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Foraminiferal patterns and palaeoenvironmental inferences from DEL-1 well, offshore Niger Delta

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ABSTRACT

The Miocene Epoch (23.3–5.3 Ma) represents a remarkable time in the Earth's geological history with significant palaeoclimatic and palaeoenvironmental relevance. In this study, microfossils recovered from the DEL-1 (4600–9460 ft) well in the western Detachment Fold Zone, offshore Niger Delta in the Gulf of Guinea were used to construe the age, palaeoenvironment, and palaeoecology of the penetrated successions. Standard foraminiferal analyses were carried out on one hundred and forty-eight (148) ditch cuttings retrieved from the studied interval following standard laboratory and identification procedures. *Globigerinatella* spp./*Catapsydrax dissimilis* Concurrent-range Zone (M3/N6), *Fohsella birnageae* Lowest Occurrence Subzone (M4b/N7), and *Orbulina suturalis* Lowest Occurrence Zone (M6/N9) of early to middle Miocene were identified. An overall progradational coastal and shelfal facies dominated by argillaceous and arenaceous sediment in the early and middle Miocene is construed, whereas interpreted palaeoenvironment of deposition indicates fluctuation between coastal deltaic, inner, middle, and outer neritic system with some fluvio-marine incursions between 4600 and 9460 ft intervals. The identified early Miocene succession is characterised by significantly high ecological parameters (diversity, evenness, richness), low salinity, and relatively high occurrence of foraminifera faunas compared to the middle Miocene. The relationships between the foraminiferal faunas and environmental factors suggest the local ecologic niche exhibits environmental heterogeneity that might have influenced even distribution of different microhabitat faunal preferences. Whereas the contributing influence of arenaceous sediment on the general dearth of microfossils in the upper section of the well cannot be neglected, the foraminiferal signatures reflect the ubiquitous middle Miocene carbonate crash event, and thus confirm its occurrence in the Gulf of Guinea.

1. Introduction

The Miocene Epoch (23.3–5.3 Ma) represents a geologic time with significant palaeoclimatic and palaeoenvironment relevance to global terrestrial and marine realms (Netto and Rosseti, 2003; Fontanier et al., 2014; Asis et al., 2019). Physicochemical oscillations and generally unstable environmental conditions characterised the early Miocene, while the middle Miocene (17.5–13.5 Ma) experienced fluctuating global warmth associated with ubiquitous carbonate dissolution that have been identified in different oceans of the World (Matthews et al., 1980; Flower and Kennett, 1993; Fadiya and Salami, 2012; Lübbers et al., 2019). Consequently, marine facies/ocean water samples contain information about sea-surface temperature (shallow-dwelling planktic foraminifera), the stratified structure of the thermocline (deeper-dwelling planktic foraminifera), bottom water temperature (benthic foraminifera), and local salinity condition in which foraminifera grew (Woodruff and Savin, 1991; Flower and Kennett, 1993). Recent studies have investigated the response of biogenic proxies to changes in solar insolation, salinity, nutrient availability, and ocean composition, relative to climate variability across regions (Woodruff and Savin, 1991; Preiss-Daimler et al., 2013, 2021; Antonarakou et al., 2018; Schenk et al., 2018). Changes in the abundance and composition of marine organisms or communities, which are influenced by intriguing climate changes, affect the global biogeochemical cycles (Fontanier et al., 2014; Zhang et al., 2017). The bulk of recent studies focused on inferring ancient climate and environment largely relied on the use of fossil records to reconstruct paleoconditions (Flower and Kennett, 1993; Fontanier et al., 2014).

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The importance of foraminifera micropalaeontology as a tool for probing the basin's palaeodepositional events, chronostratigraphic, and hydrocarbon exploration cannot be overemphasised (Van Hinte, 1978; Venturelli et al., 2018). Foraminiferal examinations on different assemblages within marine-sediment columns are useful for construing oceanic responses to past ecologic and climatic events. Variations in environmental constituents such as pCO_2, pH, temperature, salinity, light, oxygen, and nutrient levels are often associated with regional or local effects of sediment loading, subsidence or uplift dynamism, and flexure (Miller et al., 2020). The interplay of these parameters defines the palaeoceanographic character of the water mass. Thus, depicting natural cycle inferences derived from sediment physical properties and biostratigraphic data among other concrete geologic data to construct precise and robust spatial and temporal palaeoecology models (Venturelli et al., 2018).

The Miocene events have been severally tested across diverse basins, leveraging on palaeoecology, palaeobathymetry, and palaeoenvironmental datasets (e.g., Smart and Murray, 1994; Diester-Haass et al., 2009; Müller et al., 2012; Fontanier et al., 2014; Asis et al., 2019). However, the Miocene oceanic ecosystems along the West African coast (Gulf of Guinea) are still poorly understood due to wide reasoning on some factors that are responsible for the changes in oceanic physicochemical parameters. Examples can be drawn from the small contribution of Northern Component Water (NCW) to the Southern Ocean Water to define the water properties, while sedimentary organic matter, carbon dissolution, and dissolved oxygen could have some impacts on defining the habitable ecosystems for faunal microhabitats (Wright and Miller, 1996; Omoboriowo et al., 2011). In the offshore Niger Delta, studies that focused on deciphering environmental palaeo-conditions are generally few (Fadiya and Salami, 2012; Okosun et al., 2012; Ajayi and Okosun, 2014; Adetola, 2014), as most of the subsurface research efforts are hitherto geared towards petroleum exploration and production in the oil-rich Niger Delta Basin and its associated onshore and offshore depobelts (e.g., Weber and Daukoru, 1975; Avbobvo, 1978; Evamy et al., 1978; Doust and Omatsola, 1989; Obiosio, 2013; Adepehin, 2014). In this study, microforaminifera datasets are construed to better understand the local ecological traits and palaeoenvironmental conditions from the marine successions of the western Detachment Fold Zone (DFZ), offshore Niger Delta. The objectives of the study were to (i) document the fauna assemblages and zonation from the western DFZ succession, (ii) detail the palaeobathymetry and palaeoenvironment, and (iii) infer local ecological fluxes in the studied area to portray palaeoenvironmental imprints that might be of global relevance.

2. Study location, geological setting, and stratigraphy

Located within the western offshore Niger Delta, the DEL-1 well penetrated an estimated 9400 ft siliciclastic succession within the western (DFZ) Niger Delta, which sits directly on the Gulf of Guinea (Fig. 1). The study area is bounded by latitude and longitude values of 4° 55′ 22.65″ N and 004° 01′ 30.58″ E, in a water depth of 5988 ft. The geologic history of the Niger Delta Basin is linked with the opening of the North and South Atlantic Oceans, and the successive break-up of the Gondwana (Whiteman, 1982). The setting for the development of the Cenozoic Niger Delta was provided by the regional-scale tectonism and stratigraphical framework of its linked rift systems (Allen, 1964). The Cenozoic delta is situated at the Benue Trough - South Atlantic Ocean intersection, which represents an aulacogen delta at the front zone of the third and failed arm of the late Jurassic triple junction that evolved during the parting of the South American and African plates (Whiteman,

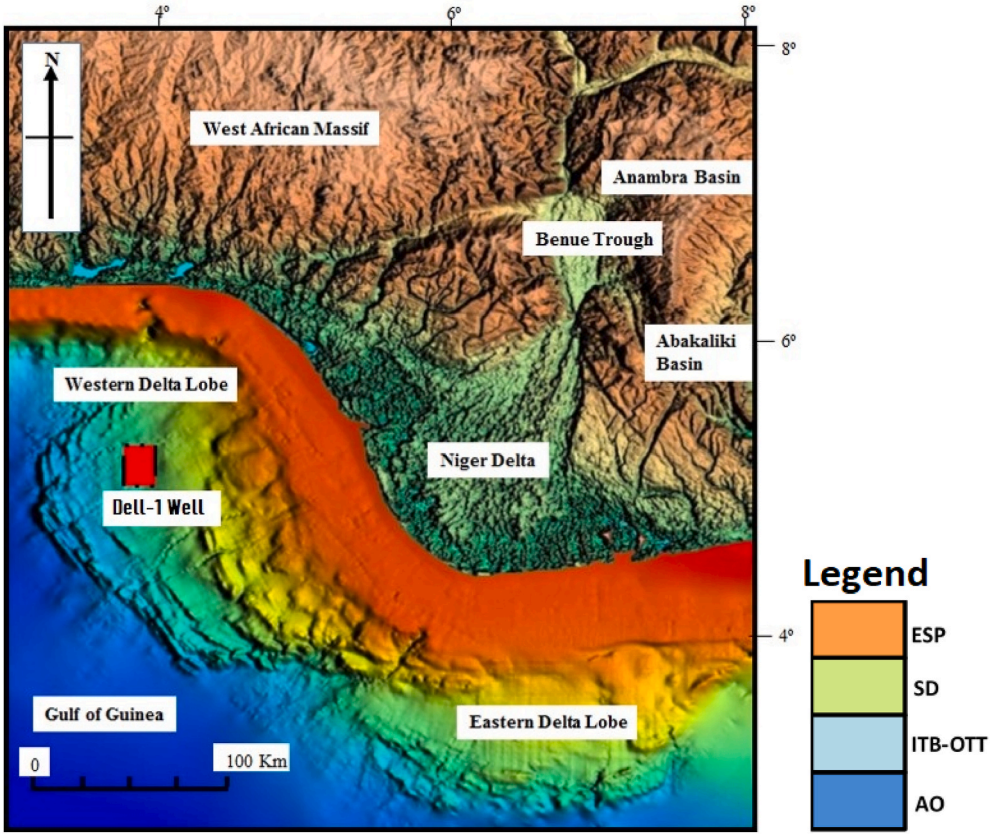

Fig. 1. Regional map of Southern Nigeria, showing major basement and basins in reference to the development of Niger Delta. Note the offshore depobelt is structurally divided into Western and Eastern Delta lobes. The study well is located within the Western Delta lobe (modified after Matthew et al., 2010). Note that ESP, SD, ITB-OTT, and AO represent extensional structural province, shale diaper, inner thrust belt-outer toe thrust, and Atlantic Ocean respectively.

1982). In the early Cretaceous, subsidence of the African continental margin owing to the cooling of the newly formed oceanic lithosphere took place after the separation. The large-scale synsedimentary subsurface features such as mud diapirs, rollover anticlines and growth faults, largely affected the development of the Cenozoic Niger Delta complex (Evamy et al., 1978).

