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Research Paper

Biofacies and Sequence Stratigraphy of AT-4 Well Offshore Eastern Dahomey Basin, Southwestern Nigeria

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Abstract
The biofacies and sequence stratigraphy of the AT-4 Well in the offshore eastern Dahomey Basin have been investigated to unravel its stratigraphic succession and paleoenvironmental conditions. The sediments, mainly shale and sandstone, from varying depths (2,880 ft to 6,180 ft) in the AT-4 well were subjected to foraminiferal analysis. Important foraminiferal species recorded include planktic foraminifera such as Hedbergellaholmdelensis, Hedbergellamonmouthensis, Hedbergellaplanispira, Hedbergelladelrioensis, Globotruncanahavanensis, Heterohelixglobulosa, Heterohelixreussi, Heterohelix pulchra, and Heterohelix striata. Associated benthic foraminiferal species recorded include Praebulimina fang, Praebulimina addi, Praebuliminaprolixa, Buliminellaquadrilobata, Cibicidesharperi, Hanzawaiamantansis, Lenticulinastephensoni, Haplophragmoidesexcavata, Haplophragmoidesbauchensis, Haplophragmoideshausa, Trochamminatexana, and Trifarinaangulosa. Two possible depositional environments were inferred. The outer Neritic biofacies is characterised by fossil assemblages dominated by Haplophragmoides excavata and Hedbergellaholmdelensis, indicating a shallow marine environment associated with sand lithology, and the upper Bathyal biofacies is characterised by fossil assemblages dominated by planktic and benthic foraminifera, indicating a deep marine depositional environment associated with shale lithology. Sequence stratigraphic analysis identified two sequences, Transgressive Systems Tracts (TST) and Highstand Systems Tracts (HST), marked by Maximum Flooding Surfaces (MFS) at 5100 ft (correlated with 69.5 Ma) and 4020 ft (correlated with 67.5 Ma), respectively, both within the Maastrichtian. The integration revealed retrogradational and progradational parasequence signatures of inner Neritic to upper Bathyal environment, suggesting deepening and shallowing cycles linked to global sea-level changes.
Keywords: *Foraminifera, Depositional Environment, Transgression-Regression, Sea-level changes*

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I. Introduction

The Dahomey Basin, located along the Gulf of Guinea (Figure 1), is a significant sedimentary basin that spans from the southeast of Ghana, through Togo, the Benin Republic, and southwestern Nigeria (Coker and Ejedawe, 1987). The Nigerian sector, also referred to as the eastern Dahomey Basin, terminates at the Okitipupa hinge line, which is located to the west of the Niger Delta Basin. It is a marginal sag/ pull-apart basin (Kingston et al., 1983). The basin formed during the breakup of the Gondwana supercontinent in the Mesozoic era, particularly during the Late Jurassic to Early Cretaceous periods, as a result of the separation of the South American and African plates (Omatsola and Adegoke, 1981; Bassey et al., 2013). Omatsola and Adegoke (1981) were among the first to propose a sequence stratigraphic model for the basin, identifying major depositional sequences and their associated systems tracts. Sequence stratigraphy is a concept that groups genetically related strata, denoted as a sequence, by conformable or unconformable boundaries. Biofacies analysis reveals stratigraphic sequence changes marked by the abundance and diversity of several microorganisms. The integration of these two concepts provides an enhanced mappable and correlative unit of sedimentary formation successions.

