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Benthic foraminiferal morphogroups from the Oligocene – Early Pliocene, deep offshore southwestern Niger Delta

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Abstract

Morphogroup analysis of the Oligocene – Early Pliocene benthic foraminiferal assemblages of the deep offshore southwestern Niger Delta has been carried out from the study of four wells. The wells yielded highly abundant and diverse assemblages of both benthic and planktic foraminifera species. The benthic species were categorized into eighteen morphogroups based on their general test outline, chamber arrangement and mode of coiling. The morphogroups are the agglutinated tubular, unilocular (MG A); globular, single chambered (MG B1); coiled, flattened (MG B2); flattened or lenticular, planispiral and globular (MG B3); elongate, tapered (MG C1); milioline with agglutinated coat (MG C2); low trochospiral (MG D). The calcareous morphogroups are the flattened elongate (MG F); tapering or flaring, circular apertural view (MG G); cylindrical forms with circular apertural view (MG H); lenticular, biconvex, sharply angled tests (MG I); planoconvex, trochospiral forms (MG J); overall spherical or pyriform tests (MG K); trochospiral, broadly rounded periphery (MG L); flattened ovoid, biconvex, carinate periphery (MG M); trochospiral, biconvex tests (MG N); rounded planispiral compact tests (MG P) and flattened, elliptical, milioline tests (MG Q). Benthic foraminiferal species were also categorised based on their (supposedly) life position within the sediments as either epifaunal or infaunal. The epifaunal taxa belong to MGs B1, B2, B3, D, J, L, N and Q while the infaunal ones are species assigned to MGs A, C1, C2, F, G, H, K, M and P. Samples with relatively high abundances of infaunal morphogroups have been interpreted as rich in organic matter preserved under dysoxic condition ideal for the formation of hydrocarbon source rocks in the Niger Delta while high epifaunal abundances suggest oxygen rich, organic matter deficient sediments. The deep offshore southwestern Niger Delta consists of two major depositional facies based on interpretation from morphogroup distribution pattern, these are the (i) slope submarine fans and (ii) muddy submarine fans.

***Keywords*:** Morphogroup, Foraminifera, Niger Delta, Offshore, Oligocene, Pliocene.

Introduction

The term morphogroup has been defined by Murray *et al*. (2011) as the general groupings of analogous shapes or patterns of growth of foraminiferal tests without regard to taxonomy. Foraminiferal morphogroups can be differentiated based on certain morphological characteristics like test outline, chamber arrangement and mode of coiling. Morphogroups of benthic foraminifera were proposed by Jones and Charnock (1985) based on Recent faunas. Similar morphological groupings of fossil assemblages have been proposed in subsequent studies, so as to interprete paleoenvironmental conditions, such as trophic or oxidation-reduction conditions (Nagy, 1992; Nagy *et al*., 1995, 2009; Reolid *et al*., 2008, 2010, 2012). The studies of recent and ancient foraminiferal assemblages showed that the morphology of the foraminiferal test can be directly related to microhabitat and feeding strategies (Corliss, 1991).

The use of morphological categories in palaeoenvironmental analyses, rather than species, can be valuable because the morphological approach allows reliable comparisons of assemblages of different ages in that it reduces the effect of taxonomic and nomenclature inconsistences that could arise from one paleontologist to another. Such comparisons are of particular importance for accessing the habitats of fossil morphotypes by relating them to their Recent counterparts (Nagy, 1992). Although this vital paleoecological tool is not yet in use among Nigerian micropaleontologists and biostratigraphers, elsewhere around the world, the use of foraminiferal morphogroups in the interpretation of sedimentary environments has proven to be of considerable economic value. For instance, it has been used in "biosteering" through the submarine fan reservoir in the Andrew Field in the North Sea, so as to ensure optimum oil production (Murray *et al*., 2011). This study is intended to categorise the benthic foraminiferal assemblages of the offshore southwestern Niger Delta into morphogroups and to determine the paleoenvironmental implications of the morphogroup distribution patterns.

Geologic setting of the Niger Delta Basin

The Niger Delta province formed at the culmination of Late Jurassic to Early Cretaceous tectonism that was characterized by both block and transform faulting superimposed across an extensive Paleozoic basin during the breakup of the African and American paleocontinents (Tissot, *et al.*, 1980; Mascle, *et al.*, 1988). The fracture zone ridges subdivide the margin into individual basins, and, in Nigeria, form the boundary faults of the Cretaceous Benue – Abakaliki trough, which cuts far into the West African shield. The trough represents a failed arm of a rift triple junction associated with the opening of the South Atlantic (Burke *et al.*, 1971; Tuttle *et al.*, 1999). In the Niger Delta area, rifting commenced towards the close of the Jurrasic and continued into the Mid-Cretaceous and diminished altogether in the Late Cretaceous (Lehner and De ruiter, 1977).

The onshore part of the Niger Delta (Figure 1) is defined by the geology of southern Nigeria and southern Cameroon. The Benin flank (an east-northeast trending hinge line south of the West Africa basement massif) marks the northern boundary. The northeastern boundary is delineated by the Cretaceous rocks on the Abakaliki High and to the east-south-east by the Calabar Flank, a hinge line adjoining the Precambrian Oban Massif (Short and Stauble, 1967). The offshore boundary of the province is defined by the Cameroon volcanic line to the east, the eastern boundary of the Dahomey Basin to the west and the two kilometer sediment thickness contour or the 4000-meter bathymetric contour in areas where sediment thickness is greater than two kilometers to the south and southwest. The province covers 300,000km^2 and includes the geologic extent of the Tertiary Niger Delta petroleum systems (Tuttle *et al*., 1999).

Since the Eocene to the present, the Niger Delta has prograded southwestward to form depobelts that represent the most active segment of the delta at the various stages of its development (Doust and Omatsola, 1990). Kulke (1995) noted that these depobelts constitute one of the biggest regressive deltas in the world. Hospers (1971) reported a sediment volume of 500,000 km^3 for the delta. At the basin's depocenter sediment thickness is believed to reach an approximate thickness of 10,000 meters.

Materials and Methods

The materials for this study are ditch cutting samples obtained from four deep offshore wells (DPW1, DPW2, DPW3 and DPW4 see Table 1) located within the southwestern part of the Niger Delta and made available by the Department of Petroleum Resources. The conventional foraminiferal sample processing technique was employed. Thirty grams (30 g) each of dried sample were weighed and 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 to allow for easy picking of foraminifera specimens. The foraminifera contents were painstakingly picked into cellules with the aid of stereoscopic binocular microscope.

Species level identification of benthic foraminifera was carried out using relevant bibliography including Loeblich and Tappan (1964, 1988) and Agip S.P.A. Foraminifera Padani (1982). Morphogroups were defined from a large data set of benthic species recovered from four deep offshore wells based on test outline, chamber arrangement and mode of coiling of the species. The foraminifera specimen identified in this study are repository in the Museum of the Department of Geology, Obafemi Awolowo University, Ile-Ife, Nigeria.