The basins' evolution started in the early Palaeocene age when sediment contributions from clastic rivers increased (Doust and Omatsola, 1989). These sediments were shed through the Benue-Niger River by weathered wreckages from the margins of the outcropped continental basement materials. According to Evamy et al. (1978), the delta has prograded more than 820,209 ft from the Benin-Calabar flanks since the Palaeocene until now, and the basinal sedimentary fill ranges in thickness from 29,500 to 39,400 ft Three diachronous stratigraphic units characterise the basin, viz, (i) the Palaeocene to Recent Akata pro-deltaic facies, (ii) the Eocene to Recent Agbada paralic facies and (iii) the Oligocene to Recent Benin fluvial facies (Short and Stauble, 1967). The Palaeocene-Eocene pro-deltaic facies of the Akata Formation is the lowermost formational unit in the Niger Delta (Mode et al., 2013). It comprises dominantly of marine shale with minor intercalations of sands, silts, and clay. It is estimated to be 20,997 ft thick in the central part of the basin (Doust and Omatsola, 1989). The enclosed sands are turbiditic in nature and their deposition indicates prodelta to deeper marine environments (Short and Stauble, 1967). It is the main petroleum source rock in the Niger Delta (Bustin, 1988; Tuttle et al., 1999; Haack et al., 2000). Plant remains and thin deep-sea fan sands have also been recovered near its top, especially near its boundary with the overlying paralic Agbada Formation (Evamy et al., 1978; Adegoke et al., 2017). Planktic foraminifera accounts for up to half of the recovered microfauna, and the benthic assemblages suggested deposition on the shallow marine shelf (Doust and Omatsola, 1989; Adegoke et al., 2017).

The Eocene to Recent Agbada Formation is the intermediate stratigraphic sequence of the Niger Delta, resting on the overpressured marine Akata Formation and overlain by the continental Benin Formation. It is mainly composed of sands, silts, and shales, which signifies sediments deposited in a typical marginal-deltaic to marine environments (Short and Stauble, 1967). The Agbada Formation recorded a thickness from 9,843 to 13,123 ft (Reijers et al., 1997). The intercalated sands in the Agbada Formation are the major exploration targets in the basin, owing to their enriched hydrocarbon content. Documented foraminifera assemblage from a segment of the offshore Niger Delta observed the abundance of planktic and benthic species (Omoboriowo et al., 2011). The alluvial and upper coastal plain sands make up the continental deposit of the Benin Formation, as it overlies the paralic Agbada Formation in the Miocene to Recent. It is the topmost stratigraphic unit in the Niger Delta with varying thicknesses that range from about 4,600 to 6,500 ft (Tuttle et al., 1999; Adepehin, 2014). These sandstones are characteristically massive, highly porous, freshwater-bearing, subangular to well rounded, and contain lignite streaks, clays as well as wood fragments (Reyment, 1965). Documented grain size ranges from gravelly to coarse to locally fine-grained sandstone, and thus it is poorly sorted.

3. Materials and methods

3.1. Lithological description

The lithological description was carried out on 148 ditch cuttings retrieved between 4600 and 9400 ft of the DEL-1 well using a stereo binocular microscope and the AAPG standard comparator following the method of Ola and Adepehin (2017). The constituted facies (sand-silt--shale), textural parameters (colour, grain size, roundness, and sorting), presence/absence of fossil fragments as well as environmentally sensitive and accessory minerals were observed and carefully described. Based on these, the lithofacies were computed using the down-hole compositional relationship of the cuttings and gamma-ray log signature. The STRATBUG Software was used to enhance the down-hole lithological presentation and qualitative interpretation. Plotted nannofossil data for the DEL-1 well (Fig. 2) was integrated with foraminifera taxa recovered through the laboratory procedures detailed below.

3.2. Preparation and analysis of foraminifera

Twenty-five (25) grams of each sample from a depth bag was taken in a pre-washed aluminium bowl, labelled for identification heated on the electric hot plates (70 °C) for some minutes to dry. The heated samples were thereafter moved to a fume cupboard and Hydrogen peroxide (H_2O_2) was added to cover the entire samples in the container. The samples were left to soak for 24 hours to enable the fine materials to sufficiently disintegrate. The now-disaggregated samples were washed under a running tap on a 43 μm sieve until the residues were clean. The cleaned residue in the sieves was transferred into an aluminium container and placed on a hot plate to dry. Sieving was thereafter carried out on the dry samples with the 63 μm + dust below (fine). The 63 μm fraction of each sample was stored in a vial for subsequent microscopic examination. A 50x magnification binocular (reflecting) microscope aided picking and analysis of foraminifera forms recovered from

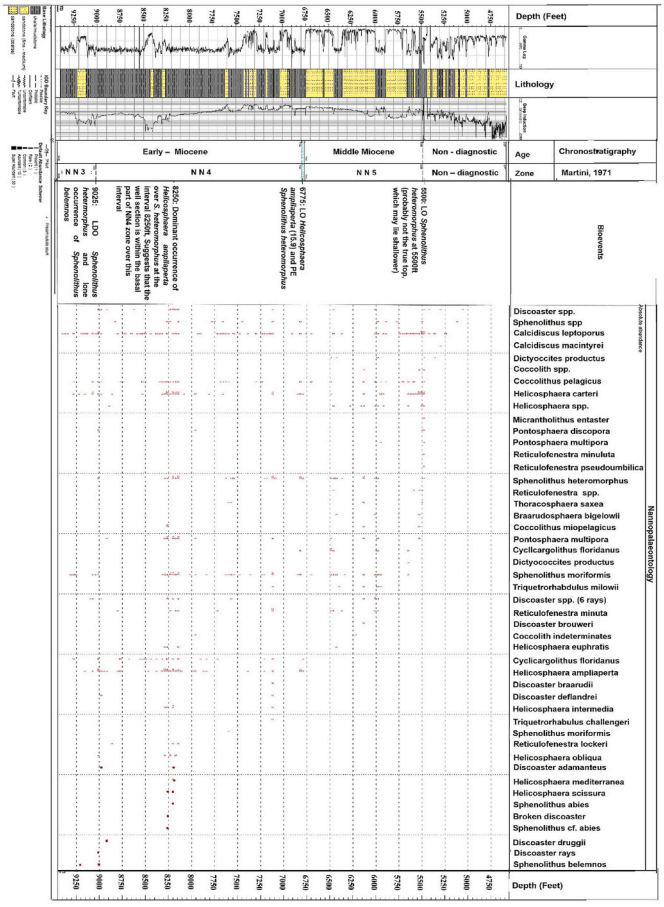

Fig. 2. Distribution chart for calcareous nannofossils in the studied succession correlated with gamma-ray signature and lithological facies (After Oretade and Ali, 2021).

samples. The stored samples were sprinkled on the picking tray and scanned under the microscope. A picking pin was used to pick the identified forms and mounted on slides. The forms were thereafter sorted into identical forms, which were glued onto the slides and protected with a coverslip for further analysis. The analysis was done by organising the identified forms into different foraminifera assemblages/groups (benthic and planktic), sizes, genera, and species. Relevant catalogues and publications enhanced the identification and classification of the foraminifera in this study (e.g., Blow, 1969, 1979; Petters, 1982; Gebhardt, 2004; Hansen and Kamp, 2006).

Relative counts for each foraminifera specimen per depth were logged into the STRATABUG software's datasheet to obtain interpreted abundance and diversity trends to construe bioevents and geological relationships. The standard low latitude foraminiferal schemes (Blow, 1969, 1979; Berggren et al., 1995; Wade et al., 2011) and interpreted calcareous nannofossil biostratigraphic data of the DEL-1 well (Fig. 2) were integrated for the biozonation definition. The time-stratigraphic correlation was carried out based on the occurrence and distribution of marker species (Plate 1) per sample depth for the sequences and chronostratigraphy following the Geological Time Scale (*sensu* Gradstein et al., 2020). Cross-examination on diagnostic benthic species with the occurrence of planktic species enabled the definition and delineation of depositional environments. The foraminifera and other accessory fauna recorded were thereafter plotted on distribution charts. Diversity indices, including species richness (S), Shannon-Wiener diversity index (H) and evenness (J) were calculated using PAST statistical software (Paleontological Statistics; Version 3.05; Hammer et al., 2001). The following equations were applied:

$$\text{Richness (S)} = \text{count of the number of taxa per depth} \quad \text{Equation i}$$

$$\text{Diversity (H)} = -\sum_{i=1pi}^{s} \text{In } pi \quad \text{Equation ii}$$

Note: p_i represents the proportion of the individual taxa to the population

$$\textit{Evenness}\ (J) = H/H_{max} = H/InS \quad \text{Equation iii}$$

4. Results and discussion

4.1. Lithological and lithofacies sequence

The succession comprises sandstone, shale, siltstone, and sandy shale facies (Fig. 3). The early Miocene sequences (6800–9450 ft) contain thick pale grey to grey shale beds (blocky to platy, with moderate hardness) with packets of sandstones that are brownish to yellowish-white, dominantly fine to medium-grained, moderately to poorly sorted and angular to subangular in shape. The sequence is described as a lower monotonous paralic sequence (Fig. 3). The middle Miocene sequence (4600–6800 ft) is characterised by a preponderance of sandstone with interbeds of shale. The sandstones are brownish to off-white in colour, medium to coarse-grained, subangular to subrounded in shape and poorly sorted. The shale beds are grey to dark grey in colour, platy and moderately hard, suggesting the interval to be a transitional paralic sequence (Fig. 3). Mica, carbonaceous fragments (detritus) constitute were recorded as accessory minerals. The presented lithological composition and lithological log of the DEL-1 well inferred a progradation stacking pattern with several regressive/transgressive episodes, with overall lithofacies that suggest coastal – shelfal depositional settings.