Foraminifera are a diverse group of protist microorganisms, benthic and planktonic forms, that are specified paleontological tools for environmental reconstruction. Their survival, adaptation, and responses to climatic situations have shaped studies in depositional environments and paleoenvironmental conditions. The Dahomey Basin's Cretaceous to Quaternary sedimentary sequences have been extensively studied to understand the interplay between tectonic activity, sea-level changes, and sedimentation patterns, with foraminifera serving as key biostratigraphic and paleoenvironmental indicators. Adegoke et al. (1971) and Petters (1982) have documented the presence of diverse foraminiferal assemblages in the basin, which have been used to establish

biostratigraphic zonations and correlate sedimentary units across the basin. Recent studies (Asadu and Ameh, 2020; Agunsoye et al., 2022; Aturamu and Akinmosin, 2024) have continued to review and establish the biostratigraphy constraints of the basin. The Dahomey Basin still has many nomenclatures and historical gaps stratigraphically due to insufficient data and complexity. The biostratigraphy constraints can be resolved with palaeontology and sequence evolution. This research centres on the biofacies analysis of the AT-4 well in the eastern Dahomey Basin, Southwestern Nigeria, which provides significant insights into the foraminiferal assemblages, depositional environments, including paleoclimatic conditions, and sequence stratigraphy of the studied interval. This paper aims to establish the biozonation and interpret depositional sequence environment using foraminifera species in the sediments penetrated by AT-4 Well.

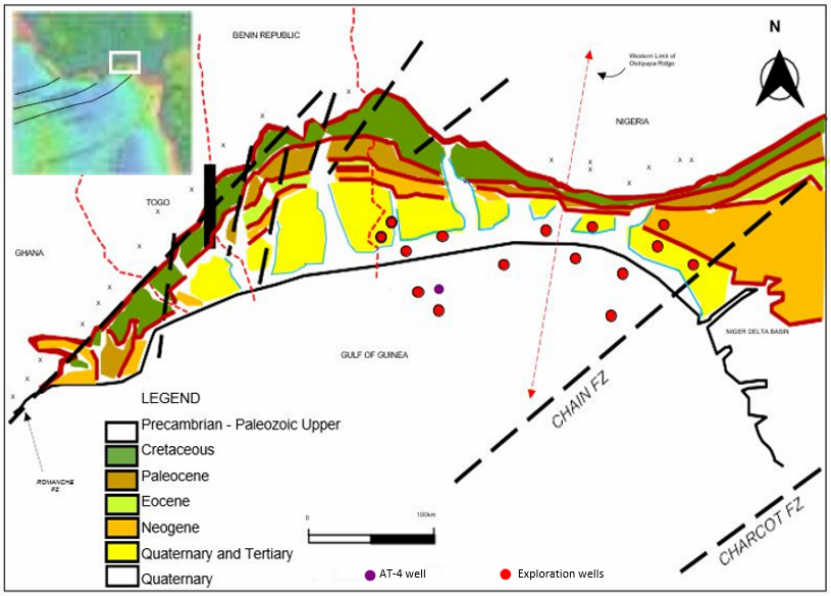


Figure 1: Geology of the Dahomey Basin, West Africa (modified after Billman, 1973)

II. Materials And Methods

Twenty ditch-cutting samples were used for this study, ranging in depth from 2880ft to 6180ft, from the AT-4 well. The lithology was described, and the sediments were characterised manually by observation based on size, colour, feel, and composition. For the foraminifera analysis, the samples were subjected to disintegration, sieve washing, decantation with different sieve sizes, and drying. Approximately 20 grams of each sample were digested using kerosene for 24 hours, and then washed over sieves with mesh sizes of 250 µm, 125 µm, and 63 µmto facilitate picking. Foraminifera species were identified using a binocular microscope, and classification was performed based on morphology and the guidance of relevant literature. The micropaleontology analysis was done at the Earthprobe Nigeria Limited Laboratory.

III. Results And Discussions

3.1Lithology Description

The AT-4 Well penetrated a total depth of 6,180 ft, with two lithology successions that include shale and sandstone within the study interval (Figure 2). The lower depth is predominantly sand, overlain by shaly sand in the middle, and sandy shale in the upper section. Each interval shows different characteristics based on its environment of deposition and the processes that led to its formation. The grains are generally fine to coarse, subangular to subrounded, with considerable ferruginous materials. The milky-white feel of the sediments suggests a calcareous composition, and the fissile nature of the grains is an indication of the high clay content. The section penetrated by the well appears to have undergone a moderate to high degree of diagenetic processes, as observed in the significant ferruginous content, and an anoxic condition is inferred from the brownish colouration.

