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EVALUATION OF PALAEO-OXYGEN CONDITIONS OF PRIABONIAN – RUPELIAN SEDIMENTS OF THE AGBADA FORMATION, NIGER DELTA BASED ON FISHER'S DIVERSITY INDEX AND BENTHIC FORAMINIFERA OXYGEN INDEX

Ukpong, Aniediobong Jonah[1]
[1] Senior Lecturer, Department of Geology, Gombe State University, Gombe, Gombe State, Nigeria- (Sabbatical), Department of Geology, University of Calabar, Calabar, Cross River State, Nigeria.

Ekhalialu Ogie Macaulay[2]
[2]MSc Research Scholar, Department of Geology, University of Calabar, Calabar, Cross River State, Nigeria.

ABSTRACT

Evaluation and assessment of ancient dissolved-oxygen levels was carried out on samples from two wells (wells C and F) in the Niger Delta, Nigeria based on Fisher's diversity index (α) and benthic foraminifera oxygen index (BFOI). This was done in order to determine the ancient dissolved oxygen levels in relation to environmental conditions. A total of eighty (80) ditch cutting samples were obtained from two wells (well C: interval 2410 – 2770m, 13 samples at 30m and well F: interval 2000-3320m, 67samples at 20m) located in the Northern Depobelt of the Tertiary Niger Delta. The obtained samples were processed based on the use of standard micropaleontological sample preparation procedures and thereafter the analysis of the foraminifera biofacies assemblages as well as discrimination into their morphologic characteristics was achieved. Age determination was possible based on the recovered planktic and benthic foraminifera forms indicating Priabonian – Rupelian age. The palaeo-oxygenation of well C is low (suboxic: 0.3 – 1.5ml/l to anoxic: 0-0.1ml/l) based on the calculated BFOI and low – moderate Fisher's diversity (α<5) which reflects stressed low-oxygen conditions depicting periods of adverse environmental conditions. The results of palaeo-oxygen analysis of well F indicates a range from dysoxic (0.1 – 0.3 ml/l) through suboxic (0.3 – 1.5ml/l) and anoxia (0-0.1ml/l) to oxic (>1.5ml/l) settings based on the calculated BFOI and supported by the low – high Fisher's diversity depicting fluctuations of dissolved oxygen level. This is strongly associated with periods of adverse environmental conditions and environmental pleasures.

KEYWORDS: *Agbada Formation, Benthic foraminifera oxygen index, Fisher's diversity plot, Niger Delta, Palaeo-oxygen, Priabonian, Rupelian.*

1. INTRODUCTION

The evaluation and assessment of ancient dissolved-oxygen levels is important because it aids our understanding of the record of ocean circulation, climate and causes of extinctions as well as the evolution of marine organisms. The determination of the dissolved oxygen levels in the past ocean have been a matter of discussion for different researchers. Different criteria have been used in studying the dissolved oxygen levels. Akpan (1992, 1996) used macrofaunal evidence while Akpan (1985) and Savrda and Bottjer (1986, 1989) used the ichnological approach (intensity of sediment bioturbation) to study the changing oxygen levels. Berner and Raiswell (1983), Gautier (1986) and Kajiwara and Kaiho, (1992) used sulfur isotopes and organic carbon/sulfur ratios respectively to study dissolved oxygen levels. Rare element concentrations have also been used by Anderson et al. (1989) to study the dissolved oxygen level. Nyong and Ramanathan (1985), Petters (1980), Petters and Ekweozor (1982), Ukpong and Ekhalialu (2015) also study dissolved oxygen of the Cenomanian – Turonian sediment based on the recovered planktic and agglutinated foraminifera. Foraminiferal morphology, test size and wall thickness was applied for the study of the oxygen levels by the following authors: Harman (1964), Bernhard (1986), Kaiho (1988, 1989, 1991, 1992), Koutsoukos et al., (1990). However, the most sensitive indicators for better understanding of changing dissolved-oxygen levels in the past oceans are the benthic foraminifera as described by the Kaiho (1991, 1994 and 1999).

Dissolved oxygen levels in water are very important limiting factors for foraminifera survival. The study of Murray (2006) and Kaiho (1994, 1999) has shown that the presence of some foraminifera species and their sizes can be used to predict the ancient oxygen levels. Most foraminifera are tolerant and can withstand oxygen depletion than most meiofaunal and macrofauna as well as some hard-shelled taxa but not for a long period of anoxia (Murray, 2006) as consequences and can be fatal when conditions persist above six months (Moodley *et al.*, 1997). This is because of their low oxygen demand and high diffusion rate (Armstrong and Brasier, 2005).

1.1 Indicator of different oxygen environments

Benthic foraminiferal assemblages are influenced by the dissolved oxygen concentrations at the sediment-water interface and this plays a major role in their morphologic characteristics (such as size, wall thickness, porosity) as well as the taxa (genera and species) of foraminifera present. These morphologic and taxonomic differences have been quantified as a dissolved-oxygen index (Kaiho, 1994).

Kaiho (1994) examined the morphologic and taxonomic characteristics that affect the Benthic Foraminiferal Oxygen Index (BFOI) based on the relationship that exist between species composition / specific morphologic characters, oxygen levels and calcareous benthic foraminiferal (FOBC) microhabitat. He separated calcareous benthic foraminifera into three (3) categories of indicators (dysoxic : 0.1–0.3 ml/l, suboxic :0.3–1.2 ml/l, and oxic :1.2 ml/l). Table 1 presents the indicator benthic foraminifera of oxic, suboxic and dysoxic environments while Table 2 presents the interpretation of the oxygen index based on foraminifera (after Kaiho, 1994).