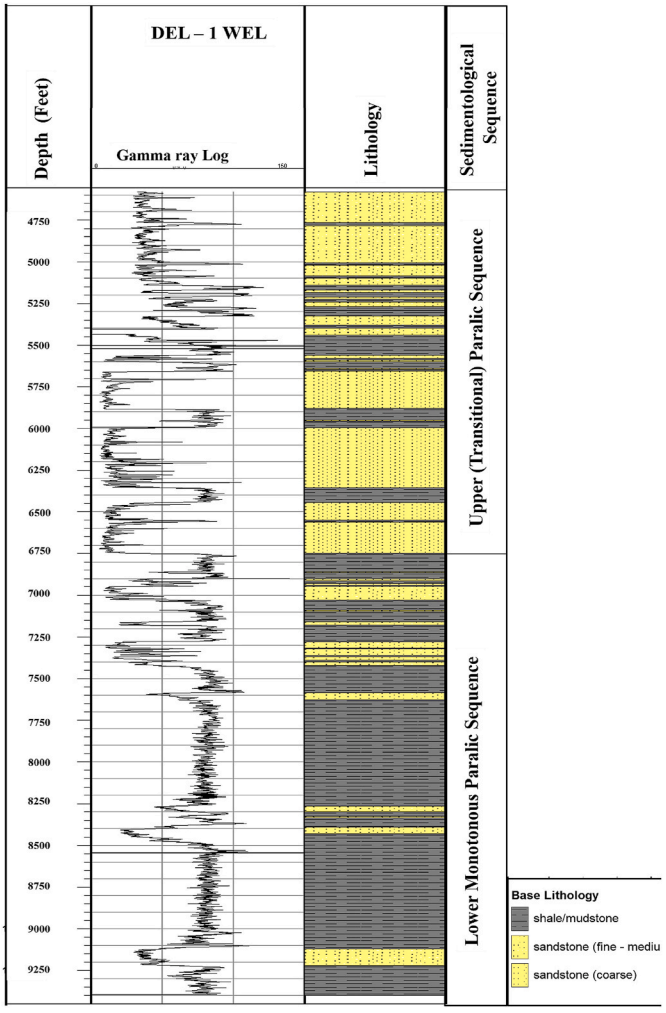

Fig. 3. Summarised lithologic log of DEL–1 Well, showing the stacking sequences of the major lithologic facies.

4.2. Foraminifera signatures in DEL-1 well

The recovered assemblages are dominated by calcareous benthic species, comprising fifty-four (54) species (Fig. 4), and nine (9) agglutinated benthic taxa (Fig. 5). There are twenty-three (23) species of planktic species (Fig. 6). Shell fragments of foraminifera, bivalves, echinoid remains, scaphopods and sponges were the accessory microfauna recovered (Fig. 5). The upper part of the well section with depth interval 4600–5400 ft was nearly barren of foraminifera, with lone occurrences of *Ammonia beccarii* and *Quinqueloculina* spp. The lower interval of 5430–9400 ft yielded low to high abundances and diversity of foraminifera (Figs. 4–6). The synthesis microfaunal distribution chart (1:8000) in Fig. 7 displays the stratigraphic distributions of foraminifera species, in occurrence and abundance. The recovered taxa that are of significance in constraining palaeoecology, palaeobathymetry, and palaeoenvironments in this study includes *Ammonia beccarii, Cassigerinella chipolensis, Catapsydrax dissimilis, Eilohedra vitrea, Trilobatus bisphericus, Trilobatus trilobus, Globoquadrina dehiscens, Spiroplectinella wrighti, Turborotalia obesa, Turborotalia peripheroacuta and Uvigerina sparsicostata* (Plate 1). The foraminifera distribution chart shows significant fossil occurrences between 8020-8090 ft and 8800–9040 ft

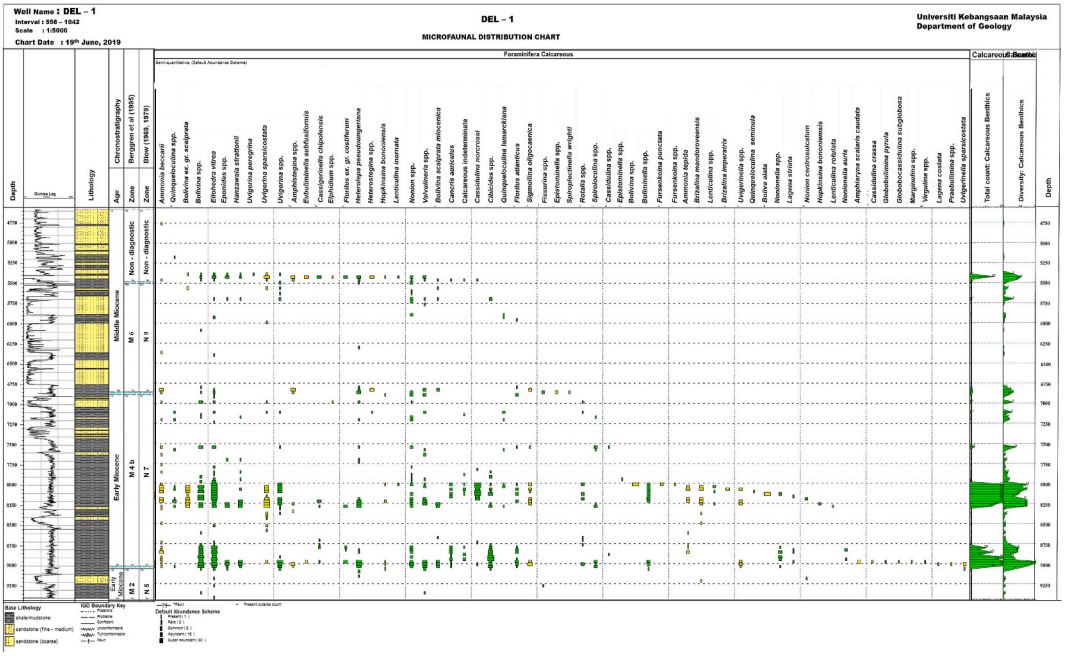

Fig. 4. Summation and distribution chart of calcareous benthic foraminifera of DEL-1 Well, with the corresponding gamma-ray log and interpreted lithologic facies.

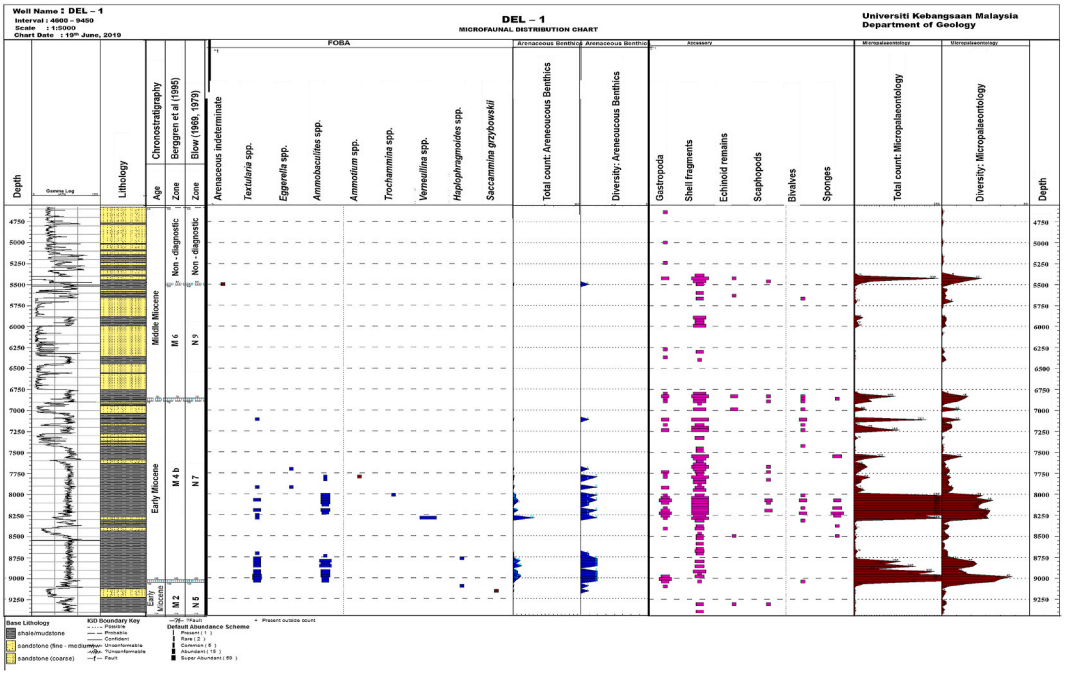

Fig. 5. Summation and distribution chart of foraminifera of benthic agglutinated (FOBA) and associated foraminiferal faunas in the studied succession, with the corresponding gamma-ray log and interpreted lithologic facies.

intervals, while other sections recorded dearth or low-to-moderate foraminifera recovery. However, these presented results depict a comparatively low-to-moderate species abundance (see Figs. 4–6).

4.2.1. Foraminifera zonation and age assessment

The planktic foraminifera zones recognised in this study are based on the revised Cenozoic geochronologic and chronostratigraphic schemes of Blow (1969, 1979), Berggren et al. (1995) and Wade et al. (2011). The chronostratigraphic subdivisions are based on GTS (2020). Four planktic foraminifera zones were identified and discussed based on the recovered taxa in the well (Figs. 4–6), these zones are described below.

Planktic Foraminifera Zone 1: N6 (M3) *Globigerinatella* spp./*Catapsydrax dissimilis* Concurrent – range Zone.

Samples/Stratigraphic Interval: This zone ranges from 9050 to 9400 ft (Figs. 6 and 7).