Table 1: Sample interval, total depth and number of samples analysed in DPW-1, DPW-2, DPW-3 and DPW-4 wells

Well	Sample Interval (m)	Total Depth (m)	Number of Samples
DPW-1	12	4060	171
DPW-2	18	3600	104
DPW-3	12	3000	176
DPW-4	10	2630	149

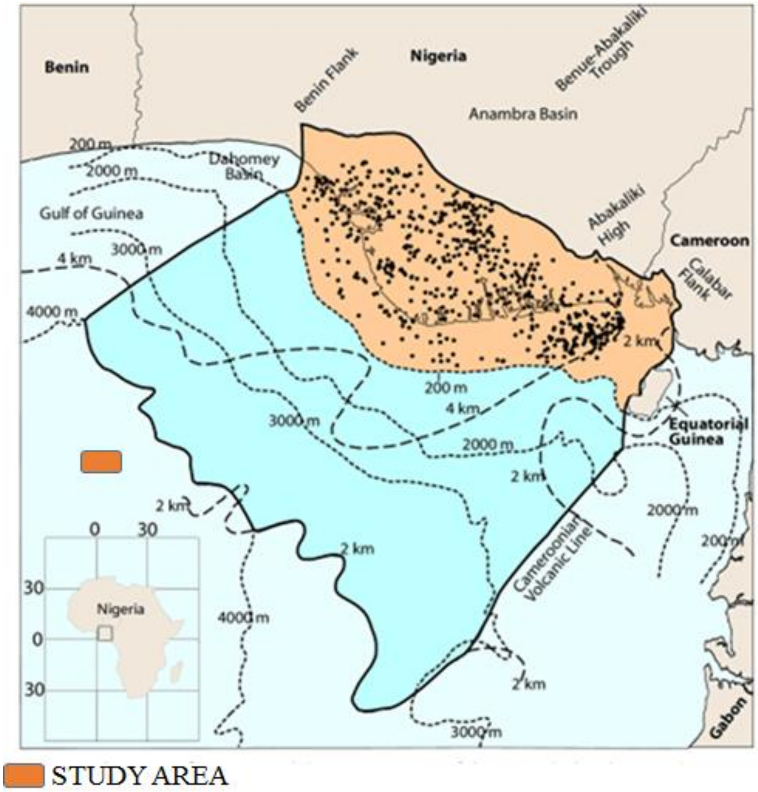


Figure 1: Geological Map of the Niger Delta Showing the Approximate Location of the Study Area (modified from Petroconsultant, 1996). The precise locations of the wells were not given for proprietory reason.

Results and Discussions

Biostratigraphy and age

The planktic foraminiferal species recovered alongside the benthic forms dated the studied section Oligocene to early Pliocene. Globally recognized biozones within this chronostratigraphic interval were delineated based on these assemblages. Typical Oligocene planktic assemblages such as *Globorotalia opima nana, Globorotalia opima opima, Cassigennella chipolensis, Pseudohastigerina micra, Globigerina ampliapertura* and benthic species: *Eponides berthelothianus, Uvigerina sparsicostata, Hopkinsina bononiensis* and *Hanzawaia concentrica* were recovered from the basal section of DPW-1 and DPW-2. In the DPW-1 the P18/P19 early Oilgocene biozone was delineated with Last Appearance Datum (LAD) of *Pseudohastigerina micra* and the middle to late Oligocene P20/N1 – P22/N3 was recognized within the basal section of the DPW-1 based on the LAD of *Pseudohastigerina micra* at 3690 m (base) and the LAD *Globorotalia opima opima* at 3582 m (top). The P22/N3 is the oldest biozone in the DPW-2 (Fig.3). The Miocene N4 – N17 biozones were identified within the intervals 2464 - 3582 m of DPW-1 and 2509 – 3582 m of DPW-2 wells based on the occurrence of diagnostic planktic species which include *Globigerinoides primordius, Orbulina universa, Globorotalia fohsi fohsi, G. fohsi peripheroacuta, G. continuosa, G. acostaensis, G. merotumida / plesiotumida, G. mayeri, G. margaritae margaritae, G. margaritae primitiva, Hastigerina siphonifera, Globigerina nepenthes* and *Globigerinoides obliquus extremus.*

Benthic species within the Miocene section include *Brizalina mandoroveesis, Epistominella vitrea, Eponides eshira, Uvigerina sparsicostata, Lenticulina grandis, Stilostomella monilis, Heterolepa pseudoungeriana, Globocassidulina subglobosa, Gyroidina neosoldanii, Spirosigmoilina oligocaenica, Cancris auriculus, Cassidulina laevigata, Uvigerina peregrina, Planulina arinimensis, Cibicorbis inflata, Saacammina complanata, Ammodiscus glabratus, Alveolophragmium crissum, Cyclammina cancellata, Valvulina flexilis, Textularia parvula, Trochammina proteus and Karreriella siphonella.* The N17 (late Miocene) is the oldest biozone in DPW-3 and DPW-4. The early Pliocene N18 and N19 zone were identified in DPW-2, DPW-3 and DPW-4 based on the occurrence of planktic species such as *Globotalia margaritae primitiva, Globorotalia margaritae margaritae, Globorotalia miocenica, Globorotalia tumida, Globorotalia pseudopima, Globorotalia menardii cultrata, Globorotalia crassaformis, Globorotalia exilis Spheroidinellopsis seminulina, Globigerinoides ruber, Neogloboquadrina dutertrei,* and *Globorotaloides variabilis.*

Morphogroup classification

The four wells used in this study yielded very abundant and highly diverse assemblage of foraminiferal taxa. One hundred and eighty-one calcareous benthic and forty-eight agglutinated species were recovered from the well sections. These species have been categorized into eighteen foraminiferal morphogroups. The agglutinated taxa were classified following the morphogroup classification schemes of Jones (1986) and Nagy *et al.* (2009). Seven agglutinated morphogroups designated alphabetically from A to D were identified based on these schemes. Two of these groups, B and C were further subdivided into three (B1, B2 and B3) and two (C1 and C2) subgroups respectively.

The calcareous benthic assemblages of the sections are very much diverse that not all the species could be assigned to existing classification schemes (e.g. Jones and Charnock, 1985; Nagy *et al.*, 2009 and Reolid *et al.*, 2012). Jones (1986) and Nagy *et al.* (2009) identified agglutinated morphogroups A – D while Reolid *et al.* (2008) and Reolid *et al.* (2012) identified agglutinated groups A – E and calcareous groups F – K. In this present study, we have not only identified all of the morphogroups (except morphogroup E) described in the earlier studies, five (5) additional calcareous benthic foraminiferal morphogroups have also been differentiated. These are morphogroups L, M, N, P and Q. The distinguished foraminiferal morphogroups are related to their trophic strategies and microhabitats.

Description of the morphogroups

The eighteen morphogroups defined within the studied sections of the wells are described below and summarily presented in Figures 2a-c.

Agglutinated foraminiferal morphogroups

1) Morphogroup A (MG-A): This group comprises foraminifera species with tubular and unilocular test adapted to stationary epifaunal / infaunal habitat and suspension feeding. The group is represented by *Bathysiphon* in all the studied well sections. The tubular and unilocular forms are relatively sparsely represented in DPW-1, DPW-2 and DPW-4. Although occurrences of 15 – 30% were recorded in few samples, the morphogroup A constitutes <5% of the benthic population in some samples and is generally absent in most samples. In DPW-3, abundances of up to 50% were recorded in some samples. Members of the group were largely recovered from middle Miocene to early Pliocene section.

2) Morphogroup B1 (MG-B1) consists of various globular single chambered forms assumed to be largely passive detritus feeders. This group represented by the genus *Saccammina* in this study is believed to be adapted to epifaunal to shallow infaunal habitat. Apart from interval 3530 – 3627 m (early Miocene) of DPW-1 where the group constitutes between 12 – 83% of benthic foraminifera, the globular single chambered morphology is

generally sparsely represented across the wells. They are totally absent in many samples particularly in the N18 – N19 (early Pliocene) biozones.

3) Morphogroup B2 (MG-B2): The group comprises coiled, usually flattened forms adapted to epifaunal / epiphytal mode of life. Members of this group are assumed to be active detritus feeder. Morphogroup B2 is represented by the genera *Glomospira*, *Ammodiscus* and *Arenoturrispirilina*. The coiled flattened group follows a pattern of distribution akin to that of morphogroup A in all the wells.

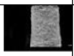
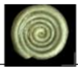
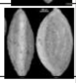
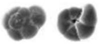
MORPHOGROUP	TEST SHAPE	POSITION WITHIN SEDIMENT	FEEDING STRATEGY	REPRESENTATIVE GENERA
A 	Tubular, unilocular	Epifaunal / infaunal	Suspension feeder	*Bathysiphon*
B1 	Globular, single chambered	Epifaunal	Detritus feeder	*Saccammina*
B2 	Coiled, usually flattened forms	Epifaunal / epiphytal	Detritus feeder	*Ammodiscus* *Glomospira*
B3 	Flattened or lenticular, planispiral & globular tests	Epifaunal	Herbivore, detritivore	*Haplophragmoides, Cyclammina, Alveolophragmium*
C1 	Elongate, tapered test	Infaunal	Detritivore, Bacteria scavenger	*Textularia* *Spiroplectammina*
C2 	Milioline test with agglutinated coat	Infaunal	Detritus feeder	*Sigmoilopsis*
D 	Low trochospiral forms	Epifaunal	Herbivore	*Trochammina*

Figure 2a: Agglutinated foraminiferal morphogroups in deep offshore southwestern Niger Delta differentiated according to test morphology. Inferred microhabitat (i.e. position within sediment), feeding strategies and representative genera are also indicated.