The following equations of Kaiho (1994) were used to obtain the Benthic Foraminiferal Oxygen Index (BFOI):

(1) When O is greater than 0, O/ (O+D) x 100 (where O and D are numbers of specimens of oxic and dysoxic indicators, respectively).

(2) When O equals zero and SD (S is the number of specimens of suboxic indicators) is greater than zero, I = [S/(S+D) – 1] x 50. The level of dissolved oxygen in the past environment can be determined by the benthic foraminifera oxygen index (BFOI) used by Kaiho (1994). Benthic foraminifera oxygen index (BFOI) is a quantitative estimate of the dissolved oxygen levels.

Table 1: Indicator benthic foraminifera of oxic, suboxic and dysoxic environments (after Kaiho 1994;1999)

Environments	Oxygen concentration (ml/l O_2)	Indicator benthic foraminifera	Morphological characteristics
Oxic	>1.5	Species of *Cibicidoides*, *Nuttallides*, *Stensioina*, *Gavelinella*, *Globocassidulina* *Quinqueloculina*	Thick walls, large tests, planoconvex, biconvex, rounded trochospiral, spherical, epifaunal under high oxygen bottom-water but absent in low-oxygen environment
Suboxic	0.3–1.5	Small specimens of oxic species, *Lenticulina*, *Nodosaria*, *Dentalina*, *Pleurostomella*, *Bulimina*, *Stilostomella*, *Uvigerina*, *Oridorsalis*, *Gyroidina*, *Hoeglundina, Valvulineria*	Small and/or thin walled, rounded planispiral, flt ovoid, spherical, biconvex trochospiral
Dysoxic	0.1–0.3	Species of *Bolivina*, *Chilostomella*, *Fursenkoina*, *Globobulimina, Bulimina*	Thin wall, small, flt or elongate tapered, high porosity tests
Anoxic	0 – 0.1	Barren of calcareous benthic foraminifera	-

Table 2: Benthic foraminifera oxygen index and the corresponding level of oxygen concentration (after Kaiho 1994)

Oxygen condition	Oxygen level (ml/l)	Oxygen index
High oxic	3.0–6.0+	50–100
Low oxic	1.5–3.0	0–50
Suboxic	0.3–1.5	−40 to 0
Dysoxic	0.1–0.3	−50 to −40
Anoxic `	0.0–0.1	−55

1.2 Species diversity patterns

The species diversity index adopted in this study is the Fishers- index developed by Fisher *et al.*, (1943) in a classic paper taking into account the species abundance as well as the number of species. Fisher index of species diversity is given as $\alpha = n_1:x$. X is a constant with a value of <1, n1=N(1-x), N denotes the number of individuals. The measure of the distribution of species abundance can be approximated using the Fisher's log series. The Fisher's log series used here is after Wright (1972).

Species diversity can also be useful in determining the dissolved oxygen levels. Low oxygenated environment demonstrate low species diversity (α<7) and they are dominated by 2-3 species comprising over 80 percent (80%) of the total number of individuals in the samples (Valchev, 2003).

1.3 Location of the study well

The study wells (wells C and F) are located in the Northern Delta depobelt of the Niger Delta which forms a segment of the Niger Delta petroleum province of Nigeria (figure. 1).

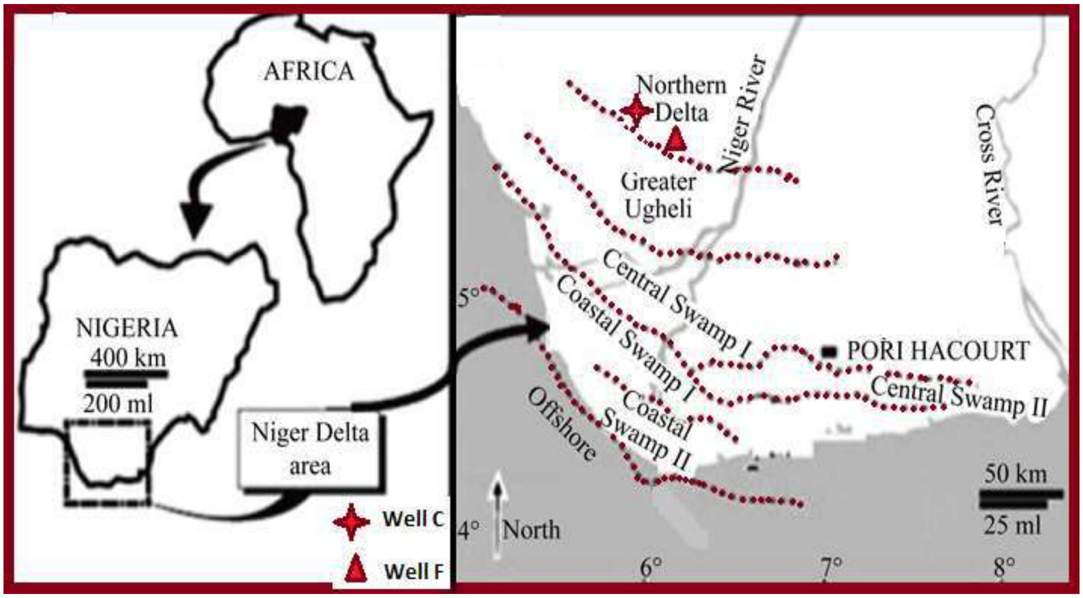

Figure 1: Map of the Niger Delta showing the depobelts and location of the study wells (C and F)

The Niger Delta basin is a prolific hydrocarbon province that contains enormous hydrocarbon both on the onshore, shallow and deep offshore areas and it is located between Latitudes 3° and 6° N and Longitudes 5° and 8° E respectively in the Gulf of Guinea, on the margin of West Africa (figure 2).