Age: early Miocene **(**Burdigalian stage**).**

Definition: This zone is distinguished as the concurrent-range zone of the nominate taxa between the lowest occurrence (LO) of *Globigerinatella* spp. and the highest occurrence (HO) of *Catapsydrax dissimilis* (Wade et al., 2011). This zone is equivalent to *Catapsydrax dissimilis* partial–range zone of Berggren et al. (1995). In this study, the top of the N6 (M3) zone is approximated at 9050 ft associated with the probable

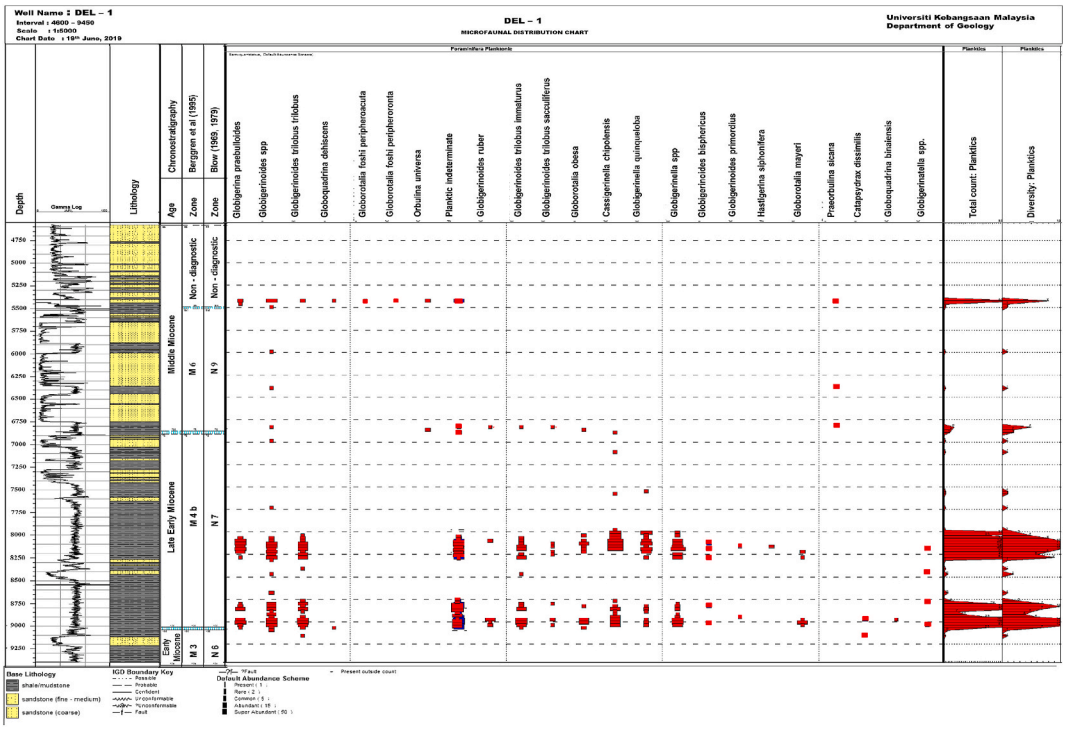

Fig. 6. Distribution chart for calcareous planktic foraminifera in the studied succession correlated with gamma-ray signature and lithological facies.

first downhole occurrence (FDO) of *Globigerinatella* spp. and probable FDO of *Catapsydrax dissimilis* and *Globoquadrina binaiensis* (Fig. 6).

Associated taxa/foraminifera assemblages: This interval is characterised by low abundance and low diversity of planktic foraminifera species, with few benthic species recorded. Documented planktons include *Trilobatus trilobus, Globoquadrina dehiscens, Globigerinoides immaturus*, *Globigerinatella* spp, *Cassigerinella chipolensis*, *Dentoglobigerina binaiensis,* and *Paragloborotalia mayeri* (Fig. 6). The benthic species include *Eubuliminella subfusiformis*, *Uvigerina sparsicostata*, *Brizalina mandoroveensis* and *Sigmoilina oligocenica* (Fig. 4).

Discussion concerning age assigned: The top of this zone is placed at 9050 ft, with probable LO of *Globigerinatella* spp. Consequently, the LO of *Globigerinatella* spp. at 9050 ft, probable LO of *Dentoglobigerina binaiensis* (Fig. 6) mark the bioevents for the N6 (M3) zone in this study. The presence and probable FDO of *Catapsydrax dissimilis* with First Occurrence (FO) of *Sphenolithus belemnos* (calcareous nannofossil – Fig. 2) at 9050 ft signifies the base of Zone N7, and further defines the standard Zone boundary of N6/N7. Thus, the concurrent occurrence of the nominate taxa (*Globigerinatella* spp. and *Catapsydrax dissimilis*) between the depth interval 9050–9150 ft suggest a Concurrent–range Zone in agreement with previous authors (Blow, 1969, 1979; Cushman and Renz, 1947; Bolli, 1957; Berggren et al., 1995). This zone (that occur below 19.4 Ma) was assigned an estimated age of early Miocene (Burdigalian stage) based on biohorizon definition relative to the age calibration of *Globigerinatella* spp. and evolutionary lineage of *Globigerinatella* as proposed by Spezzaferri (1994) and Wade et al. (2011), thus, both species are connected with the documented 19.4 Ma condensed section in the Niger Delta (Haq et al., 1988). Thus, the condensed section is marked by an increase in abundance of *Globigerinatella* spp. (19.66 Ma), *Dentoglobigerina binaiensis* (19.43 Ma), *Catapsydrax dissimilis* and FO of *Sphenolithus belemnos* (calcareous nannofossil – 19 Ma) (Fig. 2) between 9800 – 9100 ft relates to the 19.4 Ma. (Fig. 7), which is of the Burdigalian stage *sensu* GTS (2020). The interval's base is tentatively placed at 9400 ft, which corresponds to the lowest sample studied (Figs. 4–7).

Planktic Foraminifera Zone 2: **N7 (M4b)**/*Fohsella birnageae* Lowest Occurrence Subzone.

Samples/Stratigraphic Interval: This zone ranges from 6850 to 9050 ft (Figs. 6 and 7).

Age: early – middle Miocene (late Burdigalian stage).

Definition: This biostratigraphic interval is defined as the interval between the LO of *Fohsella birnageae* and the LO of *Praeorbulina sicana* (Wade et al., 2011). The presence of *Fohsella birnageae* and *Globoconella praescitula* with the LO of *Praeorbulina sicana* in this study is a probable indicator of the *Fohsella birnageae* Lowest Occurrence Subzone (M4b) of Wade et al. (2011) and *Globigerinoides bisphericus* of Berggren et al. (1995) (Figs. 6 and 7). The defined nominate taxon characterises this interval with an estimated age of late Burdigalian stage.

Associated taxa/foraminifera assemblages: The interval is generally characterised by up-hole decrease in abundance and low to moderate diversity of planktic foraminifera species (Fig. 6). The planktic species recorded include *Cassigerinella chipolensis*, *Globorotalia praescitula*, *Paragloborotalia mayeri*, *Turborotalia obesa, Trilobatus trilobus* and other long-ranging species of *Globigerina* and *Globigerinoides/Trilobatus*.

Discussion concerning age assigned: This interval's top is placed tentatively at 6850 ft, the next sample below the LDO of *Orbulina universa* and probably the First Consistent Occurrence (FCO) of *Sphenolithus heteromorphus* (calcareous nannofossil) that marks the base of Zone N8 (Blow, 1969). This interval is of low (6850–8000 ft) and moderate to high (8000–9000 ft) foraminiferal abundance and diversity (Figs. 4–6). Thus, the subjective occurrences of *Praeorbulina sicana* and *Orbulina universa* with other species are perhaps indicative of condensed sections

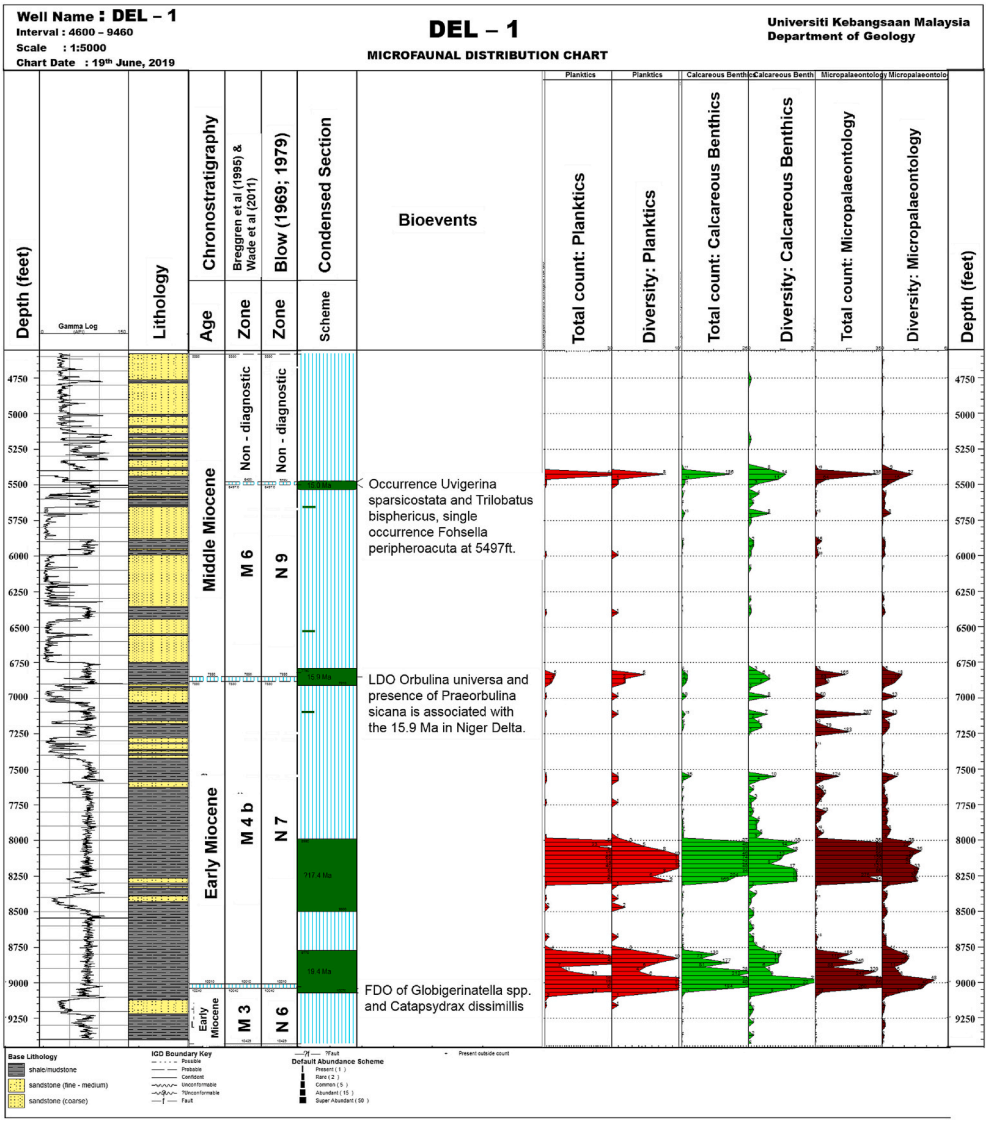

Fig. 7. Summation and synthesis chart of microfauna in DEL–1 Well, highlighting major early-mid Miocene bioevents in the western DFZ, offshore Niger Delta.

related to the 15.9 Ma Maximum Flooding Surface (MFS) condensed section of Haq et al. (1988) and linked to the late Burdigalian stage *sensu* GTS (2020). Consequently, another condensed section characterised the depth interval 8000–8500 ft with relatively high abundance and diversity of foraminifera species could fairly be dated due to the absence of marker/calibrated species. However, it could be related to the 17.4 Ma condensed section as it is stratigraphically straddled between the 15.9 and 19.4 Ma MFSs (Haq et al., 1988). However, sparse to low occurrences of foraminiferal species and poor delineation of zone boundary with N8 in the upper horizon of this interval could be a result of dissolution effect within the water column and/or physical removal (erosion) of sediments that could have possibly influenced the temporal and spatial deep-sea Miocene hiatuses reported by Singh and Verma (2014). The base of the interval is tentatively placed at 9050 ft (Figs. 4–6).

