies

have been carried out in the aspects of the basin's tectonics, stratigraphy, geochemistry and hydrocarbon reserve estimates. Although several studies have been reported on the biostratigraphy of Niger Delta sequences, results arising from most of these studies are being shelved as unpublished technical reports in oil exploration and production companies operating within the delta. Most of these companies have erected in-house, local biozonation schemes based on their area of operations within the Niger Delta. A number of biozonation studies have also been done by researchers from the academia; nonetheless,

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such zonations are often not applicable on a delta-wide basis. Consequently, these disparate zonation schemes were harmonized by a Stratigraphic Committee on the Niger Delta in a book: *Cenozoic Foraminifera and Nannofossil Biostratigraphy of the Niger Delta*, published in 2017.

Many published biostratigraphic works on the Niger Delta appear to be focused on the Miocene epoch (e.g., [2, 11, 24, 25, 30]). Few published biostratigraphic studies on the Niger Delta investigated biozonation across the Miocene/Pliocene boundary. One of such is Ajaegwu et al. [4] in which the palynostratigraphic zonation of Late Miocene to Early Pliocene section of Ane-1 well, eastern Niger Delta, was carried out. According to these authors, the section belongs to the *Echitricolporites spinosus* zone of Evamy et al. [16]. Also, Fadiya and Salami [18] reported calcareous nannofossil zones across the Miocene / Pliocene from four Niger Delta wells.

In a bid to further elucidate the biostratigraphy of the Niger Delta, the planktic foraminiferal biostratigraphy of the deep offshore southwestern portion of the delta has been investigated from three wells. The result obtained from the studied section revealed four planktic foraminiferal zones within the Late Miocene to Early Pliocene sequence of the deep offshore.

1.1 Evolution and geology of the Niger Delta Basin

The Gulf of Guinea (of which the Niger Delta Basin is a component part) began to form in the Late Jurassic to Early Cretaceous during the breakup of the African and American paleocontinents [22, 29]. In the Niger Delta area however, the rifting persisted into the Middle Cretaceous and diminished altogether in the Late Cretaceous [20]. The onshore portion of the Niger Delta Province (Fig. 1) is delineated by the geology of southern Nigeria and southern Cameroon. The northern limit is the Benin Flank—a hinge line trending east-northeast south of the West African Massif. The Cretaceous outcrops of the Abakaliki High forms the northeastern boundary. To the east–south–east of the basin is the Calabar Flank which is a hinge line adjacent to the Precambrian Oban Massif [28]. The offshore margin of the Niger Delta is demarcated to the east by the Cameroun volcanic line and in the west by the Dahomey (Benin) Basin. The southern offshore border of the basin is either the 2 km sediment thickness contour or the 4000 m bathymetric contour where sediment thickness is more than 2 km. From the Eocene to the present, the Niger Delta province which covers 300,000 km² has prograded southwestward [15] forming depobelts that gave rise to

Fig. 1 General outline of onshore and offshore Niger Delta showing the location of studied wells. The exact coordinates of the individual wells were not provided for proprietary reasons (Adapted from USGS Open file Report No. 99–501)

one of the largest regressive deltas in the world [19]. At the basin's depocenter, sediment thickness is believed to reach an approximate thickness of 10,000 m. The delta contains huge hydrocarbon reserves making it one of the world's most petroliferous Tertiary basins. The Niger Delta is divided into three stratigraphic units, viz. Akata (marine shales), Agbada (paralic sequence of sand and shale) and Benin (alluvial sands) formations. The vast hydrocarbon deposit of the delta is contained chiefly within the sands of the Agbada Formation, while the shales of the Akata and Agbada formations are believed to be the sources rocks.

2 Materials and methods

The materials for this study are 383 ditch cutting samples obtained from three deep offshore wells—DPW-1, DPW-2 and DPW-3. The wells are located within the southwestern part of the Niger Delta, and samples were made available by Department of Petroleum Resources (DPR). The exact coordinates of the individual wells were not provided for proprietary reasons. Sixty-nine samples from DPW-1 (1709–2963 m), 165 samples from DPW-2 (2140–3000 m) and 149 samples from DPW-3 (1560–2630 m) taken at 18-m intervals were subjected to conventional foraminiferal sample processing

technique. Thirty grams (30 g) each of dried sample was weighed and soaked in kerosene for about one hour after which they were soaked in soap solution to facilitate disaggregation of the samples. The disaggregated samples were subsequently washed through a 63 μm sieve, dried and the residue sieved into coarse, medium and fine fractions from which foraminifera were painstakingly picked into cellules with the aid of reflected light stereoscopic binocular microscope.