The geology of the Niger Delta is well documented. For further study on the Niger Delta the following papers can be consulted: Short and Stauble (1967), Evamy *et al.* (1978), Ejedawe (1981), Knox and Omatsola (1987) Petters (1979, 1981, 1982, 1983, 1984, 1995); Doust and Omatsola (1990), Stacher (1995), Reijers et al (1997), Reijers (2011), Ukpong *et al* (2017a, 2017b)

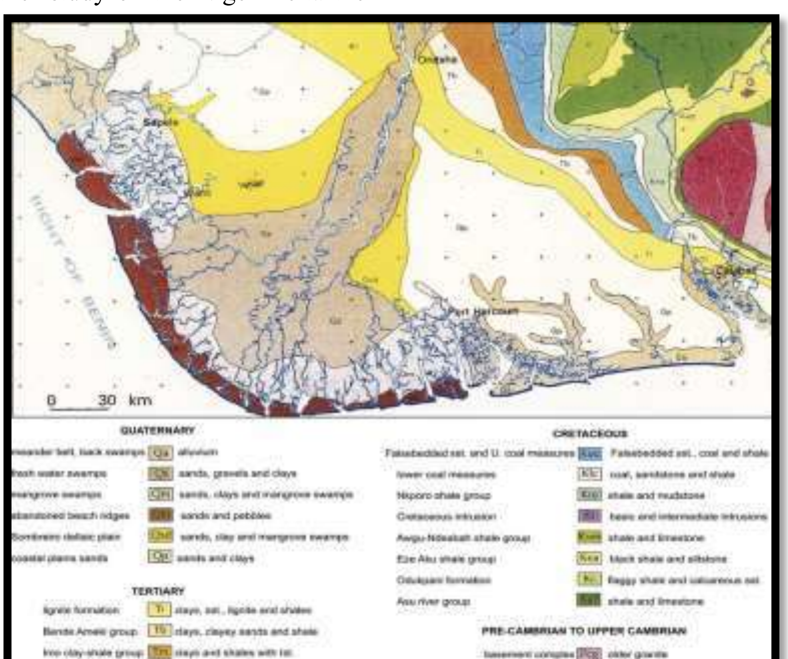

Figure 2. Geologic map of the Niger Delta (Reijers, 2011)

2. MATERIAL AND METHODS

2.1 Materials

Ditch cutting samples from the study wells (well C and well F) were obtained. A total of eighty (80) ditch cutting samples were used. Well C ranges from depth 2410m - 2800m consisting of thirteen (13) samples at 30metres interval whilst well F ranges from depth 2000m – 3320m consisting of sixty seven (67) samples at 20m interval.

2.2 Micropaleontological sample processing

One of the standard approaches for the foraminifera sample processing method was applied in this study. The anhydrous sodium carbonate procedure outline by Brasier (1980) and Armstrong and Brasier (2005) were utilized in the preparation of samples from wells C and F. The sample preparation is in three (3) phases: soaking, wet sieving and drying of residues. The residues obtained after the extraction of foraminifera from the prepared samples were properly stored in well labeled sample bags for lithologic/sedimentologic analysis. Identification of the foraminifera extracted from the samples was done by comparing picked forms with previously published forms.

3. RESULT AND DISCUSSION

3.1 Age determination

The recovered foraminifera from both wells are presented in biostratigraphic chart (fig 3 and 4). The recovered foraminifera was used to assigned Priabonian – Rupelian age to the study wells after careful analysis and interpretation. Details of this is presented elsewhere (Ukpong and Ekhalialu, in press)

