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Late Eocene - Early Miocene paleoredox condition in Greater Ughelli Depobelt, Niger Delta, Nigeria: insight from Foraminifera and Inorganic Geochemical Proxies.

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Abstract

Multiproxy analysis, involving Foraminifera indices and inorganic geochemistry (laser ablation inductively coupled plasma mass spectroscopy and X-ray fluorescence) of ditch cutting samples from M and N wells, provided a basis for evaluating *Late Eocene to Early Miocene* paleo-oxygenation in the Niger Delta Basin, Nigeria. The first downhole occurrence of age diagnostic fossils, such as *Cassigerinella chipollensis, Spiroplectammina wrightii, Chiloguembelina cubensis, Eponides berthelotianus, Nonion oyae, and Hanzawaia stratonii,* confirms a *Late Eocene to Early Miocene* age for the sediments. In addition, integrating biozones of the foregoing age diagnostic fossils with deductions from planktonic/benthonic foraminifera ratios and arenaceous/calcareous benthonic foraminifera ratios suggests a shallow marine inner neritic to outer neritic paleodepositional environment with a water depth ranging from 7m to 200 m. Similarly, the higher proportion of calcareous foraminifera signifies deposition above the calcium carbonate compensation depth, which is characterized by oxic waters and warm temperatures. This deduction is strengthened by low average Uranium concentration (1.76 ppm and 1.97 ppm for N and M wells respectively), as well as moderate to strong positive covariation of redox-sensitive trace elements (Th, Co, Cu, Ni, Cr, V, Zn, and U) with Al, which denotes a non-hydrogenous origin of redox-sensitive trace elements typical of oxic bottom waters.

Keywords: *Foraminifera; Inorganic geochemical data; Paleo-oxygen condition; Paleogene*

1. Introduction

The current study examines Late Eocene to Early Miocene foraminifera species and the inorganic geochemical datasets from M and N wells in the Niger Delta Basin. The wells (M and N) used for this research are among the several thousands of oil and gas wells drilled onshore the Niger Delta Basin, southern Nigeria (Fig.1). Ozumba and Amajor (1999), Obaje and Okosun (2013), Fadiya et al. (2014), Usman (2016), Ukpong and Ikediasor (2018), Amiewalan and Edegbai (2021), among others, have successfully undertaken studies aimed at age determination and biozonation based on foraminifera with well data from the Niger Delta. Okosun et al. (2012) carried out foraminifera biostratigraphy and sequence stratigraphic analysis on the Akata Field, eastern Niger Delta, using samples from Akata-2, Akata-4, Akata-6, and Akata-7 wells. The authors established three planktonic (*Globorotalia continuosa, Globorotalia obesa/ Globorotalia mayeri,* and *Globorotalia peripheroacuta*) and three benthonic (*Spirosigmoilina oligocaenica, Uvigerina sparsicostata, and Eponides eshira/Brizalina mandorovensis*) foraminiferal biozones in Akata-2 and Akata-4 wells. One planktonic (*Praeorbulina glomerosa*) and one benthonic (*Brizalina mandorovensis / Eponides eshira* and *Poritextularia panamensis*) foraminiferal biozone were proposed for Akata-6 and Akata-7 wells, respectively. In addition, Calcareous nannofossil analysis yielded one biozone (*Sphenolithus heteromorphus*) from the Akata-6 and Akata-7 wells, assigning a Miocene age to the studied intervals of the four wells. Three third-order maximum flooding surfaces were recognized in Akata-2 and 4, while two were recognized in Akata-6 and 7 wells. Chukwu et al. (2012) inferred a Miocene age based on foraminifera biostratigraphy carried out on samples from the Oloibiri-1 well. The authors established one informal planktonic biozone (*Praeorbulina glomerosa* Zone) and a taxon range benthonic biozone (*Poritextularia panamensis* Zone). Littoral-deltaic to marine environments of deposition were inferred based on the occurrences of environmentally restricted benthic foraminifera taxa, some of which belong to the genera *Quinqueloculina, Hopkinsina, Spiroplectamina, Lenticulina, Heterolepa, Alveolophragmium, and Textularia*. Obaje and Okosun (2013) interpreted a shelf paleoenvironment of deposition of the subsurface Niger Delta based on the planktonic to benthonic foraminifera (P/B) ratio and average percentage ratios of calcareous and arenaceous benthonic foraminifera in five wells (Tomboy-1, 2, 4, 5, and 6) from the Tomboy- field. Ajayi and Agboneni (2016) used benthonic agglutinating foraminifera from four wells (A, B, C, and D) in the deep water of the Niger Delta to erect six agglutinated foraminifera biozones:Eggerella scrabra taxon range biozone, *Ammobaculites strathearnensis–Eggerella scabra, Haplophragmoides narivaensis - Eggerella scabra,*

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Cyclammina cancellata–Ammobaculites strathearnensis, Cyclammina complanata–Glomospira gordiales, and *Cyclammina cf. minima–Ammobaculites strathearnensis* interval range biozones. These biozones were calibrated to the geologic timeframe using planktonic foraminifera and calcareous nannofossils, and were dated as Late Miocene to Early Pliocene in age.

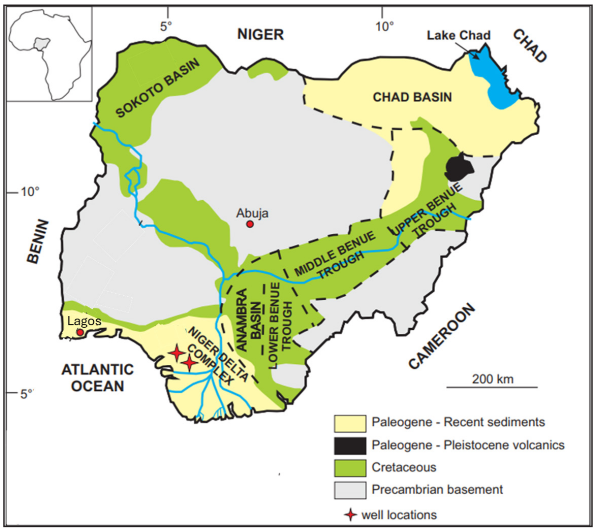

Figure 1. Simplified geologic map of the Niger Delta Basin indicating the well locations (Obaje, 2009).