The variation of the sand/shale ratio is related to a coastal-influenced environment, where brackish conditions and coastline cycles are prevalent. The alternation of the same lithology and mixture of different grain sizes supports a high-energy environment, contrasting with a low-energy environment at the point of deposition. The AT-4 well sediments suggest a deltaic/ shallow marine environment.

Depth(ft)	Symbol	Lithology	Description
2880 3000 3180		Sandyshale	milky white to glassy, fine to medium to coarse, subangular to subrounded, poorly sorted, Greyish to brownish, flaggy to fissile, moderately hard shale. Few ferruginous materials and few mica flakes.
3420 3690 3930 4020 4470 4620 4890 5010 5100 5460		Shalysand	Milky white to glassy, fine, but occasionally coarse, subangular to subrounded, fairly sorted sands. slightly calcareous. Greyish to brownish, flaggy to fissile, moderately hard shale. Glauconite and mica flakes
5640		Sandyshale	Milky white to glassy, fine, subangular to subrounded, well sorted sands. highly calcareous. Greyish, fissile, moderately hard shale
5790 5850 5910		Shalysand	Milky white to glassy, fine, subangular to subrounded, well sorted sands. highly calcareous. Greyish to brownish flaggy to fissile, moderately hard shale with glauconite as accessory.
5970 6180		Sandshale	Milky white to glassy, fine, subangular to subrounded, well sorted sands. rarely calcareous. Greyish to brownish, flaggy to fissile, moderately hard shale with shell fragments

Legend
Sandyshale
Shalysand

Figure 2: Lithostratigraphic chart of AT-4 well

3.2 Biostratigraphy

3.2.1 Species discoveries and diversities

The distribution, abundance, and diversity chart of the recorded foraminiferal species, together with the foraminiferal zones recognised, is presented in Figure 3. The studied interval shows the presence of one hundred and thirteen (113) foraminifera species. The species are composed of 26 planktonics, 87 Benthonics (40 calcareous, 47 agglutinated).