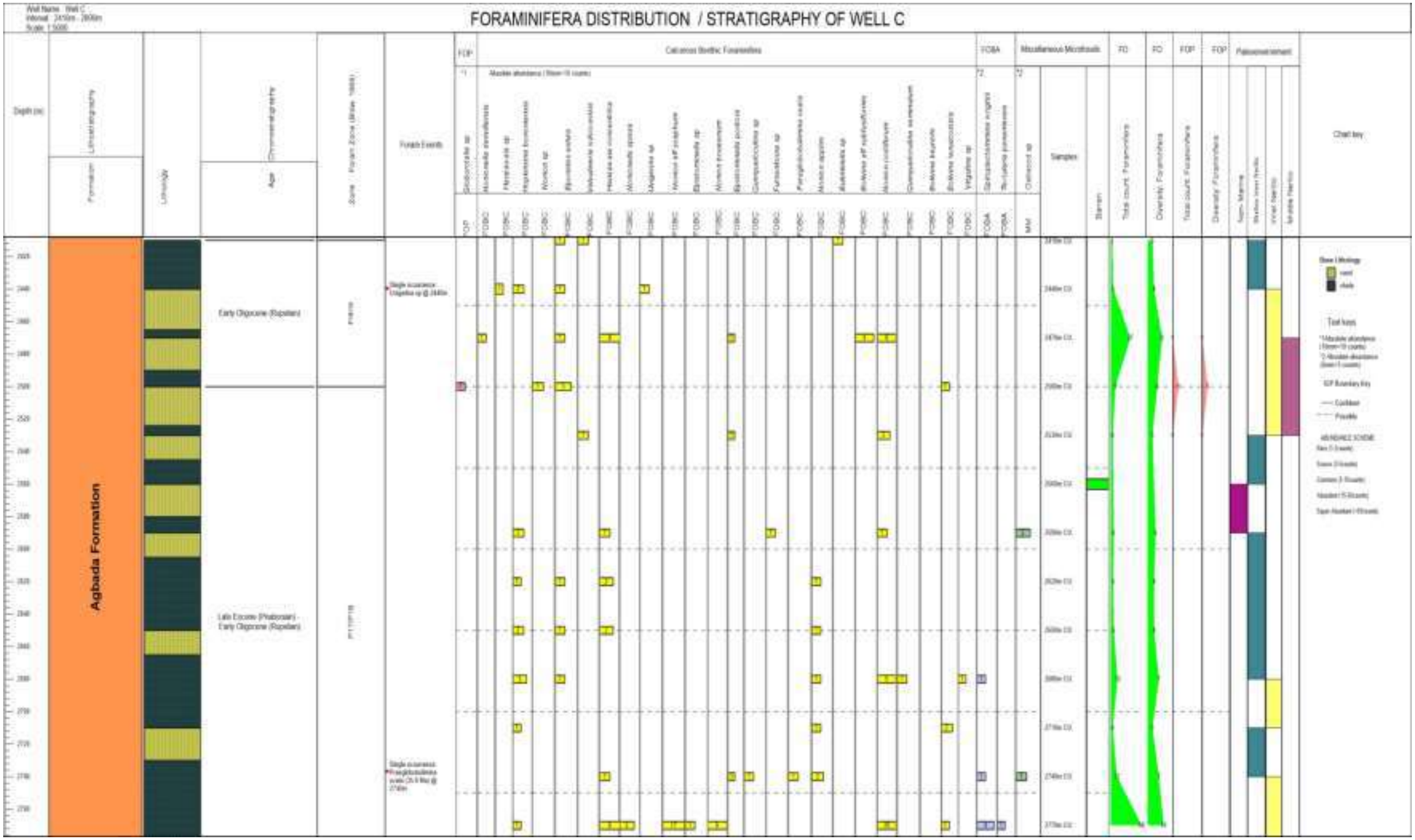

Figure 3. Foraminiferal chart of well C

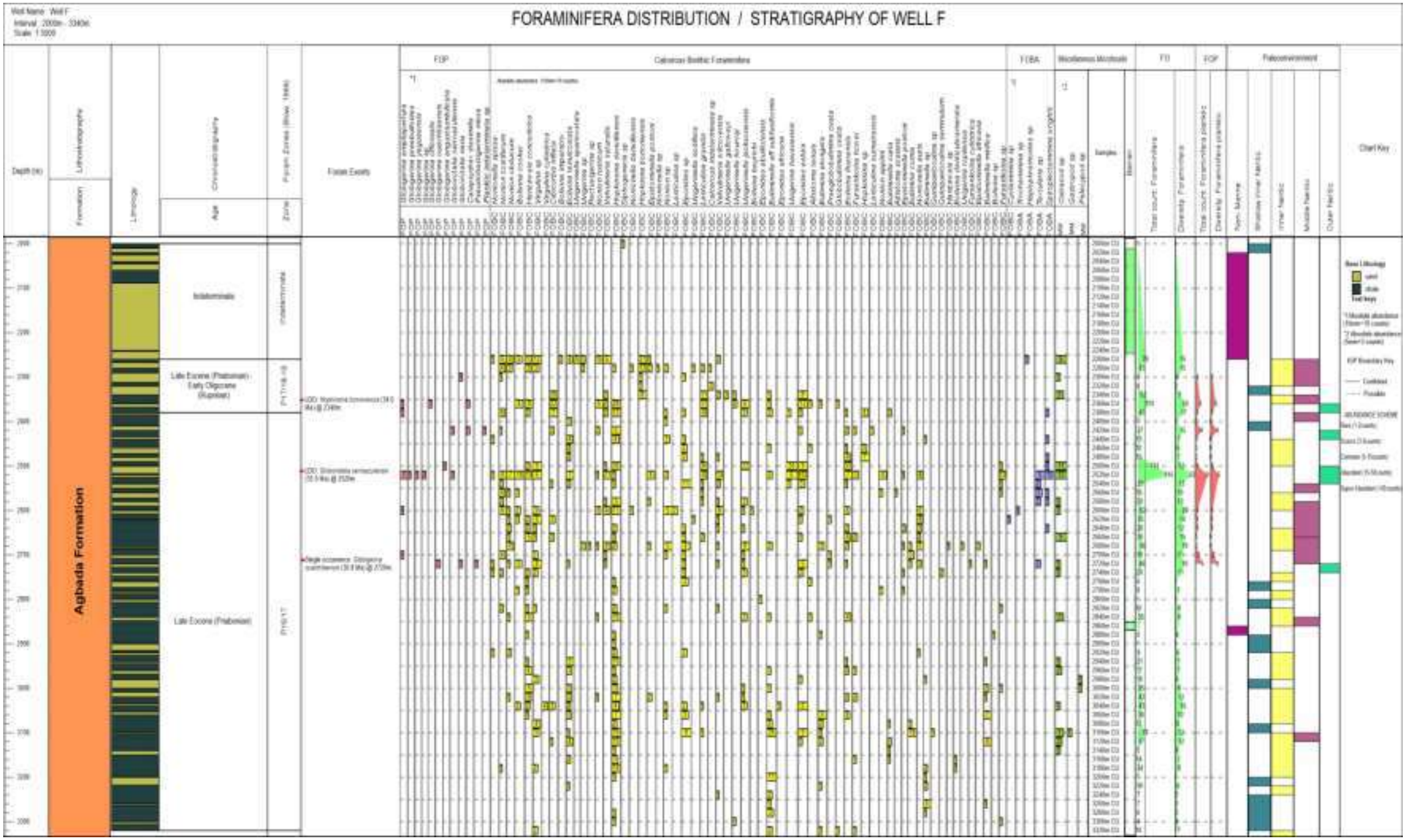

Figure 4. Foraminiferal chart of well F

3.1 Palaeo-oxygenation analysis of well C

The palaeo-oxygenation of well C is low (suboxic setting: 0.3 – 1.5ml/l) to anoxia (0-0.1ml/l) based on the calculated BFOI (Table 3 and figure 5 show the calculated BFOI and the BFOI plots for well C respectively). This suggests lack of availability of oxygen.