Planktic Foraminifera Zone 3: N9 (M6) *Orbulina suturalis* Lowest Occurrence Zone.

Samples/Stratigraphic Interval: This zone ranges from 5497 to 6850 ft (Figs. 6 and 7).

Age: middle Miocene (Langhian stage).

Definition: Wade et al. (2011) defined this planktic foraminifera zone by the nominate taxa between the LDO of *Orbulina suturalis* and LDO of *Fohsella peripheroacuta*. With the absence of *O. suturalis* in this study, the LDO of *Praeorbulina sicana* (a marker species for M5a and associate foraminifera assemblage of *O. suturalis*) at depth 6850 ft and the LDO of *Fohsella peripheroacuta* at depth 5497 ft could be inferred as the lower and upper boundary for this zone (Fig. 6).

Associated taxa/foraminifera assemblages: The few planktic species recorded include *Globigerinoides immaturus*, *Trilobatus sacculifer*, *Cassigerinella chipolensis*, *Turborotalia obesa* and *Globigerinoides* spp. Whereas, *Bolivina* ex gr *scalprata*, *Uvigerina sparsicostata*, *Hopkinsina*

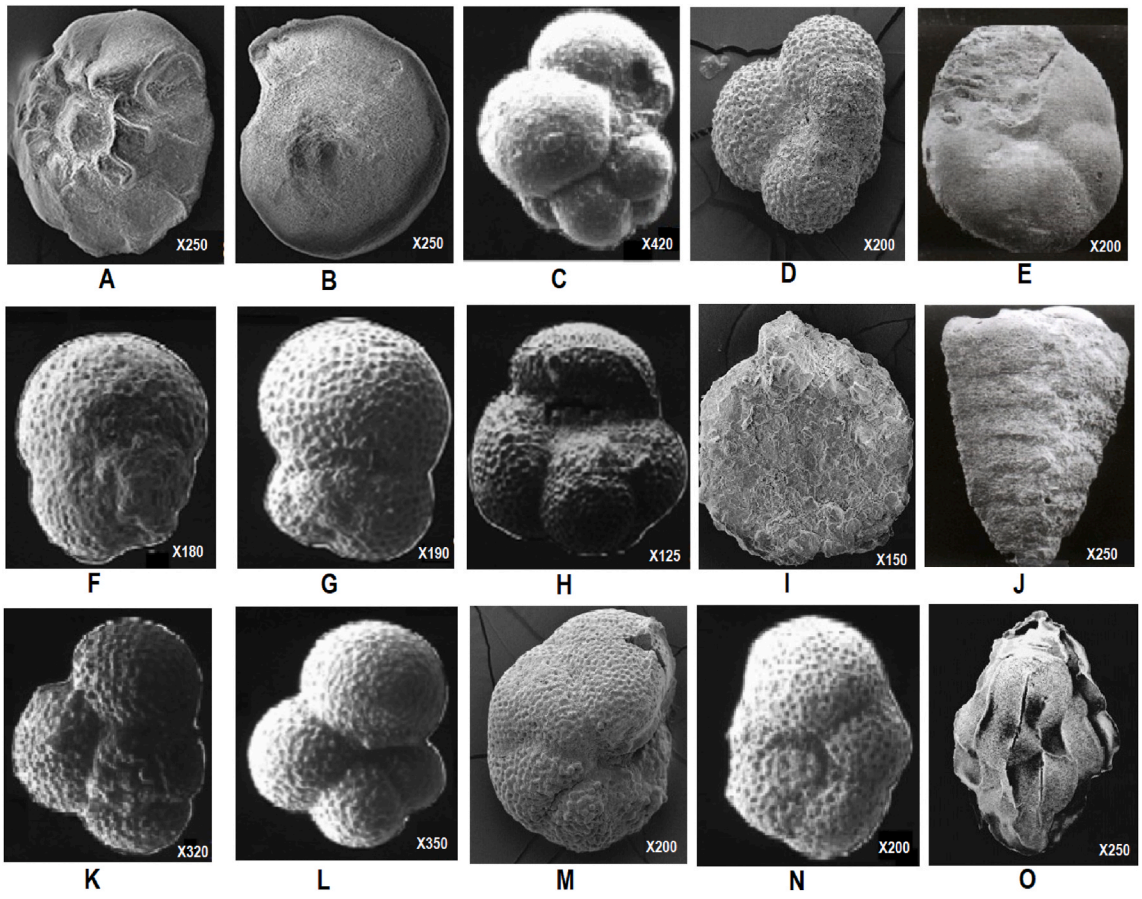

Plate 1. Scanning electron microscopy images of key taxa from the studied successions. (A) *Ammonia beccarii* (apertural view), (B) *Ammonia beccarii* (spiral view), (C) *Cassigerinella chipolensis* (apertural view), (D) *Catapsydrax dissimilis* (apertural view), (E) *Eilohedra vitrea* (apertural view), (F) *Trilobatus bisphericus* (spiral view), (G) *Trilobatus trilobus* (spiral view), (H) *Globoquadrina dehiscens* (apertural view), (I) *Saccammina grzybowskii* (side view), (J) *Spiroplectinella wrighti* (side view), (K) *Turborotalia obesa* (spiral view), (L) *Turborotalia obesa* (apertural view), (M) *Fohsella peripheroacuta* (apertural view), (N) *Fohsella peripheroacuta* (spiral view), (O) *Uvigerina sparsicostata* (side view).

bononiensis, *Brizalina mandoroveensis* are the associated benthic species (Figs. 4–6). The top of the interval is approximated at 5497 ft with lone occurrences of *Fohsella peripheroacuta* and *Trilobatus bisphericus* (Fig. 6). The stratigraphic range of this species straddles the N10 – N9 zones (Bolli and Saunders, 1985), although, Berggren et al. (1995) reported that the species evolved at the N10 (M7)/N9 (M6) zone boundary. If the lone occurrence of *Fohsella peripheroacuta* is *in-situ*, it implies that the sample at depth 6498 ft is stratigraphically dated 14.24 Ma. Thus, suggests the sample depth is not older than the N10 (M7) zone and not younger than the N9 (M6) Zone. Consequently, it marks the boundary between the aforementioned zones. The base of this zone is tentatively placed at 6850 ft, the probable LDO of *Orbulina universa.*

Discussion concerning assigned age: The increased foraminifera abundance and diversity recorded within the depth interval 5490–5550 ft is a possible relic of the MFS tied to 15.9 Ma condensed section due to its association with *the Fohsella peripheroacuta* (Fig. 6; Haq et al., 1988). Although the condensed section is also associated with *Uvigerina sparsicostata* (a benthic foraminifera species that its FDO was used to characterise the 12.8 Ma condensed section in the Niger Delta, Fig. 5), the high abundance (94 individuals) of this species at its Highest Occurrence Level of 5497 ft suggests the true top of this benthic foraminifera species may lie shallower than the condensed section and that the condensed section is probably older than 12.8 Ma (Fig. 7).

Planktic Foraminifera Zone 4: Non-diagnostic.

Samples/Stratigraphic Interval: This zone ranges from 4600 to 5497 ft (Figs. 6 and 7).

Age: middle Miocene.

Remarks: The interval's top is tentatively put at 4600 ft being the first (shallowest) sample studied. Planktic foraminifera species were not recorded in the interval, as it is virtually barren. This notwithstanding, the occurrence of *Uvigerina sparsicostata* at 5450 ft, with documented abundance and association in the middle Miocene succession of the Niger Delta, though not exclusive, somewhat suggest a middle Miocene age (Okosun et al., 2012; Okosun and Chukwuwa-Orji, 2016; Adegoke et al., 2017). The base of the interval is tentatively placed at 5500 ft, the next sample below the spot occurrence of *Fohsella peripheroacuta* at the depth of 5498 ft.

4.3. Palaeobathymetry

The palaeoenvironmental deductions in this study were guided mainly by the identified foraminifera assemblages, vis-à-vis the gamma-ray signature, and sedimentological data (Fig. 8). Criteria used include environmental diagnostic benthic species (Adegoke et al., 1976; Murray, 1991), foraminifera abundance and diversity, planktic/benthic ratio, and calcareous/agglutinated benthic ratio. Plotted palaeobathymetry indicates an overall coastal deltaic to an outer neritic system (Fig. 8). The entire sequence can be bathymetrically subdivided into four sections; the lowermost section (8000–9600 ft) is interpreted as inner neritic to outer neritic (Fig. 8). This progressed into a predominant coastal to an inner neritic setting (6750–8000 ft), while depth interval (6750–8000 ft) is dominant of coastal to inner neritic settings. The depth interval 5400–6750 ft depicts middle to outer neritic settings and the shallowest portion of the succession (4500–5400 ft) is of dominant