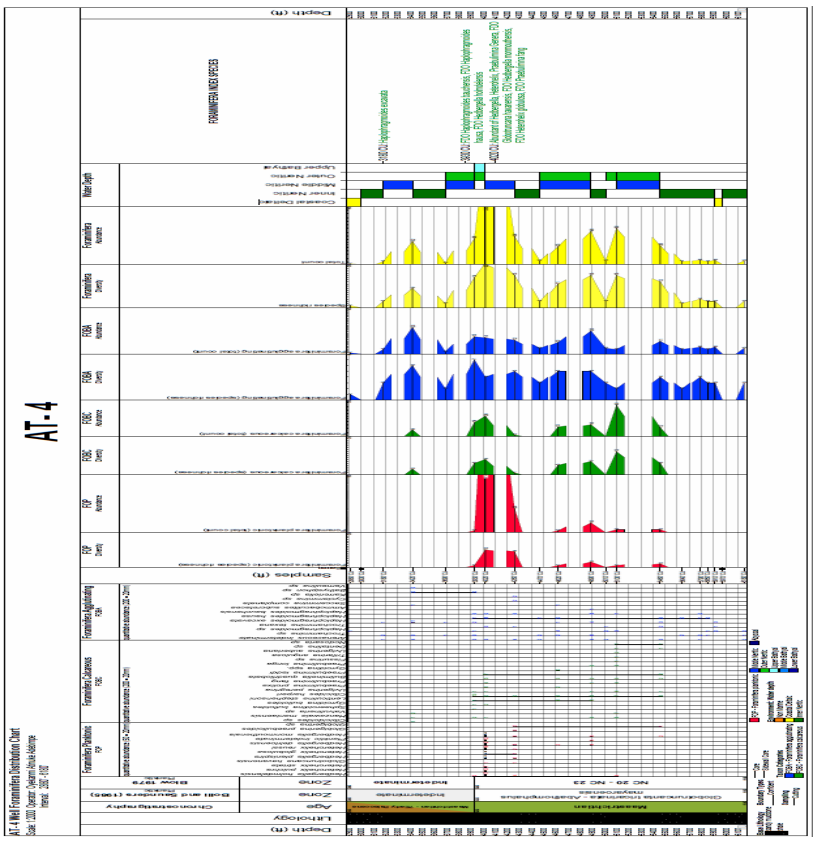
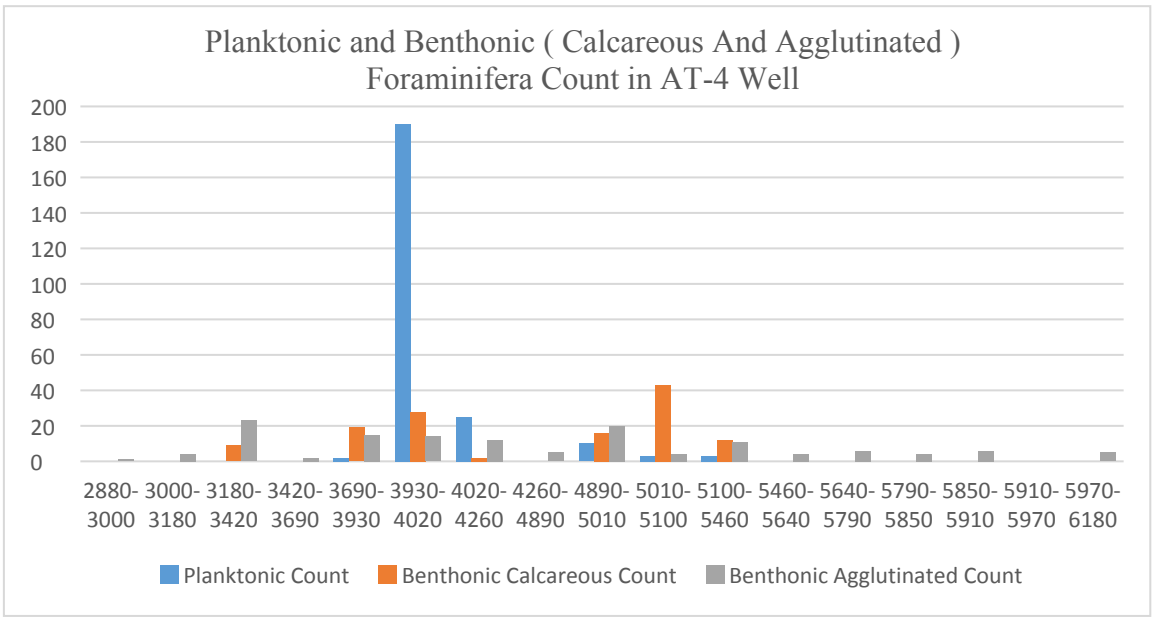