Ni/Co, V/Cr, and U/Th trace elements ratios have been used to evaluate paleo-oxygenation conditions of ancient sediments by several authors, such as Suttner and Dutta (1986), Deng and Qian (1993), Jones and Manning (1994), Nath et al. (1997), Nagarajan et al. (2007), Akinyemi et al. (2013) Adebayo et al. (2015), and Ilevbare and Adeleye (2023). Adebayo et al. (2016) investigated strata within the Agbada Formation in the Niger Delta Basin using inorganic geochemical and palynological data. The geochemical results suggest a provenance region with felsic source rock characteristics, together with deposition in oxygenated bottom water. Amiewalan et al. (2020) utilized sedimentological and geochemical tools to evaluate the provenance, tectonic history, sandstone petrology, maturity, paleoclimate, and paleo-oxygenation conditions during the deposition of the sediments in the DF-2 well, onshore Niger Delta. The authors reported quartz arenite, sublitharenite, and Fe-rich sandstone deposited under an oxic bottom water. In addition, the sediments were hypothesized to be sourced from a felsic provenance in the passive continental margin tectonic setting.

The scarcity of recent investigations, which integrate foraminifera data (planktonic/benthonic foraminifera and arenaceous/calcareous foraminifera ratios) with inorganic geochemical elemental data to constrain bottom water paleo-redox conditions during the Late Eocene to Early Miocene in the western Niger Delta Basin motivates this study. Thus, this study demonstrates the value of detailed multi-proxy analysis involving the integration of micropaleontological (foraminifera) and elemental geochemical data in evaluating the paleo-oxygenation conditions of ancient sediments. The findings of this study will contribute to the advancement of knowledge about ancient sedimentary processes in the Niger Delta Basin.

2. Geologic Setting and Lithostratigraphy of the Niger Delta Basin

An area of approximately 140,000 km², located in the Gulf of Guinea, West Africa (Doust and Omatsola, 1990; Reijers et al., 1996). This 12 km thick Basin represents the passive margin stage in the Benue Trough's tectonic history with a basin fill ranging from the Paleogene to the Recent (Doust and Omatsola, 1990; Reijers et al., 1996; Nwajide, 2013). The basin is situated above an ancient triple junction that facilitated the separation of the South American and African plates during the Late Jurassic (Whiteman, 1982). Its northern boundary is demarcated by the Anambra Basin and the northwestern boundary is bounded by the Benin Flank with the Southern Benue Trough delineating its northeastern limit. The southeastern margin is defined via the Calabar margin, to the south is offshore Gulf of Guinea. The Okitipupa basement high separates it from the Dahomey Basin in the southwest border (Tuttle et al., 1999). The Niger Delta Basin's lithic fill is categorized into three stratigraphic units (Short and Stauble, 1967): (from old to young), the Akata Formation, Agbada Formation, and the Benin Formation (Table 1).

The Paleocene to recent Akata Formation is contemporaneous with the outcropping Imo Formation (Table 1). Its deposition resulted from marine paleo-depositional processes (Salami, 1983). This lithostratigraphic unit crops out throughout the Niger Delta Basin; it is typically overpressured. It is composed primarily of a thick calcareous mudstone unit, which serves as a petroleum source rock, and sand members that act as reservoirs in deep water (Weber et al., 1978). The Akata Formation is overlain by the Agbada Formation, which has the Ogwashi-Asaba and Ameki formations as outcrop equivalents (Mode et al., 2019; Ekwenye et al., 2020) (Table 1). This Eocene to recent lithostratigraphic unit is a 4000 m thick paralic sequence characterized by intercalated sands and mudrocks, which provide entrapment conditions for a vast number of petroleum accumulations (Evamy et al., 1978; Lambert-Aikhionbare et al., 1990). The net is that gross characteristics together with continental signature increase up section (Doust and Omatsola, 1990). The Agbada Formation grades upward to Benin Formation, which is presently succeeded by diverse sediments of the Quaternary Age (Boboye and Fowora (2007). It is up to 2000 m thick (Avbovbo, 1978), deposited in an upper delta plain paleoenvironment consisting of 90% coarse-grained, generally very granular and pebbly to fine-grained continental sands, with subordinate gravels and clay strata (Short and Stauble, 1967).

3. Materials and Methods

One hundred and four (104) ditch-cutting samples consisting of forty (40) samples from M well and sixty-four (64) samples from N well obtained from the Nigerian Petroleum Development Company (NPDC) were subjected to micropaleontological and geochemical laboratory protocols. Other instruments used in this study include a reflected light binocular microscope, a digital Sony camera, a fume cupboard, anhydrous sodium carbonate, a hot plate, a Mettler PC 440 digital balance (weighing scale), sieves, distilled water, and a water jet. Safety requirements and precautionary measures were implemented to prevent sample contamination.

Table 1. Correlation of Surface and Subsurface lithostratigraphic units in the Niger Delta Basin (Short and Stauble, 1967).

SUBSURFACE			OUTCROP		
Youngest known age		Oldest known age	Youngest known age		Oldest known age
Recent	Benin Fm.	Oligocene	Plio-Pleistocene	Benin Formation	Miocene?
	Afam/Qua Iboe member				
	Agbada Formation	Eocene	Miocene	Ogwashi-Asaba Fm.	Oligocene
			Eocene	Ameki Formation	Eocene
	Akata Formation	Paleocene	Late Eocene	Imo Formation	Paleocene

3.1 Micropaleontological Sample Processing

The typical foraminifera preparation method of Brasier (1980) was used to analyze the well's samples for their foraminifera and associated microfaunal content. They were packed in suitable plastic bags for micro-faunal picking and analyzing using a reflected light binocular microscope. Photomicrographs of identified foraminifera were taken with the aid of a digital Sony camera (14.1 megapixels). Published foraminifera forms and other related foraminifera literature assisted in the identification to genus and species levels.

3.2 Foraminifera Biozonation

The First Downhole Occurrence (FDO) and Last Downhole Occurrence (LDO) of widely used, chronostratigraphically important foraminifera taxa in the Niger Delta were the essential bioevents selected for foraminifera biozonation of the intervals in the studied wells. From the abovementioned, the suggested ages and biozones allocated to the interval were recognized by using the zonal schemes by Blow (1969), (1979), Berggren and Miller (1988), and the Niger Delta (SPDC) faunal zonal scheme.