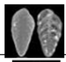
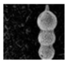
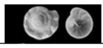
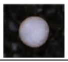
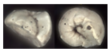
MORPHOGROUP	TEST SHAPE	POSITION WITHIN SEDIMENT	FEEDING STRATEGY	REPRESENTATIVE GENERA
F 	Elongate flattened test	Infaunal	Deposit feeder	*Bolivina, Brizalina Plectofrundicularia*
G 	Tapering or flaring, circular in apertural view	Infaunal	Deposit feeder	*Uvigerina, Bulimina, Buliminella*
H 	Cylindrical forms with circular apertural view	Infaunal	Deposit feeder	*Nodosaria, Dentalina, Stilostomella*
I 	Lenticular, biconvex, sharply angled test	Epifaunal	Deposit feeder	*Lenticulina*
J 	Planoconvex trochospiral forms	Epifaunal	Herbivore	*Heterolepa, Hanzawaia*
K 	Overal spherical or pyriform tests	Infaunal	Detritus feeder	*Oolina, Globobulimina, Lagena*
L 	Trochospiral, broadly rounded periphery	Epifaunal	Herbivore	*Gyroidina, Gyroidinoides*

Figure 2b: Calcareous benthic foraminiferal morphogroups (F to L), Inferred microhabitat (i.e. position within sediment), feeding strategies and representative genera in the Deep Offshore Southwestern Niger Delta.

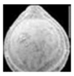
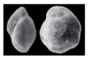
MORPHOGROUP	TEST SHAPE	POSITION WITHIN SEDIMENT	FEEDING STRATEGY	REPRESENTATIVE GENERA
M 	flattened ovoid, biconvex, carinate periphery	Infaunal	Deposit feeder	*Fissurina, Cassidulina*
N 	Trochospiral, biconvex test	Epifaunal	Herbivore	*Eponides, Ammonia, Cancris, Hoeglundina*
P 	Rounded planispiral compact test	Infaunal	Deposit feeder	*Florilus, Nonion, Nonionella*
Q 	Flattened, elliptical, milioline test	Epifaunal	Herbivore	*Quinqueloculina, Ptychomiliola, Spiroloculina, Pyrgo Sigmoilina*

Figure 2c: Calcareous benthic foraminiferal morphogroups (M to Q), Inferred microhabitat (i.e. position within sediment), feeding strategies and representative genera in the Deep Offshore Southwestern Niger Delta.

4) Morphogroup B3 (MG-B3): The group consists of flattened or lenticular essentially planispiral and globular streptospiral and trochoid forms adapted to epifaunal habitat. They are probably active herbivores or detritivores, browsing on weed or grazing for bacteria and perhaps using a more opportunistic omnivorous feeding strategy when the exigencies of the environment so dictate (Jones, 1986). Members of the group recorded within the studied wells include *Haplophragmoides, Ammobaculites, Cribrostomoides, Recurvoides, Alveolophragmium* and *Cyclammina.* Although the group is relatively rare in early Miocene samples, by and large, they occur abundantly in older (Oligocene – late Miocene) strata.

5) Morphogroup C1 (MG-C1) comprises a number of disparate taxa of varying chamber arrangements and coiling modes. They are characterised by an elongate test form which maintains volume while reducing cross-sectional area. This morphology is ideally adapted to an infaunal mode of life and a passive detrital or bacterial scavenging strategy. Genera represented include *Eggerella, Textularia, Suggrunda, Martinotiella, Karreriella, Valvulina, Verneuilina, Reophax, Gravellina, Spiroplectammina, Gaudryina, Tritaxia, Hormosina, Dorothia, Ammobaculites* and *Ammomarginulina.* Members of this group are moderately abundant in Miocene section of the studied sites but are generally rare in Oligocene and early Pliocene samples.

6) Morphogroup C2 (MG-C2): The group consists only of certain milioline or non-agglutinating taxa that possess agglutinating coats. Representative genera which include *Sigmoilopsis* and *Miliammina* are presumed to be infaunal. Species belonging to this group are generally rare across the studied wells.
7) Morphogroup D (MG-D) is represented by low trochospiral forms, a morphology thought to be associated with herbivorous feeding strategy and epifaunal mode of life. Active forms are envisaged moving over substrates eating as they go, while passive forms feed by pseudopodial extension. Example is *Trochammina* spp. The low trochospiral forms are common in Oligocene to late Miocene section of the studied wells but generally rare in early Pliocene section.

Calcareous benthic foraminiferal morphogroups
8) Morphogroup F (MG-F): Comprises elongate, flattened forms, ovate to compressed in cross-section and has parallel to subparallel sides. The group includes uniserial, biserial and palmate tests. This morphology is believed to be adapted to infaunal mode of life and active deposit feeding strategy. It is represented by *Bolivina, Brizalina* and *Plectofrondicularia.* In DPW-1, morphogroup F (MG-F) occurs in significant proportion at the base i.e. the early

Oligocene P18/19 interval. These elongate flattened forms constitute about 80% of the benthic foraminiferal population at 3776 m, but decline considerably within late Oligocene P20/N1 to late Miocene N16 interval ebbing to < 1% at some horizons within this interval. The group represented chiefly by *Bolivina* attains a second peak abundance within the latest Miocene (N17) to early Pliocene (N18) section. In DPW-2, morphogroup F constitutes <1% of the benthic population in most of the samples within the late Oligocene (P22/N3) to late Miocene (N17) section. However, in the overlying N18 – N19 early Pliocene strata, the group reached its peak abundance making up to 80% in some samples. Although the Oligocene to middle Miocene was not sampled in DPW-4, the late Miocene (N17) to early Pliocene (N19) distribution pattern of the elongate flattened group (MG-F) in DPW-4 is similar to the pattern observed in DPW-1 and DPW-2 wells. The group attains its maximum abundance in the N18 - N19 interval. However, this morphogroup is generally rare in DPW-3.

9) Morphogroup G (MG-G): This tapering, or flaring group is circular in apertural view and has tapering sides. Many triserial and multiserial forms are placed here. This morphogroup represented by *Uvigerina, Bulimina, Fursenkoina, Praeglobobulimina, Buliminella, Siphouvigerina, Uvigerinella, Reussella, Siphogenerinoides, Robertinoides, Virgulina, Altistoma* and *Hopkinsina* is adapted to infaunal microhabitat. The tapering or flaring, biserial and triserial forms follow a distribution pattern similar to that of MG- F but are generally more abundant in all the four wells with *Uvigerina* and *Siphouvigerina* being the dominant genera.

10) Morphogroup H (MG-H): This morphogroup consists of cylindrical forms with circular apertural views and parallel sides. Both rectilinear and arcuate uniserial forms are included in this group. Also, most fusiform species are categorized in this group. This morphological group is adapted to infaunal microhabitat. They are active deposit feeders, herbivores and bacterial scavengers. Representative genera include *Rectuvigerina, Nodosaria, Stilostomella, Dentalina, Pleurostomella, Marginulina, Amphycorina, Pseudonodosaria, Virginulina, Allomorphina* and *Pseudoglandulina.* The MG- H constitute < 5% of the benthic foraminiferal forms in most of the samples analysed in DPW-1. The group peaked to 24% and 16% within N9 (3167 m) and N18 (2112 m) zone respectively. The distribution pattern is similar in DPW-2, DPW-3 and DPW-4 with maximum abundance in the early Pliocene N18 zone.