Figure 3: Foraminifera distribution chart of the studied well interval



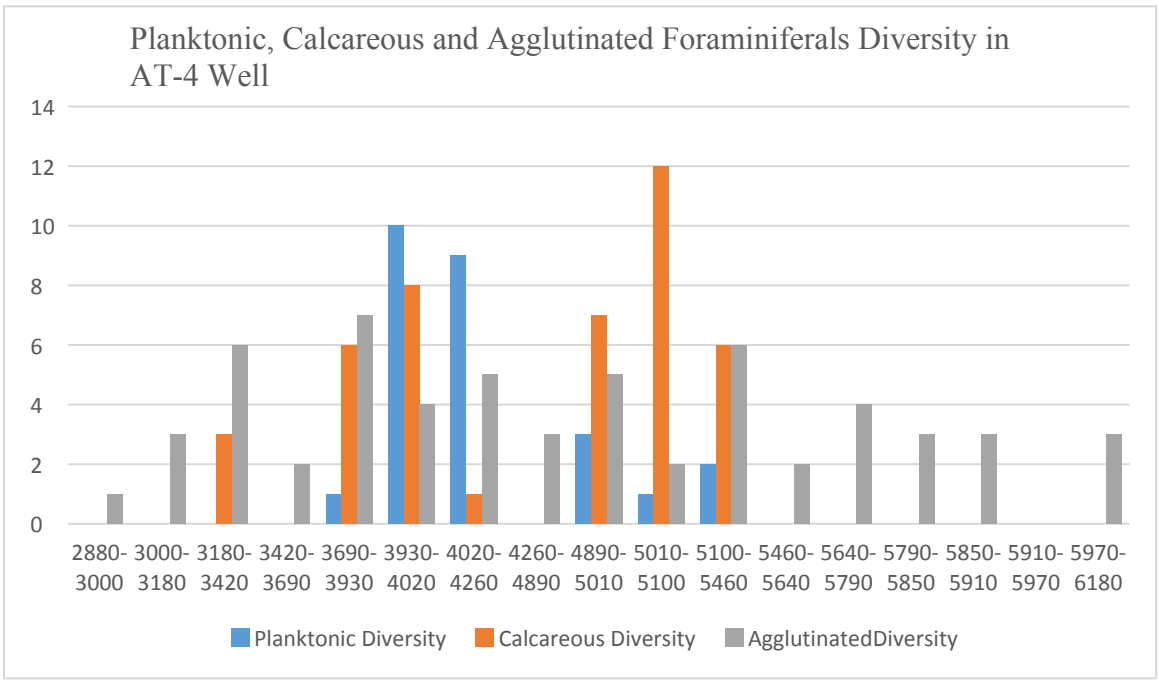


Figure 4: Abundance and Diversity of recovered species

Planktic and Benthic foraminiferal species (calcareous and arenaceous) are represented in the studied well (Figure 4). Index forms among the recovered foraminiferal species have been used to date and zone the intervals. Important foraminiferal species recorded include planktic foraminifera such as Hedbergellaholmdelensis, Hedbergellamonmouthensis, Hedbergellaplanispira, Hedbergelladelrioensis, Globotruncanahavanensis, Heterohelixglobulosa, Heterohelixreussi, Heterohelix pulchra, and Heterohelix striata. Associated benthic foraminiferal species recorded include Praebulimina fang, Praebulimina addi, Praebuliminaprolixa, Buliminellaquadrilobata, Cibicidesharperi, Hanzawaiamantansis, Lenticulinastephensoni, Haplophragmoidesexcavata, Haplophragmoidesbauchensis, Haplophragmoideshausa, Trochamminatexana, and Trifarinaangulosa.

Foraminiferal recoveries were generally sparse to moderate and moderately preserved. This may be due to freshwater incursion and the environmental salinity conditions. It could be inferred from the lithology penetrated that coastal influence is prevalent, and the sand/shale ratio is significant. The abundance of agglutinated forms suggests intense terrigenous input of sediment grains that provided support for their hard tests/wall (Helenes *et al*., 2019). The absence of planktic foraminifera within deeper depths is an indicator of an

anoxic, low-oxygen environment, which would further dissolve the calcareous forms (Peters, 1982). The assemblage of AT-4 well foraminifera species ranges from coastal to bathyal environments of deposition.

3.2.2 Biozonation and Age Determination

The foraminiferal zonation of the AT-4 Well (Table 1) was guided by the low latitude biozonation works of Blow (1969, 1979), Bolli and Saunders (1985). Foraminiferal species whose stratigraphic distributions have been well established in the Nigerian Sedimentary basins were also used to assign ages. The taxonomic classification is based on external morphology. The result of the analysis indicates that the study interval (2,880 – 6,180ft.) of AT-4 well was deposited during the Maastrichtian age within the Late Cretaceous period, of estimated numerical age of 67.5Ma to 71.0Ma, straddling the NC20 (Globotruncanatricarinata) to NC23 (Abathomphalusmayaroensis) planktic zones of Blow (1969, 1979), and Bolli and Saunders (1985).