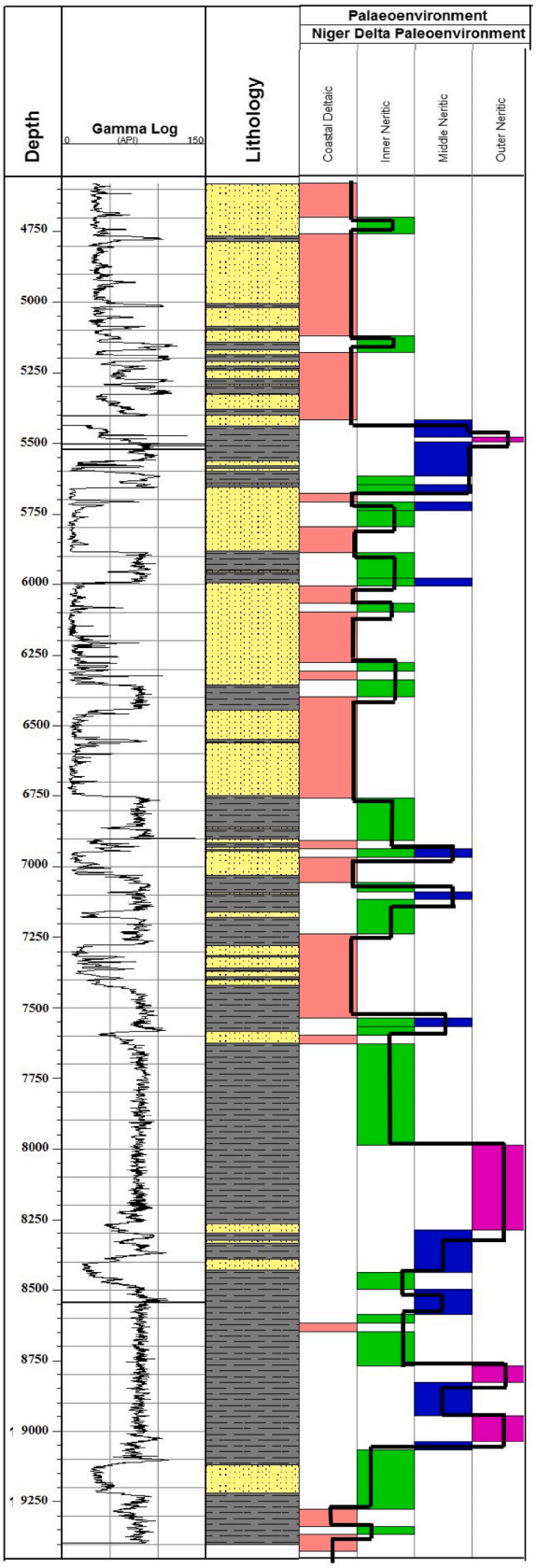

Fig. 8. Paleobathymetric curve with corresponding lithologic facies and gamma-ray log of the studied successions. Note the predomination of inner to outer neritic, coastal to inner-neritic and essentially coastal systems at the base (8000–9250 ft), middle (6750–8000 ft) and upper (4500–5400 ft) sections of the well, respectively.

coastal deltaic system with few incursions of the inner neritic (see Fig. 8). These bathymetric subdivisions and their associated fauna are briefly explained below.

4.3.1. Interval 8000–9460 ft

The depth intervals (9300–9460 ft and 8600–8640 ft) are construed as portions of a coastal deltaic system due to sparse recovery of foraminifera specimens from the shale units (Figs. 3 and 8). There is however a systematic fluctuation of depositional environment trend up-hole, as it oscillates between inner neritic, middle neritic, and outer neritic settings (Fig. 8). These depth intervals (8000–8300 ft, 8800–8850 ft, and 8950–9050 ft) consist of significant deepening sediments that are characterised by blocky, dark grey and calcareous shale units. This is characterised by high abundance and diversity of foraminifera, such as *Uvigerina sparsicostata*, *Melonis soldanii*, *Globocassidulina subglobosa*, *Cibicidoides robertsonianus*, *Ammonia beccarii*, *Eilohedra vitrea*, *Valvulineria* and *Virgulina* spp. The dominant occurrences of *Bolivina* and *Bulimina* are indicative of a restricted low oxygenated setting, which depicts outer neritic (Figs. 5 and 8; Venturelli et al., 2018). This interpretation is further buttressed by the co-occurrences of agglutinated benthic foraminifera of the genus *Textularia Haplophragmoides, Trochammina* and *Ammobaculites,* in association with a few planktic genera (*Globorotalia* and *Globigerinoides*), to suggest an appreciable level of marine productivity (Figs. 5 and 6). The shaly siltstone (white, fine-grained, micro--micaceous) and sandstone (brownish to yellowish-white, medium-grained, subangular to subrounded, well-sorted) units within the 8300–8430 ft and 9100–9200 ft respectively recorded lesser foraminiferal composition, thus indicating reduced abundance and diversity in planktic and benthic foraminifera. The array of recouped foraminifera suggests this depth interval was deposited in inner to outer neritic settings (Murray and Alve, 1994). However, this interval recorded a high recovery of test fragments of foraminifera, sponges, and gastropods bivalves as accessory microfauna with the aforementioned foraminiferal assemblages (Figs. 5 and 6).

4.3.2. Interval 6750–8000 ft

This interval comprises thick shale that grades into an intercalated sequence of dark greyish-to-greyish, soft to moderately hard, sub-fissile shales, and fine to medium-grained, occasionally coarse, subrounded to rounded, and poorly sorted sandstones. These textural signatures are suggestive of a hemipelagic succession. The occurrences of *Ammobaculites* spp. and *Eggerella* spp. are generally rare, whereas the fauna, *Eilohedra vitrea, Heterolepa pseudoungeriana, Spiroloculina* spp. are more prominent (Figs. 4–6). A predominantly inner neritic system, with middle neritic and coastal deltaic incursions, is construable from these assemblages (Fig. 8). These signatures are comparable to successions of prograding facies zones of hemipelagic Neogene shales along the continental shelf of the Niger Delta (Adegoke et al., 1976).

4.3.3. Interval 5400–6750 ft

This interval is composed of a stacked multi-storey succession of medium to coarse-grained, subangular to rounded and poorly sorted sandstones interbedded with silt, and grey/dark grey, moderately hard, sub–fissile shale (Fig. 2). In this study, the compositions of sandstones and shales packages (average sand to shale percentage of 69% sand + silt, and 31% shale) are probable indicators of a typical paralic environment and it is suggestive of an upper shelf/prodelta and neritic settings. The paucity of occurrences and distribution pattern of the foraminifera species within this depth interval could infer the sequential alternation of coastal deltaic, inner, and middle neritic environments assigned (Figs. 4–6 and 8). The foraminiferal assemblage contains calcareous benthic forms such as *Bolivina* spp., *Eilohedra vitrea*, *Eponides* spp., *Uvigerina* spp., *Elphidium* spp., *Heterolepa pseudoungeriana*, *Bolivina scalprata miocenica*, *Uvigerina sparsicostata*, *Uvigerina peregrina, Nonion* spp. and *Hanzawaia strattoni* at the upper limit of the interval (Fig. 4), thus justifying the uppermost units to be of middle to outer neritic

(Adegoke et al., 1976; Murray, 1991; Spezzaferri and Ćorić, 2001). Conversely, the dominance of the calcareous benthic foraminifera and the significant presence of agglutinated taxa within this interval (Figs. 4 and 6) indicate intermittent oscillations in the development of an oxygen minimum zone. Also recorded within this depth interval (5400–6750 ft) are accessory faunas such as shell fragments, echinoid remains, scaphopods, bivalves and sponges. These foraminifera species and their stratigraphic distributions within the entire interval (5400–6750 ft) are indicative of coastal deltaic – inner neritic fluctuations, with minor deepening to the middle-outer neritic (Fig. 8).

4.3.4. Interval 4500–5400 ft

This interval is virtually barren of foraminifera, having only *Ammonia beccarii* and *Quinqueloculina* spp. The sediments compose dominantly of medium to coarse-grained sandstone/sands characterised by moderate sorting, sub-angular grains, and the presence of carbonaceous materials. These characteristics are suggestive of a coastal plain setting/coastal deltaic environment (possibly a delta plain or estuary) (Fig. 8). This could be resolved as sediments transported within shallow waters that are texturally coarse and barren of foraminifera. It is interpreted as a typical prodelta shoreface (Katz et al., 2013).

4.4. Palaeoecological inferences

In this study, the palaeoecological interpretation was inferred from the occurrence and ecological imprints of the benthic foraminifera identified. This section relied on their depth of occurrence and ecological attributes/records to possibly depict the local palaeo-water depths and palaeo-deposition (Gebhardt, 2004). This was mostly obtained by equating the modern ecological systems and their fauna, despite the presence of some taxa that have changed their ecological preferences through time. Moreover, a prominent indicator of the favourable environment is adequately shown by species diversity. Low quantities or occurrences of species indicate probable ecological stress, whereas high diversity advocates calm conditions (Murray and Alve, 1994). Using benthic foraminiferal oxygen index (BFOI), the benthic foraminiferal taxa are classed into oxygenic indicator groups (oxic, suboxic and dysoxic) to depict dissolved oxygen levels within the oceanic depth and infer oceans' environmental conditions (Kaiho, 1994, 1999; Jorissen et al., 1995). To adequately constrain early-to-middle Miocene palaeoecology in the studied well, four parameters were considered and discussed: (i) fauna abundance and diversity, (ii) wall structure, (iii) palaeotemperature and palaeodepth, and (iv) salinity.

4.4.1. Relative roles of lithology and palaeoclimate on fauna diversity and abundance

A total of 63 taxa comprising of 54 calcareous and 9 agglutinated benthic species were identified in the DEL-1 well. In the early Miocene horizons, species richness varies with values ranging from 2 to 38, while we recorded the highest species richness value at 9000 ft (Fig. 7). These species were evenly distributed with values ranging from 0.61 to 0.91, while the Shannon diversity values vary between 1.9 and 2.54 as the minimum and maximum diversity values, respectively. The early Miocene showed an increase in richness relative to its diversity values with both agglutinated and calcareous benthic foraminifera (Figs. 4 and 5). Of these values, it could be construed that the early Miocene horizons are sediments deposited away from the land into an open ocean with probable conducive ecological conditions. However, the dominant occurrences of *Bolivina* spp., *Bolivina* ex. gr. *scalprata*, *Eilohedra vitrea*, *Eponides* spp., *Cibicides* spp. characterise the whole well section as a neritic depositional setting among other species. The species richness is favoured with the abundance of infaunal species (e.g., Bolivinid) that increases down-hole along the studied section to suggest fluxes in oxygen availability and perhaps an in-balanced chemical composition of the environment in the early Miocene horizons of the studied well (Figs. 4 and 5) (Murray, 1991; Kaiho, 1994; Venturelli et al., 2018).