11) Morphogroup I (MG-I): This lenticular group has biconvex morphology with sharply angled or carinate peripheries. It includes some planispiral and coiled biserial forms. This morphology is believed to be adapted to active deposit feeding strategy and epifaunal mode of life. The genus *Lenticulina* is a good example of members of this group. The lenticular biconvex forms are relatively few. In many of the samples, they represent <3% of the total

benthic foraminifera. The group has peak abundances in N17 / N18 zones across the four wells. An early Oligocene peak abundance was observed in DPW-1.

12) Morphogroup J (MG-J): The planoconvex group includes both spiroconvex and umbilicoconvex trochospiral forms. Ideally, a deeply convex side and a planar side are exhibited, but strictly planar forms rarely occur. The group is essentially herbivores with epifaunal mode of life. Examples in this study include *Cibicides, Anomalinoides, Hanzawaia, Heterolepa, Cibicidoides, Planulina* and *Cibicorbis.* The planoconvex forms are relatively common and fairly abundant in all the wells except within the early to middle Miocene interval where the group is either absent or constitute <5% of the benthic foraminiferal population.

13) Morphogroup K (MG-K): This group has overall spherical or pyriform morphology and includes multilocular or unilocular tests approaching spherical shapes or having three axis of nearly equal lengths. This morphology is adapted to infaunal microhabitat. Typical genera include *Oolina, Lagena, Globobulimina, Pullenia, Sphaeroidina, Globocassidulina, Baggina* and *Guttulina.* The group is sparsely represented in DPW-1 and DPW-2, constituting <3% of the total benthic foraminifera in most samples. The percentage abundance increased marginally in DPW-3 and DPW-4 especially within the N18 (early Pliocene) interval with *Globocassidulina subglobosa* being the most abundant member of the group.

14) Morphogroup L (MG-L): This group consists of forms with trochospiral mode of coiling and broadly rounded periphery. The representative genera *Gyroidina* and *Gyroidinoides* are believed to be epifaunal. The trochospiral rounded periphery forms are also sparsely represented in many of the samples, however occasional abundance spikes of between 10 -55% were observed in the N17 – N18 zonal interval across DPW-1, DPW-2, DPW-3 and DPW-4 wells. The group is absent in most samples.

15) Morphogroup M (MG-M): It is characterized by flattened ovoid test, usually biconvex with carinate periphery. Members of this morphotype are supposed to be adapted to an infaunal lifestyle. *Fissurina* and *Cassidulina* are representative genera. Although, the biconvex carinate forms are generally poorly represented in the wells, abundance peaks of 14 – 16% occur in a few samples within the N17 – N18 (late Miocene – early Pliocene) zone. An exceptionally high abundance of approximately 43% was recorded at 3142 m in DPW-1.

16) Morphogroup N (MG-N): The group includes tests with trochospiral mode of coiling and biconvex morphology. They are characterized by sharply angled to narrowly rounded periphery. Representative genera include *Ammonia, Epistominella, Cancris, Oridosalis,*

Ceratobulimina, Hyalina, Heoglundina, Laticarinata, Eponides and *Anomalinoides.* This group is believed to be adapted to epifaunal mode of life. The trochospiral biconvex forms are well distributed and appreciably represented in the studied wells. They form between 20 – 50% of the total benthic foraminifera within the late Miocene – early Pliocene and Oligocene intervals but are sparsely distributed in the middle Miocene.

17) Morphogroup P (MG-P): The group comprises rounded planispiral forms with compact tests, planispirally arranged chambers and broadly rounded periphery. The genera belonging to this group are supposed to be infaunal. Examples in this study include *Elphidium, Melonis, Florilus, Nonion, Nonionella, Pullenia* and *Anomalina.* Except for sample 1982 m of DPW-2 in which the MG-P constitutes 33%, the group is generally represented in very low abundance across the wells. The rounded planispiral forms were not recovered in most samples.

18) Morphogroup Q (MG-Q): This group consists of forms with flattened tests, elliptical outline and milioline chamber arrangement. They are active deposit feeders, herbivores and detritivores with epifaunal life style. Examples are *Quinqueloculina, Spiroloculina, Sigmoilina, Pyrgo, Triloculina, Spirosigmoilina* and *Ptychomiliola.* The milioline forms occur scantily in the offshore southwestern Niger Delta. This scanty occurrence may not be unconnected with oxygen deficiency at the deep offshore. The milioline tests are more or less non porous, hence mitochondrial gaseous exchange is hampered especially in oxygen deficient environment.

The percentage distribution of the morphogroups are presented in Figures 3a – 6b

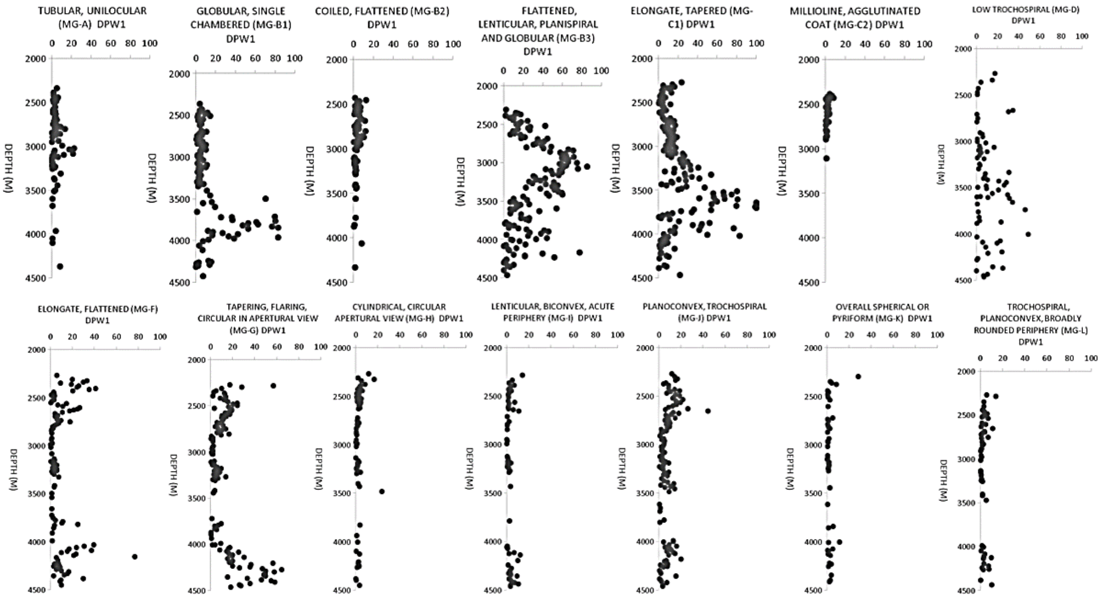


Figure 3a: Distribution of benthic foraminiferal morphogroups (MG-A to L) in DPW1, deep offshore Southwestern Niger Delta. Morphogroups are defined based on shape and chamber arrangement of foraminiferal tests. Percentage of each morphogroups is plotted for each sample. Morphogroups (MG) A-D are agglutinated forms, while MG F-L are calcareous.