Species-level identification of foraminifera was carried out using relevant literature including Agip S.P.A. Foraminifera Padani [3], Postuma [26] and Bolli and Saunders [9]. Stratigraphic distribution of species was plotted into spreadsheet using Stratabug biostratigraphic software. The first appearance datum (FAD) and last appearance datum (LAD) of certain species were used to date and delineate the studied section of wells into biostratigraphic zonal intervals. We are constrained to using FAD in that most of the species identified in this study evolved (i.e., first appearance) during the time interval under consideration and continued to either the Holocene or Recent. For this reason, their last appearance (LAD) could not be picked within the Late Miocene to Early Pliocene section investigated in this study. The photomicrographs of selected specimens are taken and displayed in Figs. 2, 3 and 4.

Fig. 2 (1) *Globigerina nepenthes*, (2) *Globigerinoides obliquus extremus* (umbilicus side), (3) *Globigerinoides obliquus extremus* (spiral side), (4) *Globigerinoides trilobus immaturus*, (5) *Globorotalia acos-*

taensis (umbilicus side), (6) *Globorotalia acostaeensis* (spiral side), (7) *Globigerinoides obliquus obliquus* (umbilicus side), (8) *Globigerinoides obliquus obliquus* (spiral side)

Fig. 3 (1) *Globorotalia plesiotumida* (umbilicus side), (2) *Globorotalia plesiotumida* (spiral side), (3) *Globorotalia pseudopima* (umbilicus side), (4) *Globorotalia pseudopima* (spiral side), (5) *Globorotalia miocenica* (spiral side), (6) *Globorotalia miocenica* (umbilicus side), (7) *Globorotalia crassaformis* (umbilicus side), (8) *Globorotalia crassaformis* (spiral side)

Fig. 4 (1) *Globorotalia margaritae primitiva* (umbilicus side), (2) *Globorotalia margaritae primitiva* (spiral side), (3) *Globorotalia pseudomiocenica* (umbilicus side), (4) *Globorotalia pseudomiocenica* (spiral side), (5) *Sphaeroidinellopsis seminulina*, (6) *Globorotalia margaritae margaritae* (umbilicus side), (7) *Globorotalia margaritae margaritae* (spiral side), (8) *Orbulina universa*

3 Results and discussion

3.1 Planktic foraminiferal zonation

Sixty-two planktic foraminiferal species were identified from samples obtained from the three sites (DPW-1, DPW-2 and DPW-3 wells). The species are generally well distributed within the sections. Nonetheless, scanty accumulations were observed within intervals 2048–2195 m (DPW-1), 2360–2516 m (DPW-2) and 2195–2316 m (DPW-3), and we believe that this may be related to the widely reported Messinian Salinity Crisis across world oceans [13, 17, 21, 23, 27]. The salinity crisis was responsible for reduction in carbonate mass accumulation rate (MAR) during the Messinian. The assemblages are dominated by *Globigerinoides* and keeled *Globorotalia*—a phenomenon characteristic of Late Miocene/Early Pliocene series. The rich planktics accumulations allow the subdivision of the well sections into four biostratigraphic zones within the Late Miocene–Early Pliocene age. These from the oldest to the youngest are *Globorotalia acostaensis*, *Globigerinoides obliquus extremus*/*Globorotalia merotumida*, *Globorotalia margaritae primitiva* and *Globorotalia margaritae evoluta*/*Globigerina nepenthes* zones. The planktic foraminiferal zones recognized in this study correlate with the zonation schemes of Blow [7, 8], Bolli and Saunders [9] and the Cenozoic foraminiferal zonation scheme erected for the Niger Delta by Adegoke et al. [1]. The zonation schemes of [7, 8] and Bolli and Saunders [9] have been widely used as accepted biostratigraphic standard schemes for low latitude regions of the world. However, that of Adegoke et al. [1] is gradually gaining acceptance among Niger Delta oil industry biostratigraphers. While this present study is on deep offshore sequences, the Adegoke et al.'s [1] scheme was largely centered on onshore and shallow offshore sequences with few deep offshore wells playing complimentary role. These authors noted that the application of planktic foraminifera in the shallow onshore sequences is constrained by deltaic facies changes. Therefore, some globally recognized standard planktic foraminiferal zones could not be carried across on a delta-wide basis, leading to the combination of a number of these zones in long-ranging stratigraphic intervals. Consequently, the zones delineated in this present study were encompassed in long-ranging zones of the Niger Delta Stratigraphic Committee zonation scheme of Adegoke et al. [1]. For instance, the *Globorotalia acostaensis*, *Globigerinoides obliquus extremus*/*Globorotalia merotumida* and *Globorotalia margaritae primitiva* zones (i.e., N16, N17 and N18 zones of [7, 8] of this present study were all

encompassed in the *Turborotalia acostaensis* (NNDf 11) zone of the Niger Delta zonation scheme.