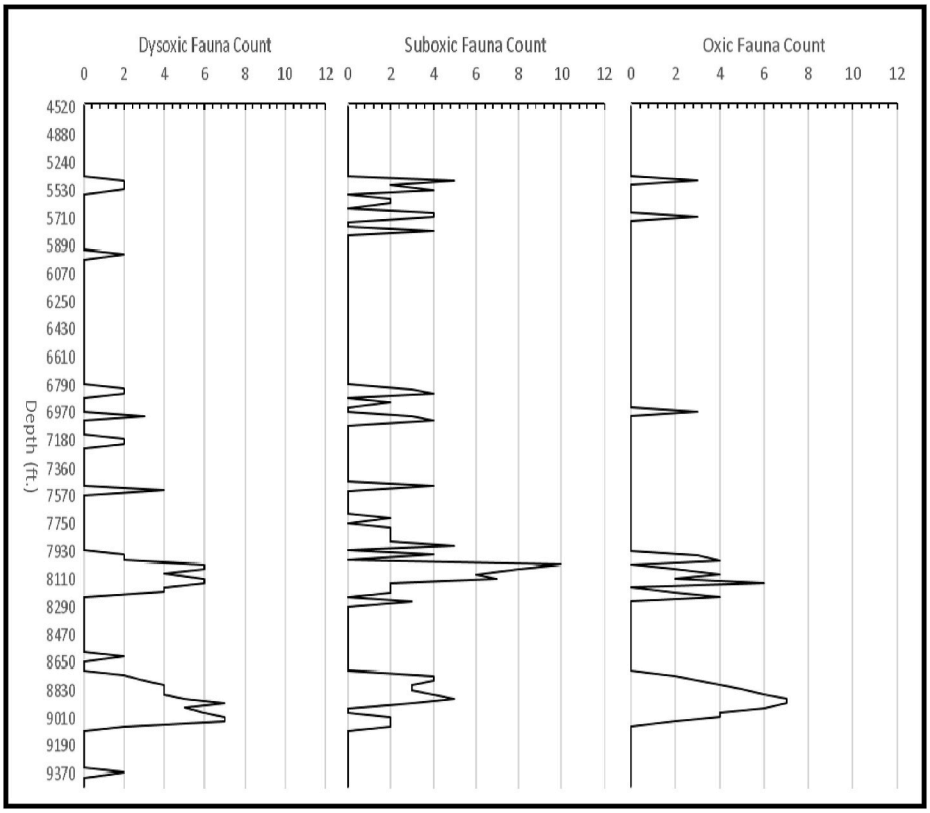

Fig. 9. Depth variability of dysoxic, oxic and suboxic faunas counts in the studied successions. The deeper part of the well (>8000 ft) shows significant abundance and diversity indices, whereas faunas in the upper portion are of less abundance with erratic signature. Note the predomination of suboxic faunas.

Consequently, the dissolved oxygen trend within the horizon (8650–9070 ft) shows almost equal dominance of dysoxic and oxic conditions (Fig. 9) (Spezzaferri and Ćorić, 2001), as evident from the proportional cyclic abundance of *Bulimina* spp. to *Nonion* spp. (Fig. 4). The late early Miocene interval (6850–8650 ft) is dominated by suboxic affinity faunal, suggesting a change in water condition (chemical composition of the environment) that could have possibly led to the gradual decrease in abundance and diversity of foraminiferal assemblages up-hole (Figs. 4 and 5). However, in the middle Miocene succession, the assemblage is dominant of suboxic taxa, with species richness ranging from 0 to 22, with the highest value at 5500 ft, whereas the species evenness ranges from 0.56 to 0.82. The Shannon diversity fluctuates across the middle Miocene horizons, with minimum and maximum diversity values at 0.7 and 2.2.

The low abundance and diversity of species in the middle Miocene succession could have resulted from the interplay of the ubiquitous carbonate crash and unfavourable preservation of forms due to the dominance of arenaceous lithology (Figs. 4–7). This upper horizon (4500–6850 ft) possess relative abundances of epifaunal (species of L*enticulina, Heterolepa*) and infaunal taxa (such as species of *Bolivina, Uvigerina*), with the dominance of suboxic taxa (such as *Nonion* spp., L*enticulina*, and *Bulimina*) and the presence of oxic taxa (*Elphidium* spp., *Cibicides* spp. - Rögl and Spezzaferri, 2003). Despite lesser foraminifera diversity and richness, the enhanced dominance of suboxic taxa suggests possible changes in water properties, including dissolved oxygen level, which perhaps range from 1.5 to 3.0 mll^{-1} (Kaiho, 1994). However, recorded differences in the lithological composition of the paralic sediments and physical properties of medium to coarse grain sandstone units could likely create microhabitat heterogeneity and fluctuating diversity, mostly for the benthic foraminifera as sandy sediments may not support their development and preservation (Bernhard and Sen Gupta, 1999; Rögl and Spezzaferri, 2003; Venturelli et al., 2018). Thus, highlight ecological tolerance for the suboxic affinity taxa in the middle Miocene amidst other changes in environmental factors such as nutrient, sunlight, pH, and salinity (Todd et al., 2020).

Pippèrr and Reichenbacher (2009) had earlier identified the influence of lithological changes, fluctuations in dissolved oxygen level, and nutrient-rich upwelling as significant controls on the abundance and diversity of foraminifera faunas in inner shelf to the slope environmental settings. Thus, the inconsistent abundance and diversity signatures of foraminiferal assemblages in the DEL-1 well (Figs. 7–9) could have resulted due to environmental heterogeneity. This can be partly arrogated to coastal influxes or river plumes (sediments deposited from the continental hinterland that were predominantly sandy). In addition, the offshore seasonal upwelling in the Niger Delta could have possibly influenced the ocean water productivity, and thus initiated a stressed environmental condition, which reduced biological productivity of phytoplankton, and ultimately reduced the abundance and diversity distributions during the middle Miocene (Corredor et al., 2005; Okosun et al., 2012). Consequently, contributing to the surface water conditions of the dominant properties of the two water masses (Northern Component Water – NCW and Tethys Outflow Water - TOW) in the Gulf of Guinea during Miocene (Fontanier et al., 2014). It is however noteworthy that the presented research data in this study strongly agree with that of Salami and Fadiya (2012) regarding low calcareous nannofossil abundance and diversity in the middle Miocene (especially in the NN5) of the offshore Niger Delta, notwithstanding subtle variations in arenaceous/argillaceous lithologies. Thus, although the contribution of arenaceous lithology cannot be completely ruled out, the general dearth of foraminiferal in the middle Miocene succession of the Western Detachment Fold Belt of the Niger Delta is construed to have resulted dominantly from the ubiquitous carbonate dissolution that characterises this time globally (Roth et al., 2001; Jiang et al., 2007; Lübbers et al., 2019).

4.4.2. Wall structure

The wall structure often relays the sensitivity of the foraminifera to their environmental condition (temperature, salinity, and depth) as the time of living (Dubicka, 2019). In an attempt to reconstruct the palaeoecological imprints of the study area, some dominant benthic taxa were studied. The *Ammobaculites* spp. generally possesses four chambers moderately inflated by depressing sutures, generally in a size range of about 2–3 mm in diameter. The chamber walls are well cemented, medium to coarsely agglutinate with nanograins of about 150 mm. The *Eggerella* spp. are highly inflated on their chambers of three per whorl, the chambers are separated by thin but depressed sutures. Moreover, the walls of the chamber are fine to medium agglutinated and canaliculated and cemented by a calcareous cement to suggest its survival in an oligotrophic environment. The *Haplophragmoides* spp. possesses slight concave, inflated 9 to 10 chambers in their uppermost whorl, and is separated by almost straight depressed sutures. The chamber walls show finely agglutinate nanograins, cemented by organic-like cement with a smooth and glassy touch. The examined *Textularia* spp. possesses agglutinated chambers of varying sizes, with decreasing sizes into the middle M4b zone. The chambers are composed of medium to coarse particles cemented with calcareous (calcite) cement. Consequently, the dominant occurrences of associated planktic (*Globigerinoides* spp.) and benthic (*Textularia* spp.) representatives in the M4b zone (early Miocene) attest to the dominance of oligotrophic condition within the horizons (Fig. 4; Spezzaferri, 1995).

Ecologically, the genera *Ammobaculites, Ammotium* and *Eggerella* spp. present within the 7750–9000 ft depth interval (Figs. 4 and 5) are known dwellers of muddy substrates in the brackish-normal marine environment, and mainly within the marsh to a bathyal setting, they endure hypoxia/dysoxic conditions and are called infaunal deposit feeders (Gebhardt, 1998). Although the *Haplophragmoides* species (8750–9000 ft) are characteristically an infaunal and detritivore that are common within muddy to sandy substrates in a marsh to a bathyal setting (marine setting), they have also often recovered from hyposaline and estuarine sediments (Murray, 1968). The genus, *Bolivina* blooms in muddy substrates of the inner shelf to a bathyal setting is a probable detritivore that lives as infaunal/epifaual in a marine system. The *Textularia* species is well-known to reside in normal marine environments, alternating from lagoonal to bathyal settings. They are epifaunal that inhabit hard substrates, muddy siltstones, and sandstones (Gebhardt, 1998). As shown in Fig. 5, the listed taxa generally reduced in abundance from lower horizons (with 6–10 count) to upper horizons (with 1–3 counts), thus typifying a systematic shift of environmental condition from oligotrophic to eutrophic in a continental shelf environment (Murray, 1991).

4.4.3. Palaeotemperature and palaeodepth

The palaeoenvironmental deductions made in sub-section 4.4.1 and 4.4.2 do help to construe the ecological inferences of the retrieved benthic foraminifera to their respective habitats. Hence, the penetrated successions in DEL-1 well palaeoecologically portray a marginal to the deep marine environments. Consequently, the lower horizons of the studied well (8000–9400 ft) ranged from coastal deltaic to outer neritic settings, with sediments dominant of faunas that have preferences to a slightly low oxygenated environment (Figs. 8 and 9). Thus, highlights the possible effect of depth and temperature changes on marine habitat and faunal distribution base on the inferred oxygenation level and sediment properties among other factors within the water column (Venturelli et al., 2018). Conventionally, the dominant occurrence of infaunal foraminifera characterises oxygen-poor marine benthic habitats. Conversely, the abundance of epifaunal foraminifera describes an oxygenated environment with warm temperatures. However, the presented datasets in this study infer possible palaeotemperature variance from some ecological proxies/taxa following the ecological guide of Blow (1969), Murray (1991) and Gebhardt (2004). The following taxa: *Heterolepa pseudoungeriana, Lenticulina inornata, Nonion* spp., *Quinqueloculina* spp., *Marginulina* spp., *Ammonia beccarii, Cibicidoides* spp. and

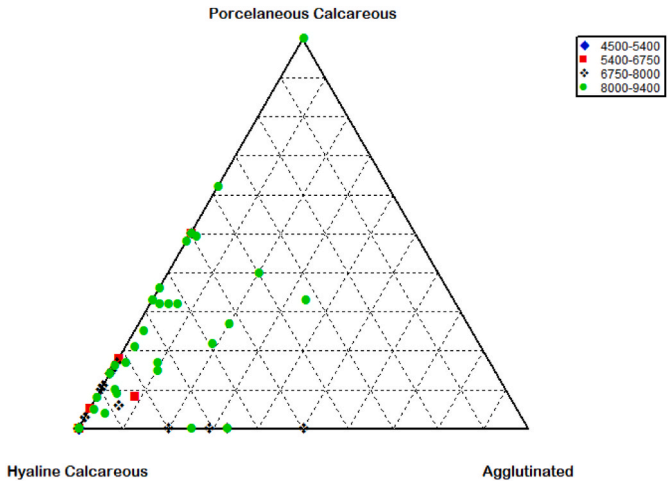

Fig. 10. Test type ratio triangular diagram for DEL–1 well, showing the microfauna encountered in the studied well are largely dominated by hyaline calcareous taxa, associated with agglutinated and porcelaneous taxa. Note the clustering of plotted points around the hyaline calcareous axis and the inserted box at right corner shows different test distribution (in colours) along depth intervals of the studied well.