3.3 Foraminifera Proportion Percentage

Equations 1-4 were used to calculate the proportion of the foraminifera groups identified from both wells. The percentage of the planktonic group was obtained by dividing the total number of foraminifera (planktonic and benthonic) present in the sediment and, then, multiply by 100 (Equation 1). Likewise, for the percentage value of benthonic group, the entire quantity of benthonic forms was compared with the total number of the foraminifera in the sediment (planktonics and benthonics) and multiplied by 100 as shown in Equation 2. To this effect, the proportion of a foraminifera group in each depth interval indicates the type of marine foraminifera found during the deposition of the sediment. In other words, it is a reliable way of determining proximality.

$$\%\ \text{of planktonic} = \frac{\sum \text{planktonic}}{\sum(\text{planktonic}+\text{benthonic})} \text{ X } 100\ \% \quad (1)$$

Arrhenius (1952)

$$\%\ \text{of benthonic} = \frac{\sum \text{benthonic}}{\sum(\text{planktonic}+\text{benthonic})} \text{ X } 100\ \% \quad (2)$$

Arrhenius (1952)

The proportion of agglutinated foraminifera was achieved by relating the total quantity of agglutinated benthonic foraminifera to the total number of both agglutinated and calcareous foraminifera recovered from the sediment and multiplying by 100 (Equation 3). Similarly, the percentage of calcareous foraminifera was calculated by dividing the total quantity of calcareous benthonic foraminifera by the total number of both agglutinated and calcareous foraminifera recovered from the sediment and multiply by 100 (Equation 4).

$$\%\ \text{of agglutinated} = \frac{\sum \text{agglutinating}}{\sum(\text{agglutinated}+\text{calcareous})} \text{ X } 100\ \% \quad (3)$$

Douglas (1979)

$$\%\ \text{of calcareous} = \frac{\sum \text{calcareous}}{\sum(\text{agglutinated}+\text{calcareous})} \text{ X } 100\ \% \quad (4)$$

Douglas (1979)

3.4 Geochemical Analysis

The experimental procedure for measuring the concentration of the major and trace elements involved weighing, pulverizing, and homogenizing 20 g of materials from twenty samples (ten samples each from both wells (M1-M10 and N1-N10) before geochemical analysis using Laser Ablation Inductively Coupled Plasma Mass spectroscopy (LA-ICP-MS) coupled with X-Ray Fluorescence (XRF) at Bureau Veritas Minerals Laboratory, Canada. Repeated measurements were taken for reproducibility and quality control.

4.0 Result and Discussion

Foraminifera recovery from the sediments from the M well was largely poor, and some intervals were barren. Planktonic species were either rare / absent, while the benthonic foraminifera species were the most dominant. The planktonic forms recovered are *Globigerina praebulloides, Cassigerinella chipollensis, Globigerina spp., Globorotalia opima nana*, and planktonic indeterminate. The calcareous benthonics recovered are *Nonion oyae, Bulimina elongate, Lagena spp.,* and calcareous indeterminate, while the recovered agglutinated benthonic species are: *Spiroplectammina wrightii, Textularia earlandi, Bathysiphon spp., Haplophragmoides spp., Verneulina spp.,* and Arenaceous indeterminate. By contrast, the recovered foraminifera in N well were fairly good. However, some taxa were not identifiable to the species/generic level; hence, they were treated as indeterminate. Most of the recorded species are planktonic and indeterminate, with moderate occurrences of benthonic forms. The species recovered under the planktonic category includes: *Chiloguembelina cubensis, Globorotalia spp., Globigerina spp., Globigerinoides spp.,* and planktonic indeterminate. The recovered calcareous benthonics forms are as follows: *Uvigerina spp., Nonionella auris, Calcareous indeterminate, Valvulinaria spp., Rotalia spp., Hanzawaia stratonii., Cibicorbis inflata, Uvigerinella spp., Epistonella pontoni, Eponides berthelotianus, Cancris spp., Cancris turgious, Uvigerinella sparsicosta, Lenticulina grandis, Bolivina dertonensis, Eponides spp., Heminwayina spp.* and *Ammonia bacarii* while the recovered agglutinated benthonic forms are: *Spiroplectammina wrightii, Textularia spp., Ammabaculates spp.* and Arenaceous indeterminate. In addition, a small amount of miscellaneous microfossils (Ostracoda, Holothuroidea, and Echinoderm remains) were recovered. Photos of some recovered foraminifera and miscellaneous microfossils (Holothuroidea and Ostracoda) from both wells are shown in Plate 1 below.

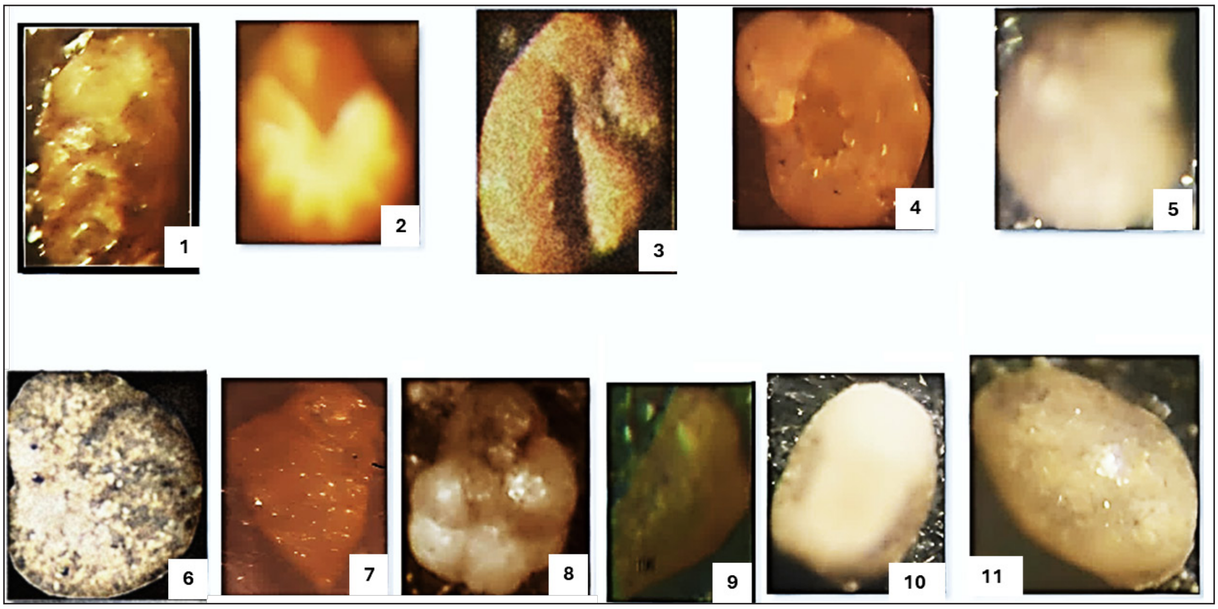

Plate 1. Photos of some selected foraminifera and miscellaneous microfossils (Holothuroidea and Ostracoda) from both wells. Explanation of plate 1: **1**. *Bolivina dertonensis* **2**. *Nonionella auris* **3**. *Cancris turgious* **4**. *Nonion oyae* **5**. *Eponides berthelotianus* **6**. *Hanzawaia stratonii* **7**. *Spiroplectammina wrightii* **8**. *Cassigerinella chipollensis* **9**. Chiloguembelina cubensis **10**. Holothuroid **11**. Ostracoda