The samples in well C showed low – moderate diversity (α<5: figure 6) with low - high abundance which reflects variation from stressed low-oxygen conditions depicting periods of adverse environmental conditions. The studies of Murray (2006), Boltovskoy and Wright (1976) validate this position. The barreness of benthic foraminifera at depth interval 2560-2590m gave credence to the low oxygen conditions (Kaiho, 1994). The dominance of some foraminifera species (*Nonion costiferum* and *Nonion aff scaphum* at depth 2770-2800m and *Nonion costiferum*, *Nonion sp.* and *Hanzawaia concentrica* at depth interval 2470 -2500m) comprising over 80percent (80%) of the total foraminifera recovery at that levels is suggestive of low oxygenated settings (0.3-1.5ml/l). The presence of arenaceous forms such *Spiroplectammina wrightii* and *Textularia panamensis* further confirms the low oxygenation conditions. Furthermore, the study of Valchev (2003) supports this dissolved oxygen levels. The dominance of benthic foraminifera over the planktic foraminifera or the total absence of planktic foraminifera further supports this interpretation in most of the depth intervals (Armstrong and Brasier, 2005). The presence of only one planktic at interval 2500-2530m suggests low oxygen level that could inhibit the bloom of the planktic forms. The foraminifera species recovered from 2740- 2770m depth interval are characterized by foraminifera assemblages consisting of hyaline forms with good proportions of agglutinated and very few porcelaneous forms suggesting a low oxygenated setting (0.3-1.5ml/l). The study of Murray (2006) gives credence to this interpretation.

Table 3: Calculated BFOI for well C

Depth (m)	Suboxic indicator	Dysoxic indicator	BFOI
2410 – 2440	Absent	Absent	Absent
2440 – 2470	Absent	Absent	Absent
2470 – 2500	18	2	-5.0
2500 – 2530	6	1	-7.1
2530 – 2560	Absent	Absent	Absent
2560 – 2590	Barren	Barren	Barren
2590 – 2620	2	1	-16.7
2620 – 2650	Absent	Absent	Absent
2650 – 2680	Absent	Absent	Absent
2680 – 2710	Absent	Absent	Absent
2710 – 2740	1	2	-33.3
2740 – 2770	Absent	Absent	Absent
2770 – 2800	43	1	-1.1