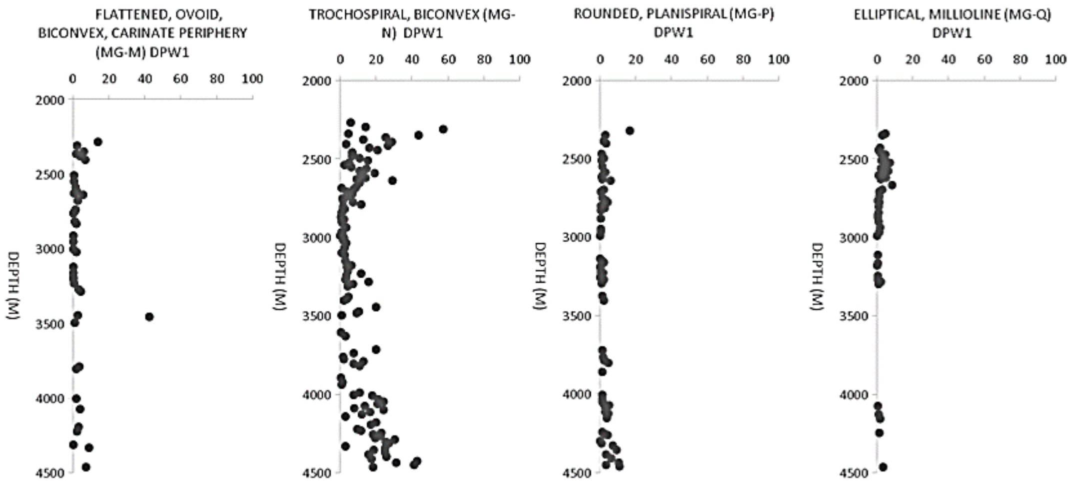


Figure 3b: Distribution of benthic foraminiferal morphogroups (MG-M to Q) in DPW1, deep offshore Southwestern Niger Delta. Morphogroups are defined based on shape and chamber arrangement of foraminiferal tests. Percentage of each morphogroups is plotted for each sample. Morphogroups (MG) M-Q are calcareous.

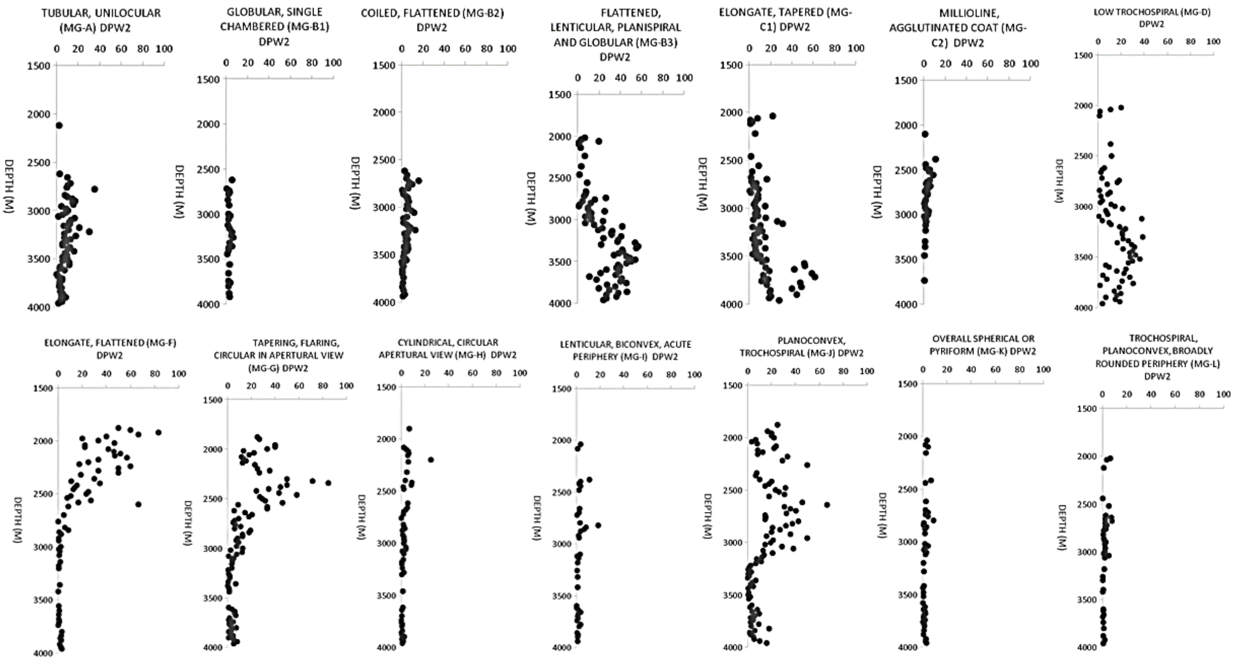


Figure 4a: Distribution of benthic foraminiferal morphogroups (MG-A to L) in DPW2, deep offshore Southwestern Niger Delta. Morphogroups are defined based on shape and chamber arrangement of foraminiferal tests. Percentage of each morphogroups is plotted for each sample. Morphogroups (MG) A-D are agglutinated forms, while MG F-L are calcareous.

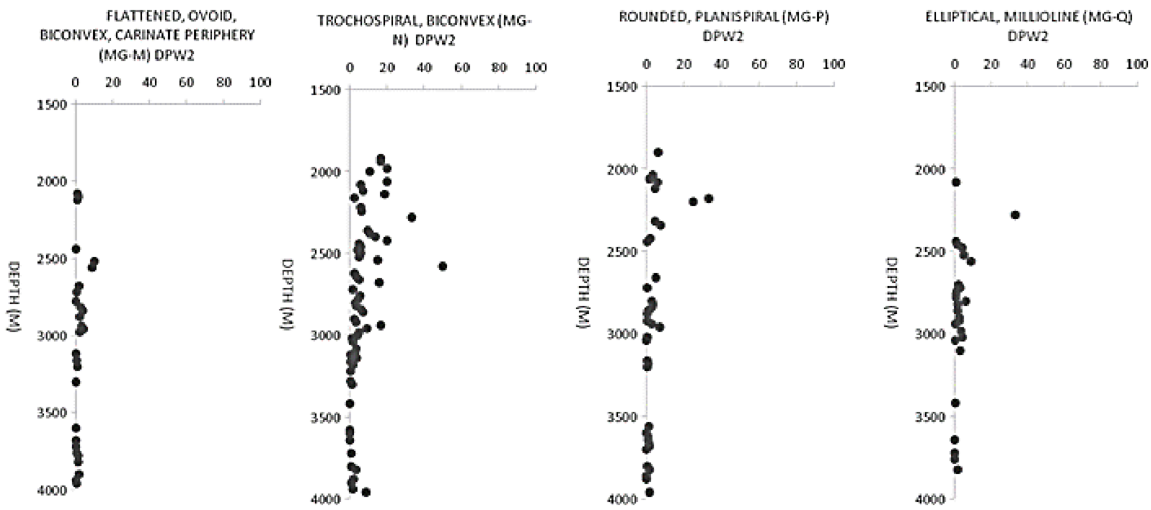


Fig. 4b: Distribution of benthic foraminiferal morphogroups (MG-M to Q) in DPW2, deep offshore Southwestern Niger Delta. Morphogroups are defined based on shape and chamber arrangement of foraminiferal tests. Percentage of each morphogroups is plotted for each sample. Morphogroups (MG) M-Q are calcareous.

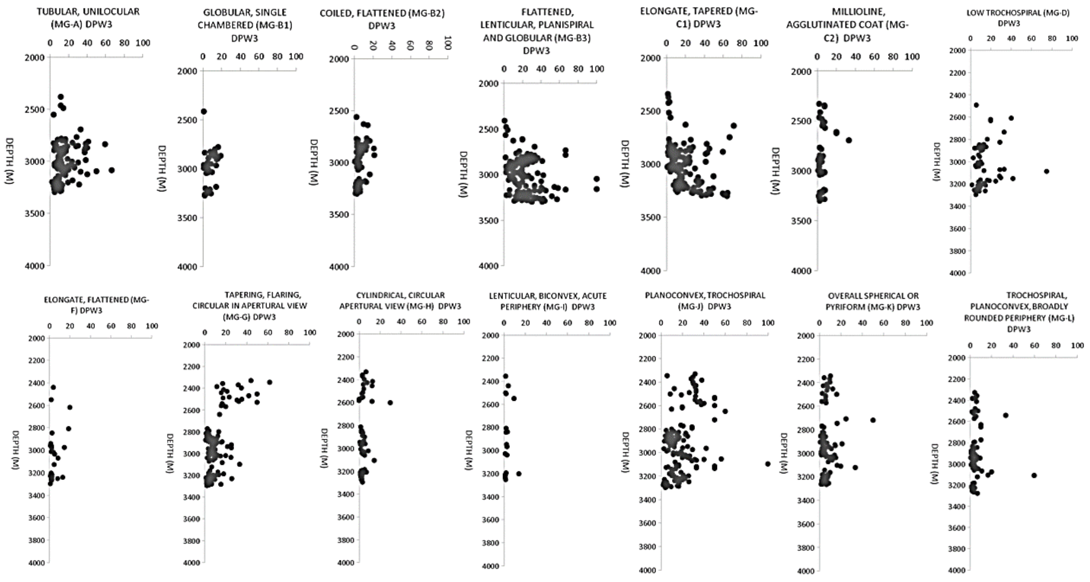


Figure 5a: Distribution of benthic foraminiferal morphogroups (MG-A to L) in DPW3, deep offshore Southwestern Niger Delta. Morphogroups are defined based on shape and chamber arrangement of foraminiferal tests. Percentage of each morphogroups is plotted for each sample. Morphogroups (MG) A-D are agglutinated forms, while MG F-L are calcareous.