4.1 Age determination

The FDO of *Cassigerinella chipollensis* at 6715 ft. enabled the allocated age (Late Eocene-Early Oligocene) to these intervals between 6715 ft.– 8300 ft. of M well. This interval correlated with P18 of the biostratigraphic zonal scheme defined by Berggren and Miller (1988). Additionally, the FDO of *Nonion oyae* and *Spiroplectammina wrightii was* used to date the well, which correlated with the Lower P16 - N2 of the zonal scheme defined by Blow (1969) and (1979). The age of the intervals (5590 ft. - 6715 ft.) was indeterminate due to the absence of an index maker specie. The results of the analyses indicated that the study interval of 6715 ft to 8300 ft in the M well spans the Late Eocene to Early Oligocene epochs. Figure 2 and Table 2.

The FDO of the following marker species (*Chiloguembelina cubensis, Eponides berthelotianus,* and *Hanzawaia stratonii*), recovered from the N well in relation to the Niger Delta (SPDC) faunal zonal scheme, were used to age-date the well. The FDO of *Chiloguembelina cubensis* at 8895 ft. was used to infer the Early Oligocene. FDO of *Chiloguembelina cubensis* is an important index marker for F7600/Early Oligocene. The FDO of *Eponides berthelotianus* at 8640 ft. and the FDO of *Hanzawaia stratonii* at 8040 ft. were also utilized to date the well. The FDO of Eponides berthelotianus is a marker for the F7800/ Late Oligocene - Early Miocene, whereas the FDO of Hanzawaia stratonii was used to identify the lower boundary of the Early Miocene/F9300. The age of the intervals 7350 ft. - 8040 ft. was indeterminate due to the absence of index maker specie, while the upper part from 2700 ft. – 7350 ft. of the well was barren of foraminifera species. Figure 3 and Table 3. The age of N well is inferred to be from the Early Oligocene to the Early Miocene. From the foraminifera stratigraphic distribution of the M well, one informal biozone: *Cassigerinella chipollensis* zone, was defined, while three informal biozones were demarcated - *Chiloguembelina cubensis, Eponides berthelotianus, and Hanzawaia stratonii* zones with their assigned ages. Tables 2 and 3.

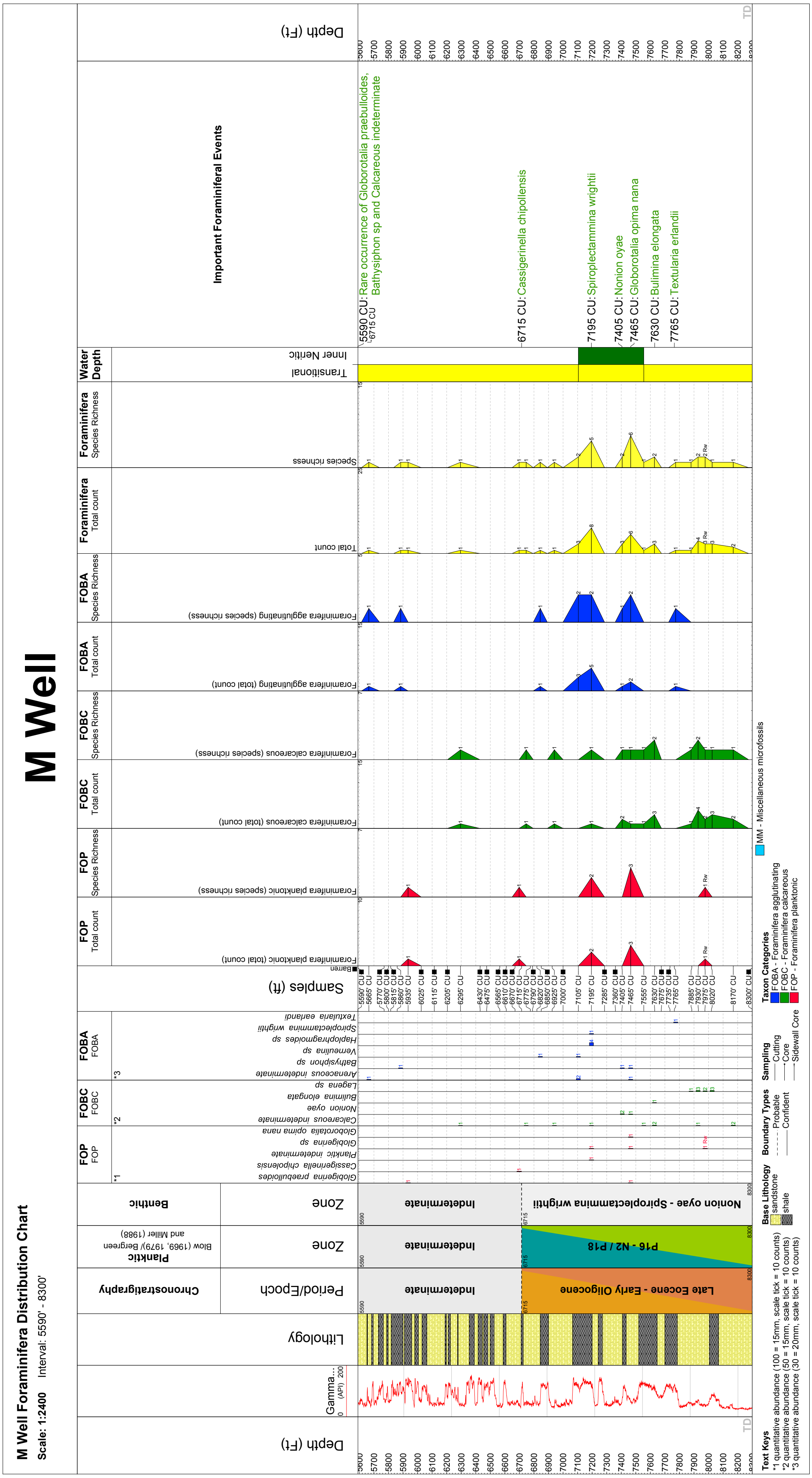

Figure 2. Stratigraphic distribution of recovered foraminifera from M well.