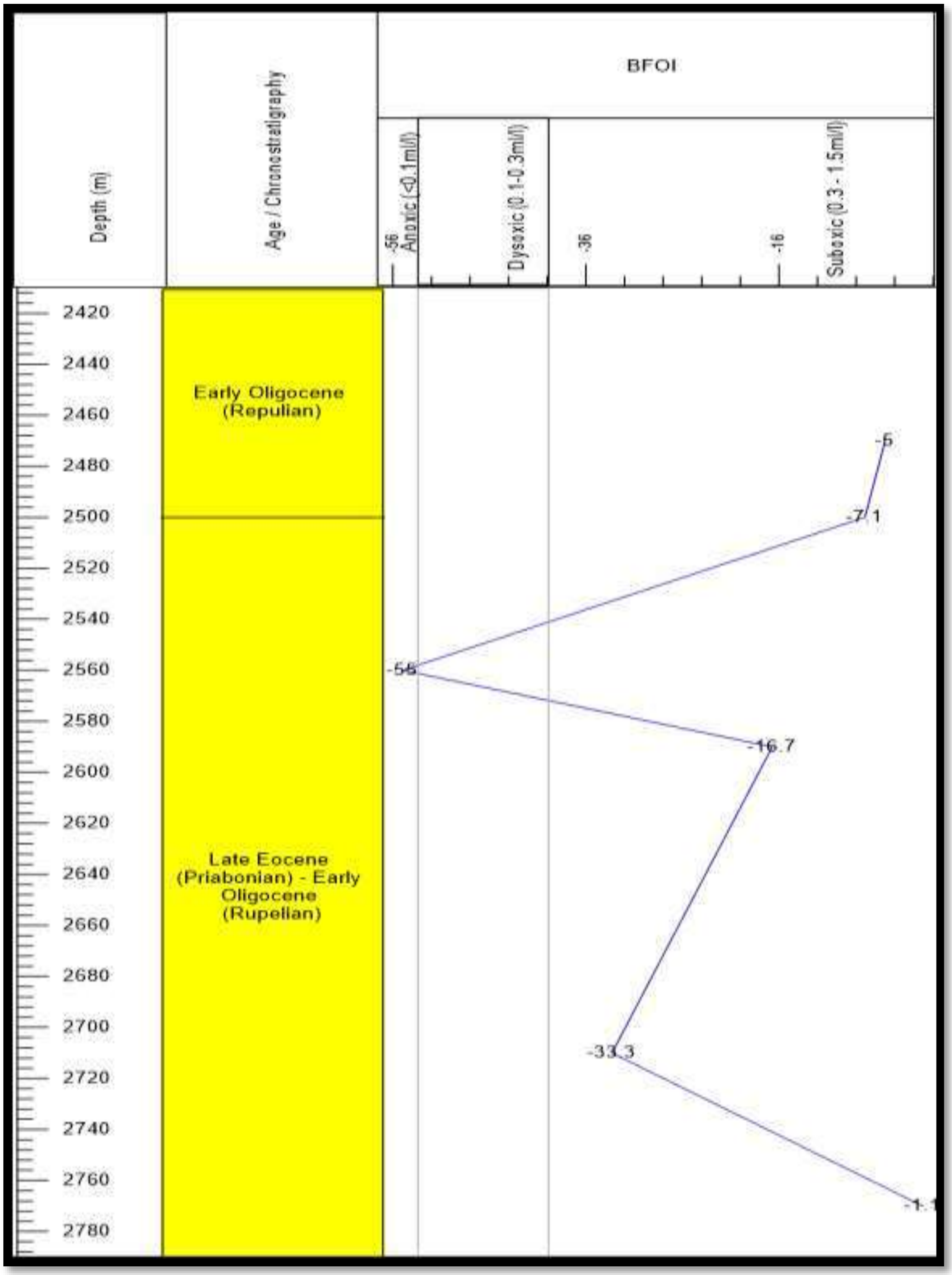

Figure 5: BFOI plot for well C

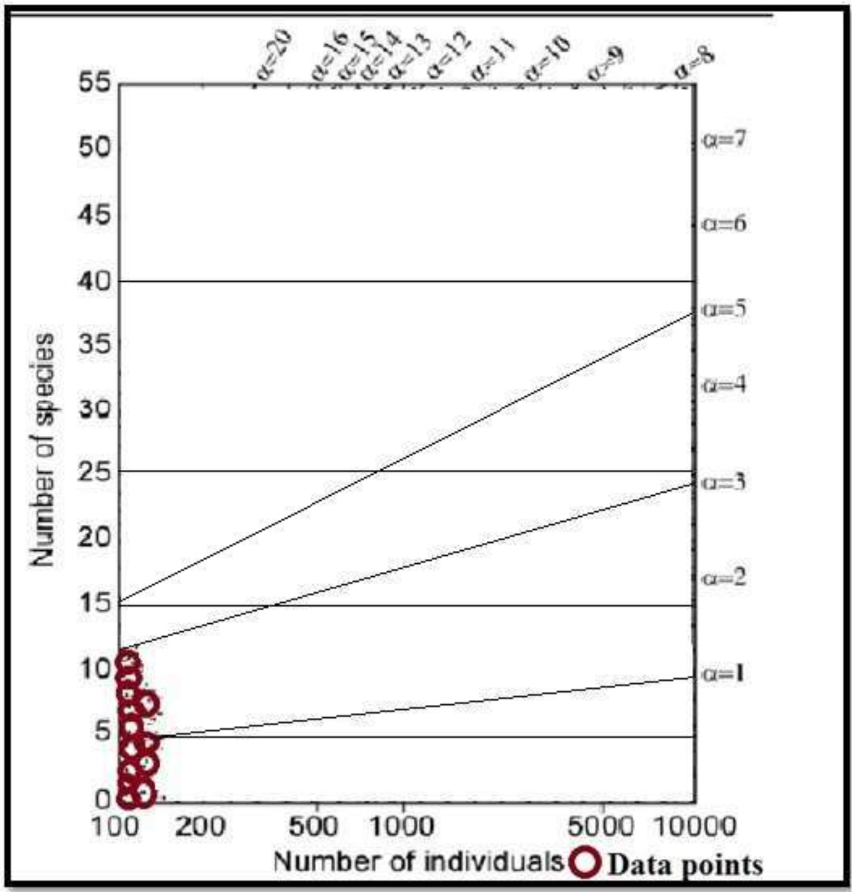

Figure 6: Fisher's log series plot for well C (after Wright, 1972)

3.2 Palaeo-oxygenation analysis of well F

The results of palaeo-oxygen analysis of well F indicates a range from dysoxic (0.1 – 0.3 ml/l) through suboxic (0.3 – 1.5ml/l) to anoxia (0-0.1ml/l) and oxic (>1.5ml/l) settings based on the calculated BFOI. Table 4 and figure 7 show the calculated BFOI and the BFOI plots for well F respectively, depicting periods of dissolved oxygen level fluctuations. The calculated Fisher's diversity of well F shows low - high diversity (α <5, α >5: figure 8) and low – high abundance variation which is attributed to periods of environmental pleasures (favorable oxygenated conditions) and the reverse (stressed low-oxygen conditions). The study of Murray (2006), Boltovskoy and Wright (1976) support the results of the dissolved oxygen levels obtained in this study. The low abundance and diversity of foraminifera species from depth intervals 2000-2020m, 2400-2420m, 2760-2780m, 2900-2920m, 2980-3000m, 3140-3160m 3200-3220m and 3240-3300m suggest low dissolved oxygen levels (dysoxic – suboxic settings). The dominance of some foraminifera species (*Hopkinsina bononiensis, Nonion rusticum* and *Hanzawaia concentrica* at depth interval 2260-2280m) comprising over 80 percent (80%) of the total foraminifera recovery and the presence of arenaceous form such as *Haplophragmoides sp* supports the low oxygen levels. The study of Valchev (2003) also gave credence to these interpretations. The dominance of benthic foraminifera over the planktic foraminifera in most of the samples further supports this interpretation (Armstrong and Brasier, 2005). The foraminifera species recovered from depth intervals 2260-2280m, 2380-2400m, 2440-2460m, 2480-2620m, 2640-2660m and 2720-2740m, is characterized by foraminifera assemblages that consist of either hyaline and agglutinated forms or hyaline and few porcelaneous forms in almost suggesting low oxygenated settings.

The even distribution of foraminifera species in the other samples (depth interval 2020-2260m and 2280- 2300m) points to moderate oxygenated conditions (Valchev, 2003). The presence of some planktic forms at depth intervals 2360-2380m, 2380-2420m, 2420-2440m, 2500-2520m, 2520-2540m, 2620-2640m and 2700-2720m suggests high oxygenation considering their strong affinities for oxygen while the barrenness of benthic foraminifera at depth intervals 2000-2240m and 2860-2880m point to an anoxic environment indicating periods of adverse environmental conditions (Kaiho, 1994).