The zonal delineations in this study were done on the basis of the first and last appearances of index taxa and characteristic assemblages. Important Late Miocene to Early Pliocene planktic species recovered from studied sites include *Globorotalia acostaensis*, *G. merotumida/plesiotumida*, *G. margaritae margaritae*, *G. margaritae primitiva*, *Globorotalia margaritae evoluta*, *Hastigerina siphonifera*, *Globigerina nepenthes* and *Globigerinoides obliquus extremus*. The meanings of the major acronyms used in the description of biozones are FAD—first appearance datum, LAD—last appearance datum. The delineated planktic foraminiferal biozones are discussed as follows with the zones summarily presented in Figs. 5, 6 and 7 and the stratigraphic distributions of the recovered taxa presented in Figs. 8, 9 and 10.

3.2 *Globorotalia acostaensis* zone

This zone was recognized only in DPW-1 within interval 2904–2944 m. The top of the zone was marked by FAD of *Globigerinoides obliquus extremus* and the zonal base by the FAD of *Globorotalia acostaensis* (Figs. 6, 7 and 8). The zone correlates with the Late Miocene N16 zone of [7, 8] and the *Globorotalia acostaensis* zone of Bolli and Saunders [9] and was defined by these authors as the interval between the first occurrence of *Globorotalia acostaensis* and first occurrence of *Globorotalia humerosa* with the nominate taxon (*Globorotalia acostaensis*) characterizing the interval. The first occurrence of *Globorotalia humerosa* used by these authors in marking the top of this zonal interval was not recorded in this study. However, the FAD of *Globigerinoides obliquus extremus* which has been used here to mark the top of this interval coincides with the top of the *Globorotalia acostaensis* zone of Bolli and Saunders [9] and N16 of [7, 8]; hence, the FAD of *Globigerinoides obliquus extremus* can be adopted in the Niger Delta for the recognition of this biostratigraphic interval. This zone partly correlates with *Turborotalia acostaensis* (NNDf 11) zone of Adegoke et al. [1].

Planktic foraminiferal assemblage recorded in the zone includes *Globigerinoides obliquus obliquus*, *Hastigerina siphonifera*, *Globorotalia acostaensis*, *Globigerina nepenthes*, *Globigerinoides obliquus extremus*, *Globigerinoides trilobus trilobus*, *Globigerinoides trilobus immaturus*, *Globigerinoides ruber seigliei*, *Globigerinita naparimaensis*, *Globigerina venezuelana*, *Orbulina univversa*, *Globoquadrina altispira*, *Globoquadrina dehiscens*, *Sphaeroidinellopsis seminulina* and *Sphaeroidinellopsis disjuncta*.

DEPTH (m)	EPOCH	PLANKTIC FORAMINIFERAL ZONES				PLANKTIC FORAMINIFERA DATUM
		N Zone (Blow, 1969, 1979)	Bolli & Saunders (1985)	Adegoke et al. (2017) (Onshore Niger Delta)	THIS STUDY (Offshore Niger Delta)	
1811 1847	Early Pliocene	N19	<i>Globorotalia margaritae evoluta</i>	NNDf 12	<i>Globorotalia margaritae evoluta</i> / <i>Globigerina nepenthes</i>	← LAD <i>Globorotalia margaritae</i> ← LAD <i>Globigerina nepenthes</i> (4.35 Ma)
1939		N18	<i>Globorotalia margaritae margaritae</i>		<i>Globorotalia margaritae primitiva</i>	← LAD <i>Globorotalia margaritae primitiva</i>
2524	Late Miocene	N17	<i>Globorotalia humerosa</i>	NNDf 11		← FAD <i>Globorotalia margaritae primitiva</i> (5.33 Ma)
2725					<i>Globigerinoides obliquus extremus</i> / <i>Globorotalia merotumida</i>	← FAD <i>Globorotalia merotumida</i> / <i>Plesiotumida</i> (8.52 Ma)
2904		N16	<i>Globorotalia acostaensis</i>		<i>Globorotalia acostaensis</i>	← FAD <i>Globigerinoides obliquus extremus</i> (8.85 Ma) ← FAD <i>Globorotalia (Neogloboquadrina) acostaensis</i> (9.79 Ma)
2944						