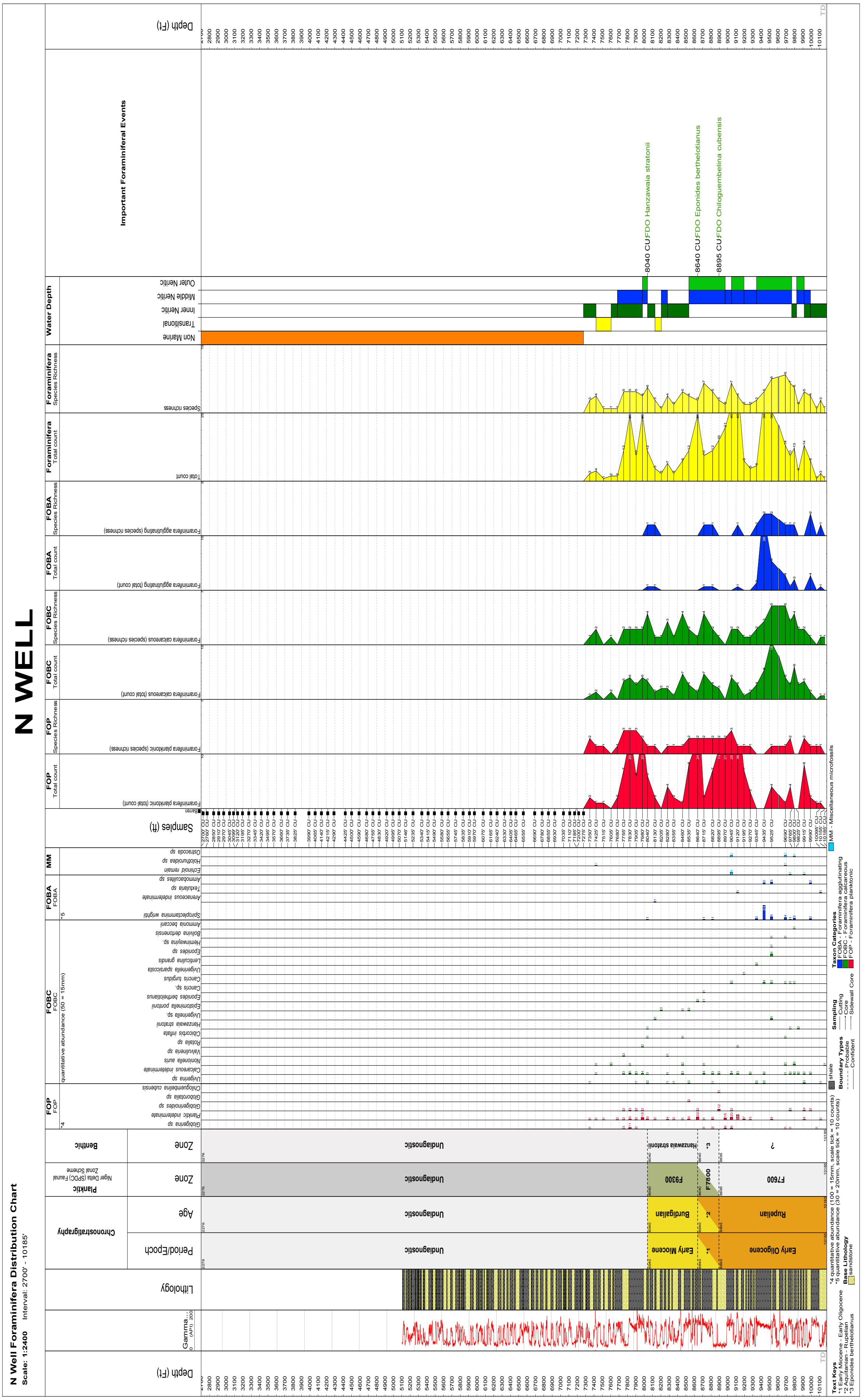

Figure 3. Stratigraphic distribution of recovered foraminifera from N well.

4.2 Planktonic/Benthonic (P/B) foraminifera Ratio of both wells

The P/B foraminifera ratio was calculated using the formula of the foraminifera proportion percentage in Equation 1. Brasier (1980) provided a useful guide to paleo-water depth / environmental inference by postulating that the higher the P/B ratio, the deeper the paleo-water depth of deposition. In the studied wells, percentage ratios were calculated for each biozone, and the values obtained were used to define the depositional environment of the successive intervals covered by the biozone. According to Murray (1991), the divisions of the environment are as follows: <20% planktonic tests signify the inner shelf, 20-50% show the middle shelf, 50-70% indicate the outer shelf, and >70% planktonic tests are interpreted as the upper bathyal zones. These percentages were related to the established biozones, from which a deduction of varying paleoenvironments, ranging from the inner neritic to the outer neritic environment, was hypothesized (Table 4 and Figure 4).

Table 2. The stratigraphic intervals, age established from the First Downhole Occurrence (FDO) of the marker species and biozones recognised in M well, related with Blow (1969, 1979), Berggren and Miller (1988) zonal scheme.

M WELL						
Depth interval (ft.)	Age	Epoch/Period	Foraminifera zonal scheme Blow (1969, 1979)	Berggren and Miller (1988)	Biozone for this study	Significant foraminifera datum
6715 - 8300	Rupelian - Priabonian	Early Oligocene – Late Eocene	P16 – N2	P18	*Cassigerinella chipollensis*	FDO of *Cassigerinella chipollensis*

Table 3. The stratigraphic intervals, age established from the First Downhole Occurrence (FDO) of the marker species and biozones recognised in N well related with the Niger Delta (SPDC) faunal zonal scheme.

N WELL					
Depth interval (ft.)	Age	Epoch/Period	Niger Delta (SPDC) Faunal Zonal Scheme	Biozonation for this study	Significant foraminifera datum
8040 -8640	Burdigalian	Early Miocene	F9300	*Hanzawaia stratonii*	*FDO of Hanzawaia stratonii*
8640 – 8895	Aquitanian - Rupelian	Early Miocene – Early Oligocene	F7800	*Eponides berthelotianus*	FDO of *Eponides berthelotianus*
8895 - 10185	Rupelian	Early Oligocene	F7600	*Chiloguembelina cubensis*	FDO of *Chiloguembelina cubensis*

4.3 Paleo-oxygenation

The mean and standard deviations for Co, Cu, Ni, Cr and Th are 7.37 and 4.19, 20.37 and 8.98, 21.05 and 7.92, 55.60 and 30.86, 7.34 and 5.0 respectively, while 76.62 and 82.94, 64.50 and 38.57, 1.87 and 1.09, 9.56 and 5.72 represent the mean and standard deviation for V, Zn, U, and Al respectively. The concentration of Co, Cu, and Ni in all the samples (Table 5) fall below the "world shale average" (WSA, Wedepohl, 1971, 1991). Whereas 20% of the samples exceed the WSA for Cr, Th, and V, 75% and 45% of the samples respectively show Zn and Al, U levels below the WSA (Table 5).