Table 4: Calculated BFOI for well F

Depth	Oxic indicator	Suboxic indicator	Dysoxic indicator	BFOI index
2000	Barren	Barren	Barren	Barren
2020	Barren	Barren	Barren	Barren
2040	Barren	Barren	Barren	Barren
2060	Barren	Barren	Barren	Barren
2080	Barren	Barren	Barren	Barren
2100	Barren	Barren	Barren	Barren
2120	Barren	Barren	Barren	Barren
2140	Barren	Barren	Barren	Barren
2160	Barren	Barren	Barren	Barren
2180	Barren	Barren	Barren	Barren
2200	Barren	Barren	Barren	Barren
2220	Barren	Barren	Barren	Barren
2240	Barren	Barren	Barren	Barren
2260	Absent	33	9	-10.7
2280	Absent	Absent	Absent	Absent
2300	Absent	Absent	Absent	Absent
2320	Absent	Absent	Absent	Absent
2340	Absent	Absent	Absent	Absent
2360	Absent	28	16	-22.8
2380	Absent	15	1	-2.6
2400	Absent	Absent	Absent	Absent
2420	Absent	5	6	-25
2440	Absent	3	4	-28.6
2460	Absent	Absent	Absent	Absent
2480	Absent	2	3	-30
2500	Absent	84	34	-24.9
2520	Absent	78	54	-22
2540	Absent	6	4	-20
2560	Absent	10	2	-9.1
2580	Absent	Absent	Absent	Absent
2600	Absent	29	6	-7.5
2620	Absent	2	2	-25
2640	Absent	10	2	-8.3
2660	Absent	8	5	-13.8
2680	Absent	26	12	-15.8
2700	Absent	7	6	-23.1
2720	Absent	4	7	-35

2740	2	6	3	40
2760	Absent	Absent	Absent	Absent
2780	Absent	2	1	-16.6
2800	Absent	Absent	Absent	Absent
2820	Absent	4	2	-16.7
2840	Absent	5	4	-22.2
2860	Barren	Barren	Barren	Barren
2880	Absent	Absent	Absent	Absent
2900	Absent	Absent	Absent	Absent
2920	Absent	2	1	-16.7
2940	Absent	Absent	Absent	Absent
2960	Absent	Absent	Absent	Absent
2980	Absent	Absent	Absent	Absent
3000	Absent	1	19	-47.8
3020	Absent	4	24	-42.8
3040	Absent	6	14	-36.8
3060	Absent	Absent	Absent	Absent
3080	Absent	Absent	Absent	Absent
3100	1	2	23	4.2
3120	Absent	Absent	Absent	Absent
3140	Absent	Absent	Absent	Absent
3160	Absent	Absent	Absent	Absent
3180	Absent	2	4	-33.3
3200	Absent	Absent	Absent	Absent
3220	Absent	Absent	Absent	Absent
3240	Absent	1	4	-40
3260	Absent	Absent	Absent	Absent
3280	Absent	Absent	Absent	Absent
3300	Absent	1	3	-40
3320	Absent	Absent	Absent	Absent