Fig. 5 Planktic foraminiferal stratigraphy of DPW-1 well

3.3 *Globigerinoides obliquus extremus*/ *Globorotalia merotumida* zone

This zone was identified within interval 2524–2904 m in DPW-1, 2765–2967 m in DPW-2 and 2164–2627 m in DPW-3. The top of the zone is marked by the FAD of *Globorotalia*

margaritae, while the zonal base is delineated by the FAD of *Globigerinoides obliquus extremus* (Figs. 6, 7 and 8). The FAD *Globorotalia merotumida* occur close to the base of the zonal interval and is a characteristic criterion for identifying the *Globigerinoides obliquus extremus*/*Globorotalia merotumida* zone. This zonal interval is equivalent to the

DEPTH (m)	EPOCH	PLANKTIC FORAMINIFERAL ZONES				PLANKTIC FORAMINIFERA DATUM
		N Zone (Blow, 1969, 1979)	Bolli & Saunders (1985)	Adegoke et al. (2017) (Onshore Niger Delta)	THIS STUDY (Offshore Niger Delta)	
2140 2143 2155	Early Pliocene	N19	<i>Globorotalia margaritae evoluta</i>	NNDf 12	<i>Globorotalia margaritae evoluta</i> / <i>Globigerina nepenthes</i>	← LAD <i>Globigerina nepenthes</i> (4.33 Ma) ← LAD <i>Globorotalia margaritae evoluta</i>
2524						← LAD <i>Globorotalia margaritae primitiva</i>
2765	Late Miocene	N18	<i>Globorotalia margaritae margaritae</i>	NNDf 11	<i>Globorotalia margaritae primitiva</i>	← FAD <i>Globorotalia margaritae primitiva</i> (5.33 Ma)
2967		N17	<i>Globorotalia humerosa</i>		<i>Globigerinoides obliquus extremus</i> / <i>Globorotalia merotumida</i>	← FAD <i>Globorotalia merotumida</i> (8.52 Ma)

Fig. 6 Planktic foraminiferal stratigraphy of DPW-2 well

Late Miocene N17 zone of Blow [8], *Globorotalia humerosa* interval zone of Bolli and Saunders [9] and partly correlates with the *Turborotalia acostaensis* (NNDf 11) zone of Adegoke et al. [1]. The base of this zonal interval as reported by Bolli and Saunders [9] is the first occurrence (FO) of *Globorotalia humerosa*. This species was not

recovered in DPW-1 and DPW-2. Although *Globorotalia humerosa* was recovered in DPW-3, the distribution of the species is considered inconsistent having its first occurrence at a much shallower level (2437 m) compared to notable zonal datums like FADs *Globorotalia merotumida* (2575 m) and *Globorotalia pseudopima* (2627 m). The zonal

DEPTH (m)	EPOCH	PLANKTIC FORAMINIFERAL ZONES				PLANKTIC FORAMINIFERA DATUM
		N Zone (Blow, 1969, 1979)	Bolli & Saunders (1985)	Adegoke et al. (2017) (Onshore Niger Delta)	THIS STUDY (Offshore Niger Delta)	
1560 1561	Early Pliocene	N19	<i>Globorotalia margaritae evoluta</i>	NNDf 12	<i>Globorotalia margaritae evoluta / Globigerina nepenthes</i>	← LAD <i>Globorotalia margaritae evoluta</i>
1579						← LAD <i>Globigerina nepenthes</i> (4.35 Ma)
1753		N18	<i>Globorotalia margaritae margaritae</i>	NNDf 11	<i>Globorotalia margaritae primitiva</i>	← LAD <i>Globorotalia margaritae primitiva</i>
2164	Late Miocene					N17
2627		← FAD <i>Globorotalia merotumida</i> (8.52 Ma)				

Fig. 7 Planktic foraminiferal stratigraphy of DPW-3 well

base seems not penetrated in DPW-2 and DPW-3 because the FAD of *Globigerinoides obliquus extremus* which has been used to mark the base of the zone appears to be deeper than the deepest sample analyzed in these wells. Planktic forms began to increase both in abundance and diversity within the *Globigerinoides obliquus extremus*

zone. Stratigraphically important planktic species recovered within the zonal interval include *Neogloboquadrina dutertrei*, *Globigerinoides ruber*, *Globigerinoides trilobus trilobus*, *Globigerinoides trilobus sacculiferus*, *Globigerinoides obliquus obliquus*, *Globigerinoides obliquus extremus*, *Globorotalia acostaensis*, *Globorotalia merotumida*, *Globorotalia*