Buliminella spp. (Figs. 4 and 9) are epifaunal foraminifera that show dysoxic to suboxic preferences within the depth range of 164–656 ft, while *Elphidium* spp. and other species of *Uvigerina* and *Bolivina* (Fig. 4) are infaunal species that are known for their dysoxic/suboxic preferences with a preferred depth range of 32–429 ft.

The species, *Heterolepa pseudoungeriana, Lenticulina inornata, Nonion* spp, *Elphidium* spp. and *Quinqueloculina* spp. thrives conveniently in warm temperatures. The persistent occurrences of these species across the studied succession depict dominance of neritic warm water conditions in the early to middle Miocene (Fig. 3). Likewise, are these taxa – *Marginulina* spp., *Ammonia beccarii,* and *Buliminella* spp. that are associated with warm water temperature (15 °C) for maximum breeding (Murray 1991) but survive across different environments. From the palaeobathymetry deductions made in section 4.3 and the illustration in Fig. 9, the lower horizons (7000–9460 ft) have a slight high abundance of infaunal taxa with low oxygen conditions and fine to medium grain sediments. Thus, the lower succession of the studied well could be defined as an oxygen-depleted benthic environment characterised by high productivity (possible high organic carbon contents), fine grain size-sediments, high sediment accumulation rates and generally homogeneous habitats (Jorissen et al., 1995; Gooday and Jorissen, 2012; Venturelli et al., 2018). The variant proportions of the epifaunal and infaunal species suggest species' ecological tolerance in a warm temperature as a result of habitat/environmental heterogeneity.

4.4.4. Salinity

The salinity inferred was based on the major constituent of various test types (agglutinated, hyaline calcareous and porcelaneous calcareous) of the foraminiferal assemblages as shown in the ternary plot in Fig. 10. The proportion of test-type has been applied to distinguish the normal marine, brackish, and hypersaline environments (Murray, 1968). Calcareous benthic foraminifera dominated (80%) the recovered foraminifera in the DEL-1 well (Fig. 4), indicating a general deposition in an open marine system (Nagy et al., 1988). The clustering of the plotted points around the hyaline calcareous axis indicates the dominance of normal marine – a neritic environment in the modern microfauna identification schemes of Corliss (1985) and Murray (1991). In support of the earlier defined palaeobathymetry, significant numbers of samples from the early Miocene interval (8000–9400 ft) of the well (Fig. 10) fall around the hyaline calcareous vertex and spread slightly towards the porcelaneous calcareous to depict a near-normal marine. Up-hole, the points representing the late early to middle Miocene (5400–8000 ft) conversely show a strong affinity to high salinity (Fig. 10) (Jorissen et al., 1995).

The foraminiferal composition and distribution are often influenced by salinity aside from temperature variation other environmental parameters within the ocean column (Boltovskoy and Wright, 1976). According to Wright et al. (2011), oceanic salinity is segmented into hyperhaline >65‰, metahaline 45–65‰, euhaline 30–35‰, polyhaline 18–30‰, mesohaline 5–18‰, oligohaline 0.5–5‰, and fresh <0.5‰ for interpretation purposes. Taking clues from Murray (1974) and Licari and Mackensen (2005) interpretative models (water salinity, temperature and depth range) on the shelf and slope-deep settings in the Gulf of Mexico and West African sea, respectively, the abundance of euryhaline taxa; *Quinqueloculina* spp., *Cibicides* spp., *Elphidium* spp., *Nonion* spp. *Trochammina* spp., and *Eggerella* spp. (Fig. 4), which are best tolerant to oligotrophic and eutrophic waters, connote preponderance of polyhaline water salinity (18–30‰) in the early Miocene. However, the relative abundance of *Ammobaculities* spp. and *Haplophragmoides* spp. (Fig. 5) indicate the water masses could attain a possible low salinity level of 5‰ salinity (Kane, 1967; Boltovskoy and Wright, 1976) to suggest conservative nature of relatively lower stress environment of the oligotrophic condition.

A decrease in abundance and diversity of faunal within the interval 6750–8000 ft with the dominance of resistant epifaunal taxa (*Eggerella* spp., *Epistominella* spp., and *Quinqueloculina lamarckiana*), suggest an increase in marine salinity (26–35‰). Of these taxa, they characterise inner shelf epifaunal specimens depicting ecological niche of mesotrophic condition (possibly of brackish water) of probable temperature −2 to 26 °C. The paucity of agglutinated foraminifera and relative abundances of *Quinqueloculina* spp., *Uvigerina peregrina* (35–36‰, temperature 5–20 °C) and *Elphidium* spp. were recorded within the interval 5400–6750 ft to suggest euhaline salinity (30–40‰). This could be attributed partly to the initial deposition of sandy sediments in the studied well. Consequently, the dearth of foraminifera species (lone occurrences of *Quinqueloculina* spp. and *Ammonia beccarii*) was recorded within 4500–5400 ft. The latter is linked to water salinity of 22–37‰ and temperature of about 10–32 °C (Murray, 1991) to signals polyhaline and euhaline salinity levels in mesotrophic to eutrophic conditions. Moreover, the constant occurrence of *Ammonia beccarii* throughout the studied horizons attests to ubiquitous salinity fluctuation of the early to middle Miocene (Boltovskoy and Totah, 1992; Vasiliev et al., 2019).

4.5. Broader implications of the research data

The high abundance and diversity of recovered taxa in the early Miocene interval of the studied succession (Figs. 4–7), and the converse paucity of foraminiferal assemblages in the overlying middle Miocene permit some inferences on the Miocene palaeoenvironment in the Gulf of Guinea and its contiguous region. The predomination of argillaceous sediment in the early Miocene successions prevented significant influx and circulation of oceanic oxygen which disallowed scavengers to significantly destroy dead forms. Conversely, the prevalence of arenaceous lithology in the middle Miocene perhaps favoured circulation of oxygenated bottom water in the Gulf of Guinea, and thus created comfortable conditions for the dead forms to be scavenged. Although highly oxygenated sediment depositional condition is traditionally ascribed to hinder the reliable preservation of microfossils, the general preponderance of dysoxic, suboxic, and oxic taxa in the early Miocene succession, and rareness of same in the middle Miocene suggest that oxygen level alone was not responsible for the abundance and diversity variations between the two Epochs. This is in strong agreement with Allison (1988), who reported from a laboratory experiment that anoxia alone is an ineffective medium for preserving soft tissue marine taxa for a long time.

A critical integration of all datasets suggests that the high influx of coarser grain siliciclastic sediments coupled with the interpreted

prevalent progradational succession (Figs. 3–8), which were occasioned by insufficient sediment accommodation (space), was a major factor on which the preservation or destruction of dead marine taxa hinged. Nevertheless, this was perhaps an enhancement to the process that led to the pervasive carbonate crash in the offshore Niger Delta, going by the general correlation of low diversity and abundance of calcareous nannofossils in middle Miocene (NN5) across the offshore Niger Delta (Fadiya and Salami, 2012; Oretade and Ali, 2021). Giving the well-documented effects of the middle Miocene Climatic Optimum, which resulted in the extinction of both terrestrial and marine forms (Matthews et al., 1980; Flower and Kennett, 1993; Pearson et al., 2006; Methner et al., 2020), the documented rarity of microfossils in the middle Miocene (~Langhian) succession in DEL-1 well points to the prevalence of conditions such as changes in the intensity of chemical weathering and riverine input of calcium and carbonate ions into the ocean reservoir and vicissitudes of biological productivity (Roth et al., 2001; Jiang et al., 2007; Lübbers et al., 2019), might have hindered reliable preservation of extinct taxa. Implying that non-carbonate sediments deposition perhaps aided carbonate reduction in the middle Miocene sediment of the Gulf of Guinea (Diester-Haass et al., 2004; Jiang et al., 2007).

5. Conclusions

The retrieved faunal assemblages consist of planktic and benthic foraminiferal communities, while the index foraminifera species distribution enabled the recognition of M2/N5 Zone (*Globigerinatella* spp./ *Catapsydrax dissimilis* Concurrent–range Zone – early Miocene), M4b/N7 zone (*Fohsella birnageae* Lowest Occurrence Subzone – early Miocene), and M6/N9 zone (*Orbulina suturalis* Lowest Occurrence Zone – middle Miocene) delineation. The integrated lithofacies and biofacies show the early Miocene succession consists of shale beds and packets of fine to medium-grained sandstones that are of inner to outer neritic environment with an occasional coastal deltaic setting within the continental shelf. Conversely, the middle Miocene succession is made up of dominant medium to coarse-grained sandstone with interbeds of shale that is of a coastal deltaic environment with occasional fluxes of inner neritic sediments to characterise the palaeobathymetric settings. The early to middle Miocene palaeoenvironmental condition/ecological fluxes in the Gulf of Guinea was generally unstable, and it is construed to be mainly controlled by lithological changes, alteration in palaeoceanic conditions from oligotrophic to eutrophic water conditions, and the salinity fluxes. Whereas the early Miocene was characterised by an increase in ecological parameters (abundance, species richness, Shanon-Wiener diversity, and evenness) and slightly low salinity, the overlying middle Miocene recorded a converse decrease in the ecological parameters with a corresponding slight increase in salinity. The observed foraminifera patterns in the Gulf of Guniea as presented in this study resulted from the interplay of lithological composition, salinity, and oxygen fluctuation. However, the lithology likely exerted a stronger influence on the other two parameters and by implication on the foraminifera abundance and diversity.

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