Table 4. The planktonic/benthonic (P/B) foraminifera ratios of M and N Wells.

M well												
Depth interval (ft.)	Age	Epoch/Period	Formation	Biozonation for this study	Total Benthonic	Total Planktonic	Total Micropaleontology	Percentage planktonic	Percentage benthonic	Ratio Murray (1991)	P/B ratio	Paleo -redox
5590 - 6715	Indeterminate	Indeterminate	Benin	*Globigerina praebulloides*	3	1	4	25	75	25:75 (Middle neritic)	P<B	oxic paleo-oxygenation
6715 - 7405	Rupelian	Early Oligocene	Benin	*Cassigerinella chipollensis s*	11	2	13	15	85	85:15 (Inner neritic)	P<B	
7405 - 8300	Rupelian - Priabonian	Early Oligocene – Late Eocene	Agbada	*Nonion oyae*	26	3	29	10	90	90:10 (Inner neritic)	P<B	
N well												
7350 - 8040	Indeterminate	Indeterminate	Agbada	*Nonionella auris*	26	59	85	69	31	69:31 (Outer neritic)	P>B	
8040 - 8640	Burdigalian	Early Miocene		*Hanzawaia stratonii*	27	23	50	46	54	46:54 (Middle neritic)	P<B	
8640 – 8895	Aquitanian - Rupelian	Early Miocene – Early Oligocene		*Eponides berthelotianus*	16	32	48	67	33	67:33 (Outer neritic)	P>B	
8895 - 10185	Rupelian	Early Oligocene		*Chiloguembelina cubensis*	125	137	262	52	48	52:48 (Outer neritic)	P>B	

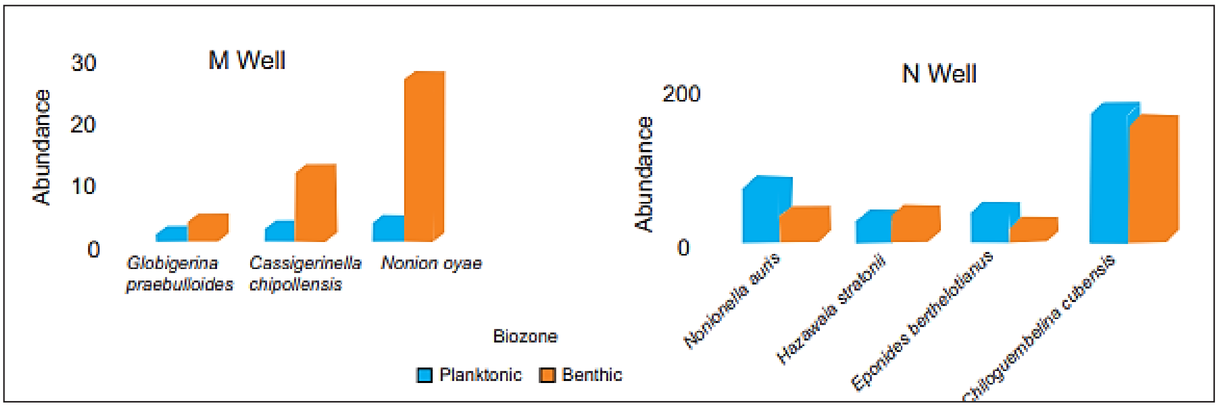

Figure 4. Comparison chart to show the distributional pattern of the planktonic/benthonic (P/B) foraminifera ratios of M and N wells.

Trace metals can originate from hydrogeneous or non-hydrogeneous (detrital and hydrothermal) sources (Tribovillard et al., 2006). Some of these trace metals become sequestered in sediments under reducing bottom water conditions (Morford and Emerson, 1999), where they form organometallic complexes with preserved organic matter (Tribovillard et al., 2006). Consequently, a positive correlation exists between organic richness and the abundance of redox-sensitive trace metals especially Mo, U, Cr, V, Ni, and Cu. Tribovillard et al. (2006) successfully used this relationship to discriminate between oxic, anoxic and euxinic paleoxygenation conditions.

Table 5. Geochemical data of M and N Wells.

S/N	Co (Cobalt)	Cr (Chromium)	Cu (Copper)	Ni (Nickel)	Th (Thorium)	U (Uranium)	V (Vanadium)	Zn (Zinc)
N1	3.6	20	10	16	3.67	0.85	18.3	18
N2	3.6	22	9	15	3.74	0.91	19.2	21
N3	3.5	24	11	14	3.39	0.99	20.1	20
N4	3.5	21	12	17	3.63	0.92	22.4	24
N5	3.5	21	7	16	3.22	0.89	21.6	16
N6	3.6	23	8	17	3.58	1	17.8	19
N7	13.5	104	22	34	18.5	3.9	127	120
N8	13.5	63	20	24	13.7	3.2	81.2	135
N9	13.2	78	21	21	14.2	3.32	77.3	86
N10	13.4	92	22	28	16.1	3.76	78.9	98
M1	3.1	30	22	10	3.21	0.74	8.6	25
M2	11.8	75	24	28	12.3	3.24	71.4	60
M3	9.6	65	35	15	10.2	2.34	56.2	70
M4	8.5	45	38	18	8.4	2.21	12.7	90
M5	2.7	36		13	2.18	1.08	10.2	100
M6	2.3	32	32	11	3.12	1.02	9.4	110
M7	8.3	89	24	30	6.23	1.58	150	74
M8	8	92	24	32	5.66	1.54	210	83
M9	7.9	86	24	28	4.68	1.43	272	45
M10	10.2	94	22	34	7.14	2.41	248	76
AV	7.37	55.60	20.37	21.05	7.34	1.87	76.62	64.50
SD	4.19	30.86	8.98	7.92	5.04	1.09	82.94	38.57
WSA	**19**	**90**	**45**	**68**	**12**	**3**	**130**	**95**

Trace element ratios (Ni/Co, V/Cr, and U/Th) have gained popularity due to the ease of discriminating paleo-redox oxygen conditions of ancient sediment (Jones and Manning, 1994; Nath et al., 1997; Akinyemi et al., 2013; Adebayo et al., 2015; Adeoye et al., 2020; Ejeh et al., 2021; Overare et al., 2020, 2021; Omietimi et al., 2022, etc.). Arising from the foregoing, it is important to note that trace element proxies for determining paleo-redox conditions are only reliable if their origin is predominantly hydrogenous (Tribovillard et al., 2006). Binary plots of Al (detrital indicator) versus Co, Cr, Cu, Ni, Th, U, V, and Zn for all samples show moderate to strong positive covariation except Ni and V (Fig. 5), implying a dominant non-hydrogenous source for the redox-sensitive trace metals, which correspond to deposition under oxic paleo-oxygenation. Similarly, the low average U content (1.76 ppm and 1.97 ppm) in the N and M well sediments also indicates an oxic paleo-redox condition during deposition (Armstrong-Altin et al., 2015).