Species Abundant Bar Scale (Applicable to Figures 6-8)

Fig. 8 Occurrence and distribution of planktic foraminiferal species within interval 1737–2944 m of DPW-1. Total count and diversity of species depicted in sawtooth are expressed as absolute numbers

plesiotumida, *Globorotalia pseudomiocenica*, *Globorotalia pseudopima*, *Orbulina universa*, *Globigerina nepenthes*, *Globigerina venezuelana*, *Hastigerina siphonifera*, *Sphaeroidinellopsis seminulina* and *Globigerinita naparimaensis*. Late Miocene peak occurrences of *Globigerina nepenthes* (8.52–5.33 Ma) was observed within the zone.

3.4 *Globorotalia margaritae primitiva* zone

This Early Pliocene zone was recognized within intervals 1939–2524 m in DPW-1, 2524–2765 m in DPW-2 and 1753–2164 m in DPW-3. The *Globorotalia margaritae primitiva* zone is marked as the total range of *Globorotalia margaritae primitiva*, the nominate taxon. The zone is equivalent to the N18 zone of [7, 8], *Globorotalia margaritae margaritae* zone of Bolli and Saunders [9] and partly correlates with the *Turborotalia acostaensis* (NNDf 11) zone of Adegoke et al. [1]. Planktic forms continue to increase in abundance and diversity within this zonal interval, with the occurrence of typical Late Miocene/Early Pliocene species such as *Neogloboquadrina dutertrei*, *Globigerinoides ruber*, *Globigerinoides trilobus trilobus*, *Globigerinoides trilobus sacculiferus*, *Globigerinoides obliquus obliquus*,

Globigerinoides obliquus extremus, *Globorotalia acostaensis*, *Globorotalia merotumida*, *Globorotalia margaritae*, *Globorotalia margaritae primitiva*, *Globorotalia plesiotumida*, *Globorotalia pseudomiocenica*, *Globorotalia pseudopima*, *Orbulina universa*, *Globigerina nepenthes*, *Globigerina venezuelana*, *Hastigerina siphonifera*, *Sphaeroidinellopsis seminulina* and *Globigerinita naparimaensis*. Peak abundance of *Globigerinoides obliquus extremus* and *Globigerina nepenthes* was recorded within this zonal interval.

3.5 *Globorotalia margaritae evoluta*/*Globigerina nepenthes* zone

This zone was recognized within intervals 1811–1939 m in DPW-1, 2140–2524 m in DPW-2 and 1560–1753 m in DPW-3. The top of the *Globorotalia margaritae evoluta*/*Globigerina nepenthes* zone is believed to occur at depths shallower than the first samples of the studied wells, while the base of the zonal interval is placed at the LAD of *Globorotalia margaritae primitiva*. The diagnostic criteria for the recognition of this zone are the LADs of *Globigerina nepenthes*, *Globorotalia margaritae evoluta*, *Globorotalia margaritae margaritae*, and the peak abundances

Fig. 9 Occurrence and distribution of planktic foraminiferal species within interval 2131–3000 m of DPW- 2. Total count and diversity of species depicted in sawtooth are expressed as absolute numbers

Globorotalia merotumida and *Globorotalia pseudopima*. This Early Pliocene zone is equivalent to the N19 zone of [7, 8], *Globorotalia margaritae evoluta* zone of Bolli and Saunders [9] and partly correlates with the *Globorotalia margaritae* zone (NNDf 12) of Adegoke et al. [1]. Diagnostic planktic species within the zonal interval comprise *Globigerina nepenthes*, *Globorotalia margaritae evoluta*, *Neogloboquadrina dutertrei*, *Globigerinoides ruber siegliei*, *Globigerinoides trilobus trilobus*, *Globigerinoides trilobus sacculiferus*, *Globigerinoides obliquus obliquus*, *Globorotalia acostaensis*, *Globorotalia merotumida*, *Globorotalia tumida tumida*, *Globorotalia miocenica*, *Globorotalia plesiotumida*, *Globorotalia pseudomiocenica*, *Globorotalia pseudopima*, *Orbulina universa*, and *Hastigerina siphonifera*.

The absolute ages of some chronostratigraphically important bioevents recognized in this study are presented in Table 1. Ages (Ma) are based on the revised planktic foraminiferal age calibration of Wade et al. [31].