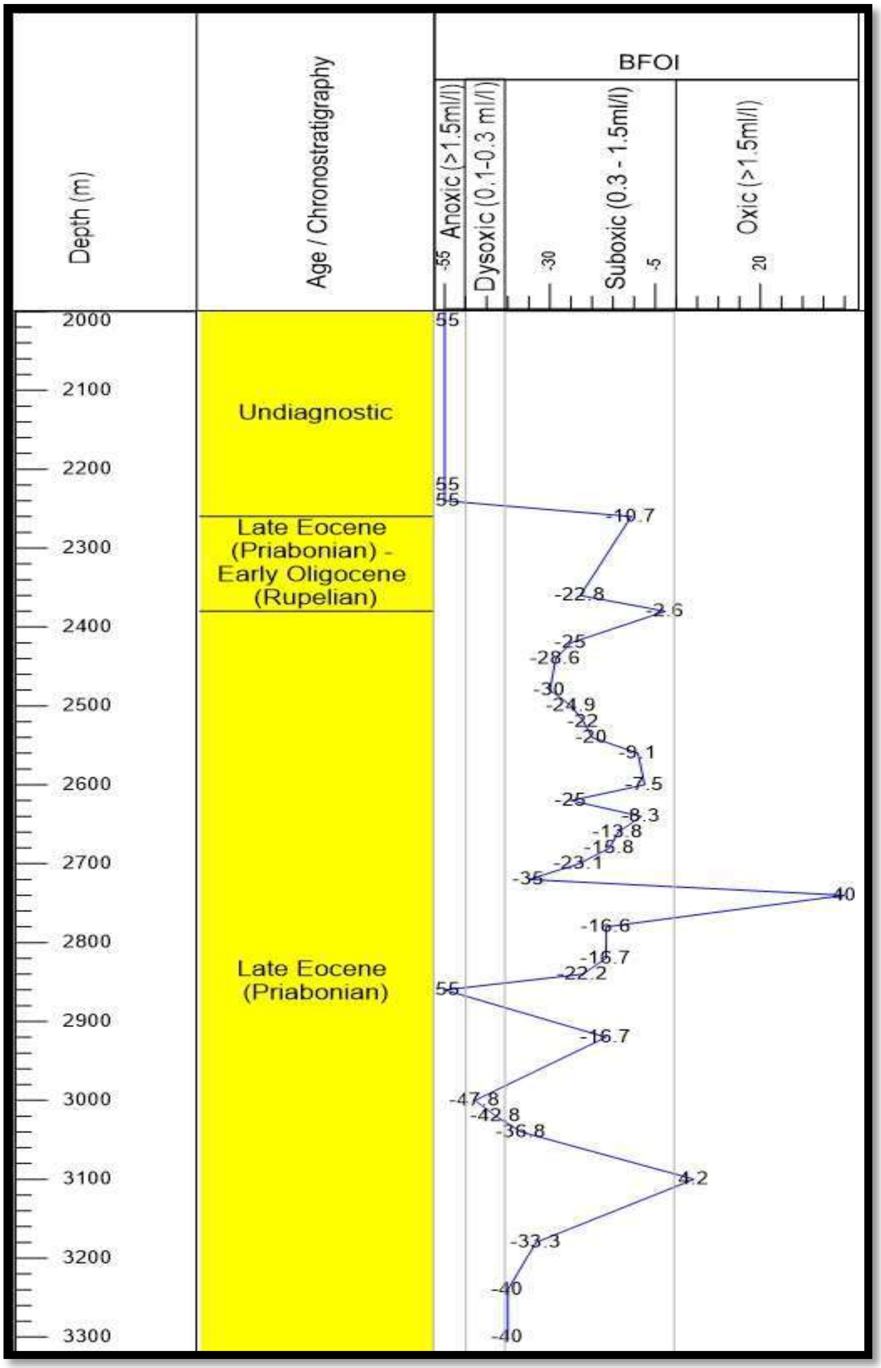

Figure 7: BFOI plot for well F

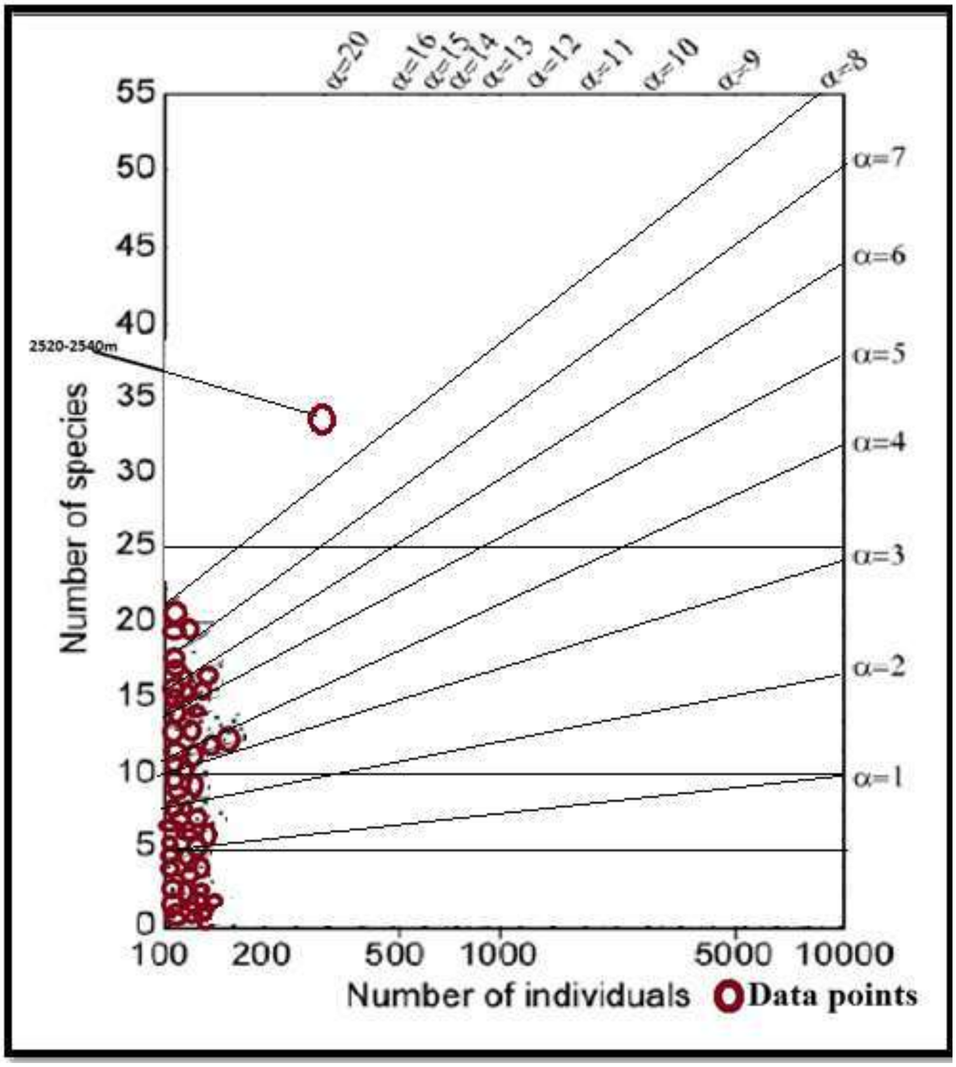

FIGURE 8: Fisher's log series plot for well F (after Wright, 1972)

4. SUMMARY AND CONCLUSION

This paper demonstrates the uses of morphologic and taxonomic differences for determining / quantifying the dissolved oxygen levels in the Niger Delta. The benthic foraminiferal oxygen index derived was used to explain the environmental conditions during the Priabonian – Rupelian times. The results of the study shows that the ancient dissolved oxygen levels appears to show an overall fluctuation from dysoxic (0.1 – 0.3 ml/l) through suboxic (0.3 – 1.5ml/l) to anoxic (0-0.1ml/l) and oxic (>1.5ml/l) settings based on the calculated BFOI and supported by the Fisher's diversity depicting periods of dissolved oxygen level fluctuations.

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