Furthermore, the widespread occurrence of arenaceous benthonic foraminifera is typical of an environment fluctuating between neritic and abyssal (Bandy and Amal, 1960). The arenaceous/calcareous percentage was calculated using a related formula of the planktonic/benthonic ratio (P/B) foraminifera proportion percentage (equation 3). The percentage ratio of calcareous to arenaceous benthonic foraminifera is also a good pointer for paleoenvironmental studies. High % FOBC: % FOBA ratio suggests shallower paleo water depths while lower % FOBC: % FOBA suggest deeper paleo water depths. The percentage of FOBC: FOBA has been known to decrease with depth (Obaje et al., 2004). The divisions of the environment were also interpreted in the following order: 0-25% indicates a low A/C ratio, 26-50% shows a moderate A/C ratio, and> 50 % was interpreted as a high A/C ratio (Table 6 and Figure 6).

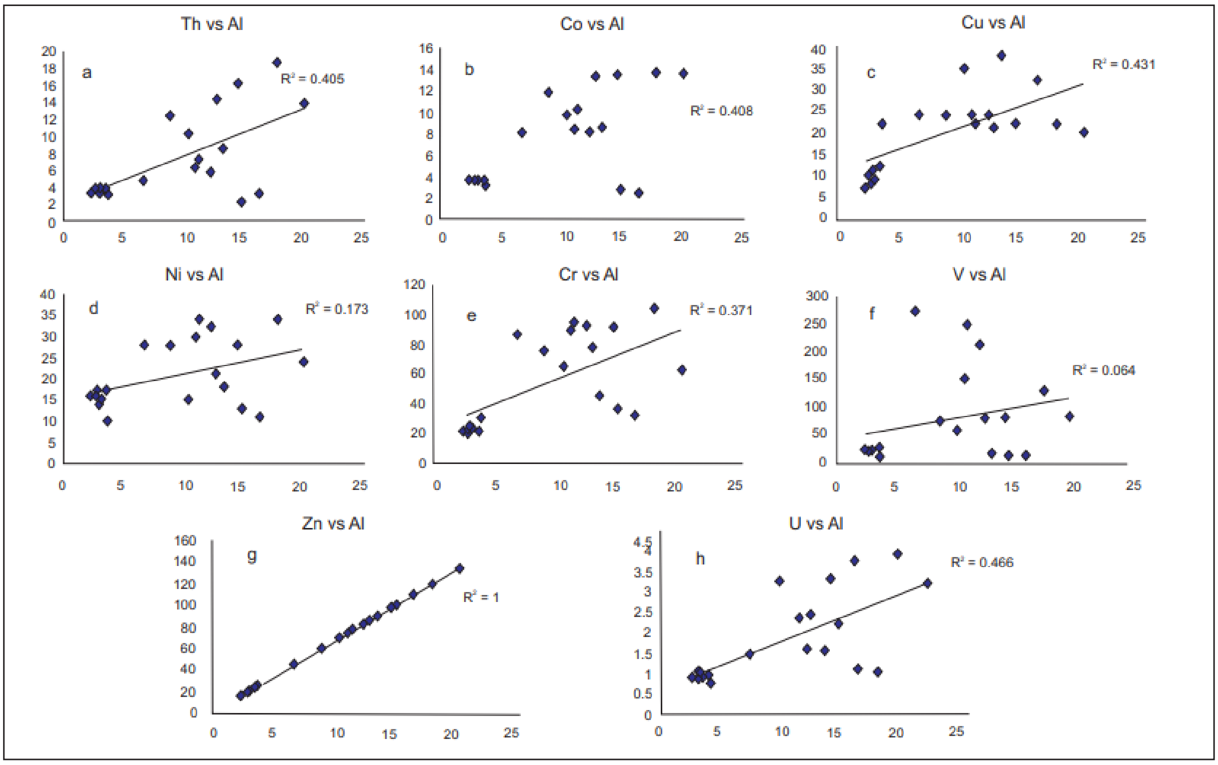

Figure 5. a-h: binary plots of redox-sensitive trace metal versus Al depicting moderate to strong positive covariation.

Table 6. The Arenaceous/calcareous (A/C) benthonic foraminifera ratios of M and N wells.

Depth interval (ft.)	Age	Epoch/Period	Formation	Biozonation for this study	Total Agglutinating	Total Calcareous	Total Micropaleontology	Percentage Agglutinating	Percentage Calcareous	Ratio Saint-Marc & Berggren (1988)	A/C ratio	Paleo -redox
M well												
5590 - 6715	Indeterminate	Indeterminate	Benin	*Globigerina praebulloides*	1	2	3	33	67	67:33 (Moderate)	A<C	oxic paleo-oxygenation
6715 - 7405	Rupelian	Early Oligocene	Benin	*Cassigerinella chipollensis S*	7	4	11	64	36	64:36 (High)	A>C	
7405 - 8300	Rupelian - Priabonian	Early Oligocene – Late Eocene	Agbada	*Nonion oyae*	20	6	26	77	23	77:23 (High)	A>C	
N well												
7350 - 8040	Indeterminate	Indeterminate	Agbada	*Nonionella auris*	0	26	26	0	100	0:100 (Low)	A<C	
8040 - 8640	Burdigalian	Early Miocene		*Hanzawaia stratonii*	1	23	24	4	96	4:96 (Low)	A<C	
8640 – 8895	Aquitanian - Rupelian	Early Miocene – Early Oligocene		*Eponides berthelotianus*	2	13	15	13	87	13:87 (Low)	A<C	
8895 - 10185	Rupelian	Early Oligocene		*Chiloguembelina cubensis*	50	78	128	39	61	39:61 (Moderate)	A<C	