3.6 The placement of the Miocene/Pliocene boundary

The placement of the Miocene/Pliocene boundary has been based on a number of planktic foraminiferal bioevents [6, 9, 12]. These include the last appearances of *Globorotalia plesiotumida*, *Neogloboquadrina dehiscens* and first appearances of *Globorotalia margaritae*, *Sphaeroidinella dehiscens*, *Globorotalia tumida*, *Globigerinoides conglobatus*. However, Berggren [5] considered the first appearance of *Globorotalia tumida* and the last appearance of *Globoquadrina dehiscens* as the most reliable bioevents marking the Miocene / Pliocene boundary. In this study, however, the Miocene/Pliocene boundary is placed at the base of the *Globorotalia margaritae primitiva* zone. This zone correlates with the N18 zone of [7, 8] and *Globorotalia margaritae margaritae* zone of Bolli and Saunders [9]. Both authors placed the chronostratigraphic boundary at the base of this zonal interval. Also Adegoke et al. [1] in a Cenozoic foraminiferal zonation scheme for the Niger Delta delineated the Miocene/Pliocene boundary at the base of *Globorotalia margaritae* (NNDf 12) zone. This zone correlates with N19–N21 zones of [7, 8] and partly at the

base with the *Globorotalia margaritae primitiva* zone in this present study. The occurrence of the FAD *Globorotalia margaritae primitiva* used here as the Miocene/Pliocene boundary marker is more consistently in the studied wells than those of the planktic foraminiferal datums used by previous authors in marking this chronostratigraphic boundary elsewhere around the world. Moreover, *Globorotalia margaritae primitiva* been restricted to the Earliest Pliocene, standard N18 zone has a shorter stratigraphic range than other taxa previously used.

4 Conclusion

The studied sections of the deep offshore southwestern Niger Delta yielded rich assemblages of planktic foraminifera. Four planktic foraminiferal zones: *Globorotalia acostaensis*, *Globigerinoides obliquus extremus*/*Globorotalia merotumida*, *Globorotalia margaritae primitiva* and *Globorotalia margaritae evoluta*/*Globigerina nepenthes* zones, were erected for the section based on the FADs and LADs of certain diagnostic species and associated assemblages. The erected zones correlate with the N16–N19, Late Miocene–Early Pliocene section of the Oligocene to Holocene low-latitude planktic foraminiferal zonation schemes of [7, 8], Bolli and Saunders [9] and with the NNDf 11–NNDf 12 zones of the Neogene foraminiferal zonation scheme of Adegoke et al. [1]. *Globorotalia acostaensis*, *Globigerinoides obliquus extremus*/*Globorotalia merotumida*, *Globorotalia margaritae primitiva* and *Globorotalia margaritae evoluta*/*Globigerina nepenthes* zones (this study) correlate with N16, N17, N18 and N19 of [7, 8] and with the *Globorotalia acostaensis*, *Globorotalia humerosa*, *Globorotalia margaritae margaritae* and *Globorotalia margaritae evoluta* zones of Bolli and Saunders [9], respectively. The three older zones and the youngest zone of this present study correlate, respectively, with NNDf 11 and NNDf 12 of Adegoke et al. [1]. The Miocene/Pliocene boundary in the southwestern deep offshore Niger Delta was placed at the base of the *Globorotalia margaritae primitiva* zone based on the correlation of this zone with the Earliest Pliocene N18 zone of the widely accepted zonation scheme of [7, 8].

Table 1 Significant bioevents and absolute ages of the studied section of the deep offshore southwestern Niger Delta

Epoch	Bioevent	Age in Ma [31]
Early Pliocene	LAD <i>Globigerina nepenthes</i>	4.36
	LAD <i>Globorotalia margaritae primitiva</i>	–
Miocene/Pliocene boundary	FAD <i>Globorotalia margaritae primitiva</i>	5.33
Late Miocene	FAD <i>Globorotalia merotumida/plesiotumida</i>	8.52
	FAD <i>Globigerinoides obliquus extremus</i>	8.86
	FAD <i>Globorotalia acostaensis</i>	9.79

Acknowledgements Our profound appreciation goes to the Department of Petroleum Resources (DPR) for providing the materials for this study.

Funding No funding, grant or other support was received for this study.

Compliance with ethical standards

Conflict of interest Authors have no conflict of interest to declare.

Ethical approval Authors have no financial or proprietary interest in any material discussed in this study.

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