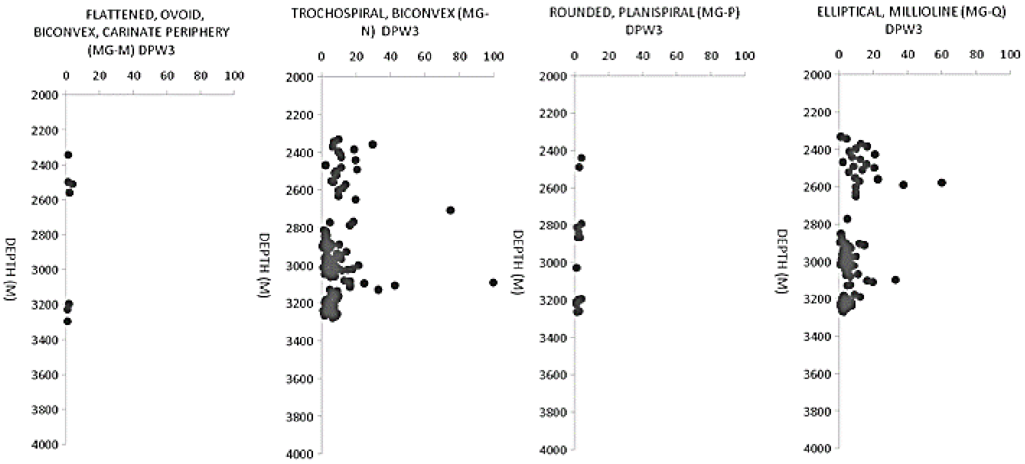


Figure 5b: Distribution of benthic foraminiferal morphogroups (MG-M to Q) in DPW3, deep offshore Southwestern Niger Delta. Morphogroups are defined based on shape and chamber arrangement of foraminiferal tests. Percentage of each morphogroups is plotted for each sample. Morphogroups (MG) M-Q are calcareous.

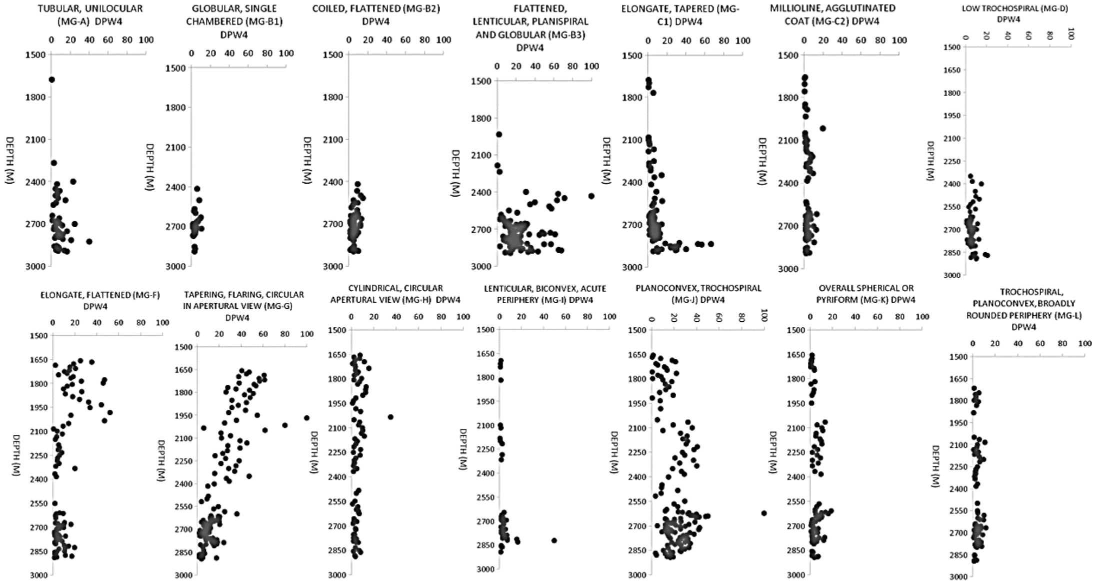


Figure 6a: Distribution of benthic foraminiferal morphogroups (MG-A to L) in DPW4, deep offshore Southwestern Niger Delta. Morphogroups are defined based on shape and chamber arrangement of foraminiferal tests. Percentage of each morphogroups is plotted for each sample. Morphogroups (MG) A-D are agglutinated forms, while MG F-L are calcareous.

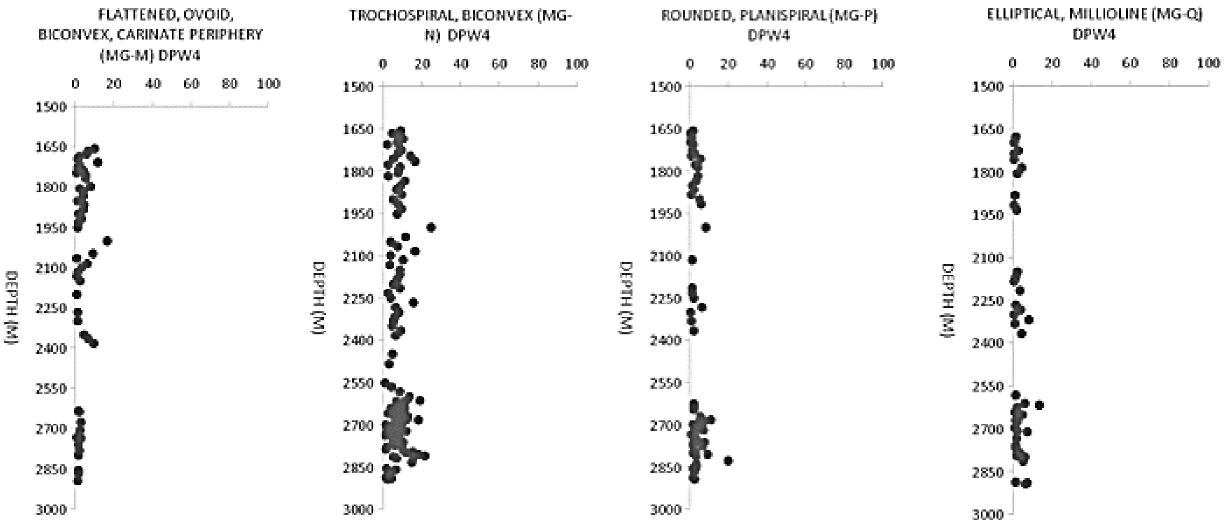


Figure 6b: Distribution of benthic foraminiferal morphogroups (MG-M to Q) in DPW4, deep offshore Southwestern Niger Delta. Morphogroups are defined based on shape and chamber arrangement of foraminiferal tests. Percentage of each morphogroups is plotted for each sample. Morphogroups (MG) M-Q are calcareous.

Some of the recovered species belonging to these morphogroups are listed in Tables 1 and 2 below;

Table 2: Species of epifaunal benthic foraminiferal morphogroups in the deep offshore Southwestern Niger Delta.