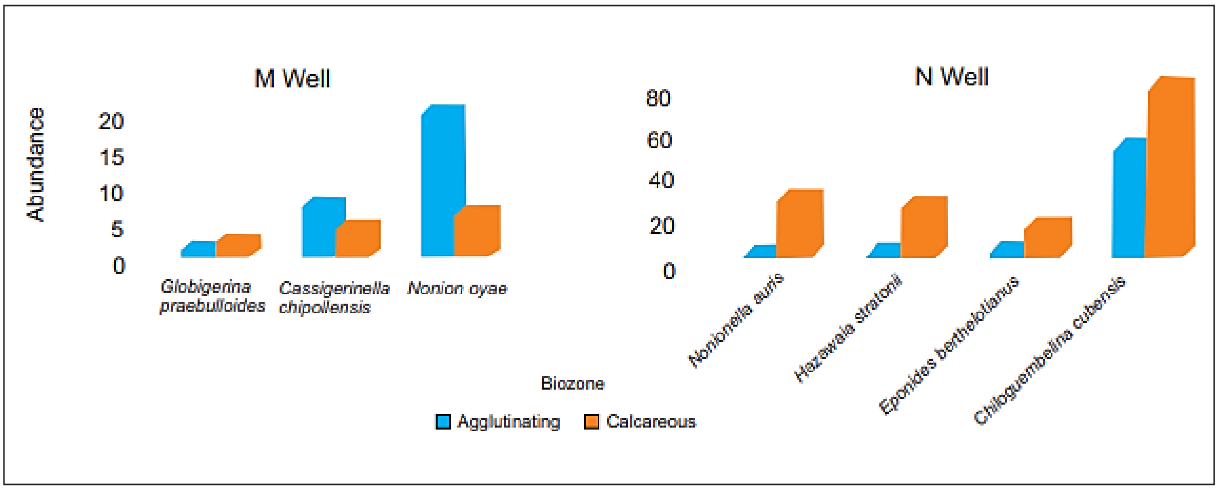

Figure 6. Comparison chart to show the distributional pattern of the arenaceous/calcareous benthonic foraminifera ratios of M and N wells.

A higher proportion of calcareous foraminifera was recovered from the wells, indicating deposition mainly above the calcium carbonate compensation depth (CCD) line, a region characterized by high calcium carbonate, sufficient oxygen, typical salinity, and high temperature (Saint-Marc and Berggren, 1988). The absence of calcareous benthic foraminifera and the presence of arenaceous types are generally used to identify the location of the CCD. Thus, an integration of inferences from redox-sensitive element data, P/B and A/C foraminifera ratios, suggests a range of paleoenvironments from an oxic middle to outer neritic environment during the Late Eocene to Early Miocene Epoch (Fig. 7) in the Greater Ughelli depobelt, Niger Delta Basin.

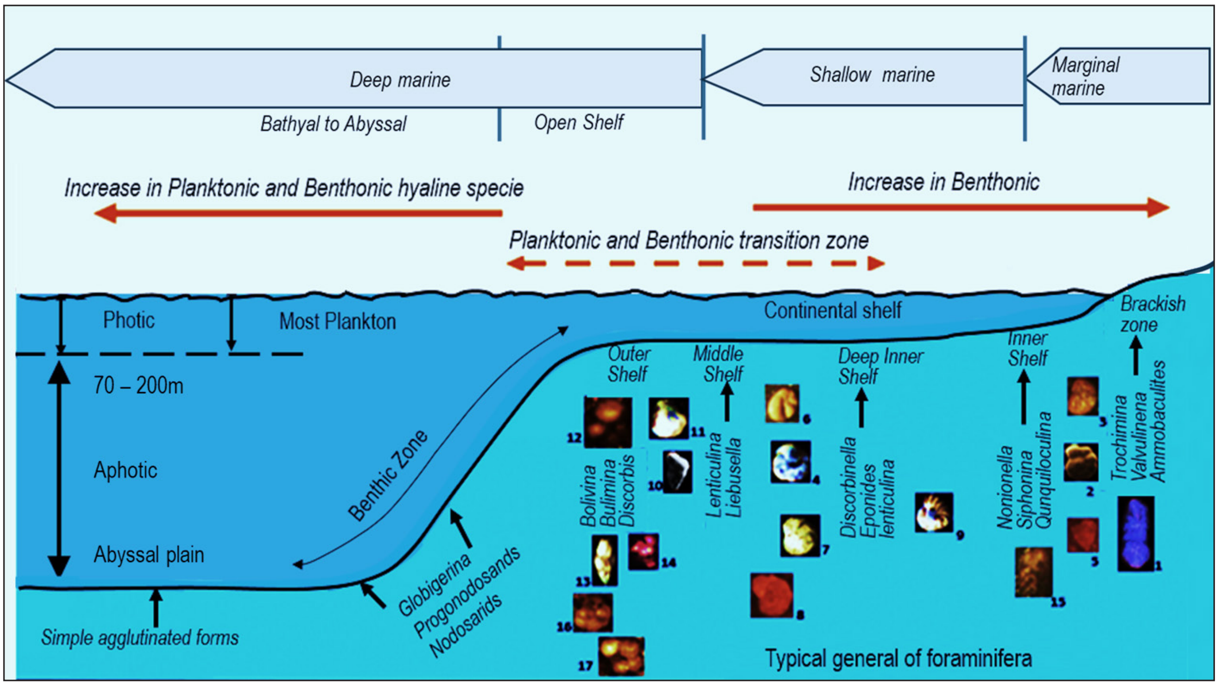

Figure 7. Diagrammatic expression of the combined Ni/Co, U/Th, V/Cr and Cu/Zn (inorganic geochemical elemental ratio) and (P/B and A/C foraminifera ratios) to derive the paleo-oxygen condition of sediments deposition from both wells. 1. *Ammobaculites spp.* 2. *Ammonia beccarii* 3. *Epistominella pontoni* 4. *Cibicorbsis inflata* 5. *Spiroplectammina wrightii* 6. *Cancris turgious* 7. *Hanzawaia stratonii* 8. *Nonion oyae* 9. *Lenticulina grandis* 10. *Chiloguembelina cubensis* 11. *Eponides berthelotianus* 12. *Globigerina praebulloides* 13. *Uvigerina sparsicosta* 14. *Bulimina elongata* 15. *Bolivina dertonensis* 16. *Cassigerinella chipollensis* 17. *Globorotalia opima nana* [Modified after Allen (1965, 1970), Youssef and El-Sorogy (2015)].

5. Conclusion

The investigated samples have been dated as Early Miocene to Late Eocene in both wells based on the First Downhole Occurrences of *Cassigerinella chipollensis, Nonion oyae, Spiroplectammina wrightii, Chiloguembelina cubensis, Eponides berthelotianus and Hanzawaia stratonii.* Furthermore, the low average content of Uranium, the moderate to strong positive covariation of redox sensitive trace elements against Aluminium for both wells, and implications from foraminifera ratios - planktonic versus benthonic (P/B) foraminifera, and arenaceous versus calcareous (A/C) benthonic foraminifera of both wells indicate paleo-water depth ranging from inner neritic to outer neritic paleoenvironment.

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