MORPHOGROUP	SPECIES
B1	*Saccammina complanata, Saccammina atlantica.*
B2	*Glomospira gordialis, Ammodiscus glabratus, Arenoturrispirillina* spp.
B3	*Cyclammina spp., Haplophragmoides narivaensis, H. obliquicameratus, Trochamminoides* spp.*, Cyclammina cancellata, Cyclammina*cf. *minima, Alveolophragmium crassum.*
D	*Trochammina* spp.*, Trochammina proteus.*

I	*Lenticulina inornata, L. curvisepta, L. rotulata, L. grandis, L. crassa.*
J	*Cibicidoides pseudoungeriana, Hanzawaia strattoni, H. mantaensis, Cibicides floridana, Heterolepa bellincioni, H. concentrica, Planulina arinimensis, Cibicides lobatulus, Planulina auris.*
L	*Gyroidina neosoldanii, Gyroidinoides umbonatus.*
N	*Epistominella vitrea, Cancris auriculus, Ammonia beccarii, Laticarinina pauperata, Ceratobulimina contraria, Globocassidulina oblonga, Hoeglundina elegans, Eponides eshira, Anomalinoides* spp.
Q	*Pyrgo depressa, Quinqueloculina microcostata, Q. seminulum, Triloculina gibba, Sigmoilina sigmoidea, Spirosigmoilina oligocaenica, Spiroloculina canaculinata.*

Table 3: Species of Infaunal benthic foraminiferal morphogroups in the deep offshore Southwestern Niger Delta

MORPHOGROUP	SPECIES
A	*Bathysiphon* spp.
C1	*Spiroplectammina wrightii, S. biformis.*
C2	*Sigmoilopsis schlumbergeri, Milliammina* spp.
F	*Bolivina isidroensis, Bolivina scalprata miocenica, Brizalina aenariensis, B. mandoroveensis, B. interjuncta, B. ihuoensis, Bolivina beyrichi, Plectofrundicularia.*spp.
G	*Bulimina exilis, B. inflata, Fursenkiona schreibersiana, Paeglobobulina ovata, Uvigerina mantaensis, Bulimina aculeata, B. costata, Uvigerina peregrina, U. asperula, U. subperegrina, Siphouvigerina auberiana attenuata, Praeglobobulimina affinis, P. pupoides, Bulimina alazaensis,*

	B. marginata, Reusella spinulosa, Buliminella multicamerata, Uvigerinella sparsicostata, Altistoma scalaris, Virgulina tenuis, Rectobulimina mexicana, Hopkinsina bononiensis.
H	*Stilostomella monilis, Rectuvigerina multicostata, Nodosaria* spp., *Pleurostomella alternans, Dentalina aciculata, Marginulina costata, Amphycorina scalaris, Pseudoglandulina comatula, Virgulina leguma, Pseudonodosaria conica.*
K	*Globobulimina pyrula, Lagena* spp., *Lagena clavata, Pullenia bulloides, Sphaeroidina bulloides, Globocassidulina subglobosa, Praeglobobulimina ovata.*
M	*Cassidulina norcrossi, Cassidulina neocarinata, Cassidulina crassa, Fissurina piriformis, Fissurina marginata.*
P	M*elonis padanum, M. pompilloides, M. soldanii, Nonionella* spp., *Nonionella auris, N. turgida, Cornuspira carinata, Nonion* spp., *Florilus boueanum,. Pullenia quinqueloba.*

Significant morphogroups distribution patterns

The calcareous morphogroups are categorised into two: epifaunal and infaunal taxa. The epifaunal category are morphogroups I, J, L, N and Q while morphogroups F, G, H, K, M and P constitute the infaunal category. Scatter plot representation of the abundance of calcareous infaunal and epifaunal morphogroups shows distinct cyclicity and antiphase relationship across the three wells (Figure 6). Peak maxima or peak abundances of infaunal taxa were observed in the wells. Among the infaunal forms, morphogroups F and G are more significant in that they constitute up to about 80 – 100 percent of the total calcareous benthic assemblage at certain intervals across the studied section. This pattern of dominance is well pronounced in the uppermost (late Miocene – early Pliocene) section of the wells and also in the lowermost (early Oligocene) section of DPW – 1. The early Oligocene section of DPW – 1 was not encountered in the other three wells.

The morphogroup J (epifaunal) occurs in constant frequency and appreciable proportions, showing peak abundance >20% in most samples. Agglutinated morphogroups B3 and C1 show relatively high abundance throughout the studied wells but decline considerably at the topmost section of the wells. Morphogroups F and G exhibit similar pattern of fluctuating frequency which is in antiphase with the abundance patterns of agglutinated morphogroups (particularly B3 and C1). The expansion in the abundance of the agglutinated morphogroups is coincident with decline in calcareous morphogroups abundance. The possible causes of this expansion in agglutinated morphogroups relative to their calcareous counterpart in the Niger Delta may include shoaling of the CCD (causing dissolution of calcareous tests) and a significant decline in phytoplankton productivity. The twin effects of carbonate tests dissolution and drastic reduction in the amount of organic matter available to the calcareous faunas may have been responsible for this decline. The agglutinated faunas seems to have a kind of trophic strategy adaptive to conditions of reduced labile organic matter. Moreover, agglutinated forms do not require $CaCO_3$ to secrete their tests, hence they tend to blossom under conditions that are not favorable to their calcareous foraminifera counterparts.

Paleoecological Interpretations

The analysis of foraminiferal morphogroups is a useful tool in paleoecological interpretations. Several authors have interpreted various aspects of paleoenvironment using the morphologies of foraminiferal tests. Sen Gupta and Machain Castillo (1993) noted the predominance of elongate, infaunal benthic foraminifera (i.e. morphogroups F and G in this study) in low oxygen conditions. Oxygenation level in sediments is strongly associated with organic matter content. In oligotrophic environments where sedimentary organic matter is low, virtually all carbon are oxidized through microbial aerobic activity. Koho *et al.* (2007) observed a positive correlation between benthic foraminiferal abundance and organic matter content of sediments. According to Koho *et al.* (*op. cit*) this relationship is especially strong for calcareous taxa and weak for agglutinated taxa suggesting that calcareous morphogroups are more sensitive to organic matter input than their agglutinated counterparts. The relationship between organic matter content, oxygenation level and microhabitat (either epifaunal or infaunal) of benthic foraminifera have also been described by Jorrisen *et al.* (1995). These authors noted that, in food limited (organic matter deficient) and well oxygenated environments, the benthic foraminiferal assemblage shows preference to living on surface sediments due to low food supply and consists predominantly of epifaunal (shallow dwelling) morphogroups specialized to live under these conditions. In eutrophic environments where food supply (in form of organic matter) is abundant and sediment pore water oxygen content is essentially reduced, the benthic foraminiferal community is dominated by infaunal morphogroups.

The dominance of infaunal morphogroups at the topmost sections (early Pliocene) of the wells and basal section of DPW – 1 and DPW-2 (Oligocene to early Miocene) suggests low sediment pore water oxygen content occasioned by relatively high organic matter input. Taxa belonging to the infaunal morphogroups F and G (e.g. *Bolivina*, *Bulimina* and

Uvigerina) have been reported to occur in high abundance in hydrocarbon seeps and are considered to be well adapted to high organic, very low oxygen conditions (Akimoto *et al*., 1994; Sen Gupta *et al*., 1997; Rathburn *et al.*, 2000; Bernhard *et al*., 2001, Hill *et al.*, 2003). Intervals of epifaunal dominance suggest well oxygenated sediment and low organic matter content. Resultant residues of samples from which dominance of morphogroups F and G were recorded in this study also contain abundant carbonaceous detritus. The most consistent morphologic characteristic of foraminiferal genera (the infaunal morphogroups e.g., *Bolivina*, *Chilostomella*, *Fursenkoina*, and *Globobulimina*) from oxygen deficient (dysoxic) environments of intense oxygen minimum zone (OMZ) is the possession of thin wall. This coupled with the high surface area to volume ratios of these morphotypes and their high-porosity may provide for improved mitochondrial oxygen uptake (Sen Gupta and Machain-Castillo, 1993). Infaunal taxa are assumed to prefer low-oxygen habitats because of a decrease in dissolved-oxygen content downward in the near-surface sediments (Corliss and Chen, 1988; Corliss and Emerson, 1990).

Common morphologic characteristics of benthic species in oxic (oxygen rich) environments of lowered oxygen minimum zone include thick walls and large tests. Oxic indicators are genera belonging to morphogroups I, J, L, N and Q. They live as epifaunal under high oxygen bottom-water conditions but are rare in low-oxygen environments (Kaiho, 1994). Such taxa are characterized by planoconvex, biconvex and rounded trochospiral test shapes (e.g., *Heterolepa*, *Ammonia*, *Eponides* and *Cibicidoides*) and by large, thick-walled miliolids (e.g. *Quinqueloculina* and *Spiroloculina*). Under intermediate conditions where organic matter is relatively abundant and oxygen level is moderate, a well-developed vertical distribution of species consisting both epifaunal and infaunal morphogroups can be observed. The dominance of infaunal morphogroups (e.g. morphogroups F and G) at the topmost sections of the wells and the basal section of DPW-1 and DPW-2 suggest low sediment pore water oxygen content occasioned by relatively high organic matter input. *Uvigerina*, a morphogroup G and an infaunal genus indicate increased export productivity and delivery rates of organic matter to the sea floor (Gupta and Thomas, 1999; Berger *et al.*, 2002). Streeter and Shackleton (1979) suggested that the distribution of *Uvigerina peregrina* (which was recovered abundantly from the wells) is controlled by the oxygen content of bottom water, with the species preferring low oxygen water. In contrast, Miller and Lohmann (1982) suggested that the organic carbon content of sediments was the primary factor controlling the distribution of this species. They reported that *Uvigerina peregrina* prefers sediments with high organic carbon content.

Organic rich sediments are potential oil source beds (Demaison and Moore, 19719). Foraminifera from modern hydrocarbon seep environments have been studied in the Gulf of Mexico (Sen Gupta *et al*., 1997), Nothern California area (Rathburn *et al.*, 2000), offshore Japan (Akimoto *et al*., 1994), Montery, California (Bernhard *et al*., 2001) and Santa

Barbara Channel, California (Hill *et al.*, 2003). These studies have shown that particular foraminiferal taxa belonging to morphogroups F, G (infaunal) and the epifaunal morphogroup N (e.g. *Bolivina, Bulimina*, *Uvigerina,* and *Epistominella*) may be adapted to the high organic, low oxygen reducing environments of methane seeps. Kaminski (1985) noted that deep water agglutinated foraminiferal assemblages in modern dysaerobic environments are often dominated by tapered, elongate morphotypes (i.e. morphogroup C1). These were considered as infaunal in life habit. Species belonging to morphogroups F, G and N in this study are associated with the Pliocene hydrocarbon source beds of the Niger Delta.

Bandy (1960) noted that a general correlation exists between benthic foraminiferal morphology and sedimentary facies. Severin (1983) identified four depositional facies on the basis of the external morphologies of 45 benthic foraminiferal species in the Texas Coast. The identified morphogroups in this study can be related to certain depositional facies within the Niger Delta sequence. Intervals with peak abundance / dominance of agglutinated morphogroups such as B3, C1 and D are interpreted as correlating to slope / submarine fans (high energy facies) in the offshore Niger Delta. Agglutinated foraminifera have been noted to show strong preference for and adaptation to high energy environments (Milam and Anderson, 1981; Kaminski, 1985). The morphogroup J consists principally of species that are able to survive high energy environment by attaching to substratum. Sections with dominance of morphogroups F and G in association with >20% peak abundances of any of morphogroups B3, C1 and J are suggested to indicate muddy submarine fan with relatively high organic matter content. Murray (2006) reported some species belonging to morphogroups F, G and K to be adapted to and abundant in muddy sediments.

Conclusions

The recorded abundant and diverse foraminferal assemblages from the studied section of the wells permitted the differentiation of the benthic taxa into eighteen morphogroups. Based on their morphologies, the benthic assemblage were adapted to two mode of life - epifaunal and infaunal. The relative abundance of epifaunal and infaunal groups is suggestive of the degree of organic matter content and pore water oxygen level of the sediments. Intervals of peak abundance of infaunal morphogroups correlate to increased organic matter content and low sediment pore water oxygen level conditions. Thus, early Pliocene (upper sections) of DPW-1, DPW –2, DPW-3 and DPW-4 and the Oligocene to early Miocene (lower part) of DPW – 1 were interpreted as intervals of relatively high organic matter and low sediment pore water oxygen level suggesting the prevalence of dysoxic condition within these intervals / periods.

The Niger Delta huge hydrocarbon accumulation was formed consequent upon the prevalence of this dysoxic condition. The middle to late Miocene sediments are rich in pore water oxygen content (i.e. prevalent oxic condition) and probably deficient in organic matter based on the dominance of the epifaunal taxa over the infaunal morphogroups. Peak abundances of infaunal morphogroups (F, G and K) are suggestive of organic, muddy (shaly) sediments. High energy facies; slope and submarine fans have been suggested from peak abundances of agglutinated morphogroups B3, C1 and calcareous epifaunal morphogroup J.

Plate 1: **1:**. *Textularia laminata* x 40 **2**. *Florilus* ex.gr. *costiferum* x 50 **3**. *Quinqueloculina lamarckiana* x 50 **4**. *Amphycorina scalaris* x 40 **5**. *Fursenkoina schreibersiana* x 40 **6.** *Plectofrondicularia* sp**.** x 40 **7.** *Hanzawaia mantaensis* x 40 **8.** *Oridosalis umbonatus* x 50 **9.** *Boliviva* sp. x 40 **10.** *Ammonia beccarii* x 40 **11.** *Florilus atlanticus* x 40 **12.** *Lenticulina inornata* x 60 **13.** *Bolivina isidroensis* x 40 **14.** *Ammonia beccarii* x 40 **15.** *Lagena striata* x 40 **16.** *Gyroidinoides neosoldanii* x 40

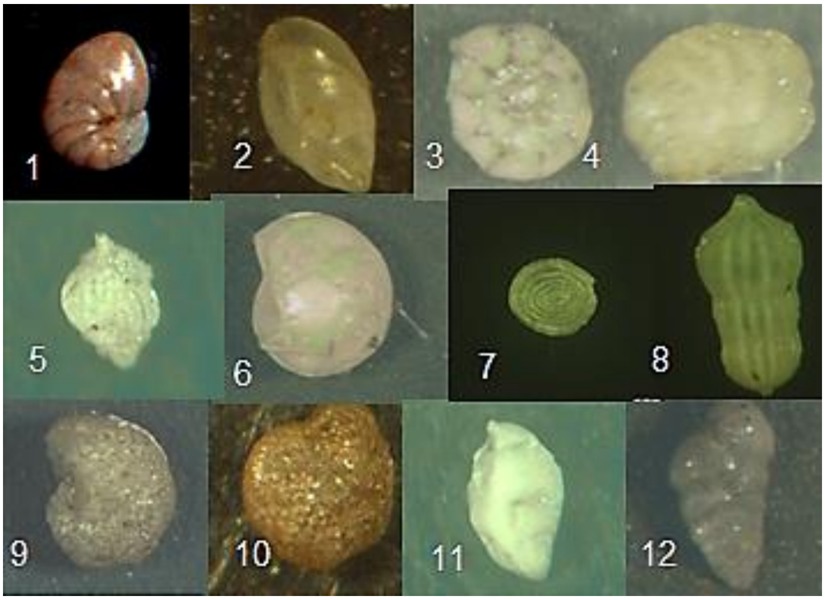


Plate 2: **1**: *Nonionella auris* x 60 **2**. *Globobulimina ovata* x 50 **3**. *Ammonia beccarii* x 40 **4**. *Cassidulina neocarinata* x 40 **5**. *Uvigerina peregrina* x 40 **6.** *Lenticulina inornata* x 50 **7.** *Ammodiscus glabratus* x 40 **8.** *Rectoglandulina comatula* x 60 **9.** *Alveolophragmium crassum* sp. x 40 **10.** *Cyclammina cancellata* x 40 **11.** *Sigmoilopsis schlumbergeri* x 40 **12.** *Spiroplectammina wrightii* x 40

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