The following Important foraminiferal dating events were used:

I. First Downhole Occurrence (FDO) of chronostratigraphically significant planktic/benthic foraminiferal species.
II. Last Downhole Occurrence (LDO) of planktic/benthic foraminiferal marker species.

Stratigraphic Interval: 2,880 – 3,930ft
Planktic Zone: Indeterminate
Age: Maastrichtian -Early Palaeocene
Estimated Numerical age: 67.5 and Younger
Definition
Interval age was based on the occurrence of Haplophragmoides excavata at 3,930ft.
Diagnostic features

a) The upper boundary of this zone is tentatively placed at the first sample analysed at 2,880ft.
b) The low recovery of foraminiferal species prevented the recognition of standard planktic foraminiferal zonal schemes of Blow (1979), and Bolli and Saunders (1985) erected for the low-latitude region. Unfavourable temperature, salinity, and pressure conditions may have prevailed during the period (Oluwajana *et al*., 2021). Few foraminiferal species recorded include Haplophragmoides excavata, Saccamminacomplanata, Haplophragmoides sp., Verneulina sp., Hanzawaiamantaensis, and Valvulineria sp.
c) The lower boundary of this zone is marked at 3,930ft by the FDO Hedbergellaholmdelensis.

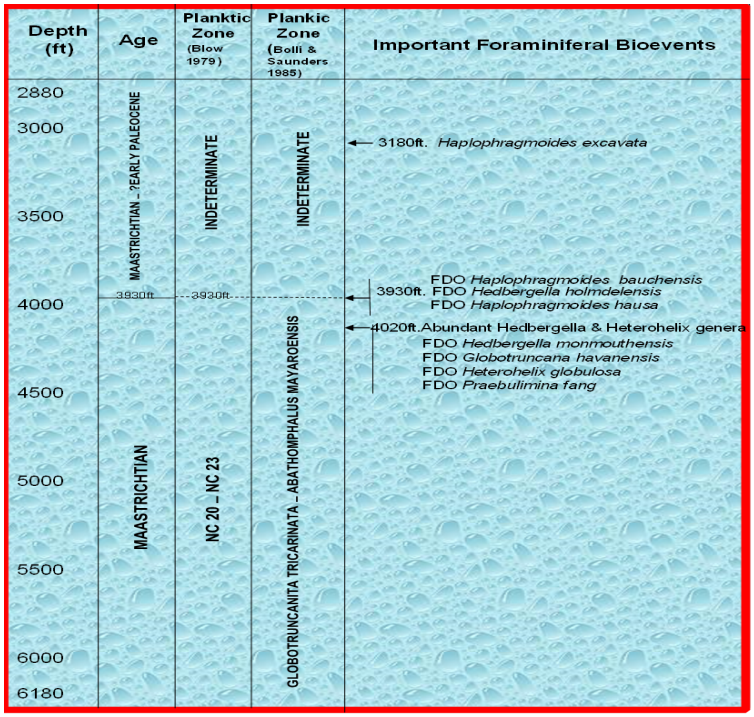
Stratigraphic Interval: 3,930 – 6,180ft
Planktic Zone (Blow 1979): NC23 – NC20
Planktic Zone (Bolli and Saunders 1985): Abathomophalus mayaroensis – Globotruncanatricarinata
Age: Maastrichtian
Estimated Numerical age: 67.5Ma - 71.0Ma
Definition
Interval age was based on:
First Downhole Occurrence of FDO Hedbergellaholmdelensis at 3,930ft.
First Downhole Occurrence of FDO Haplophragmoideshausa at 3,930ft.
First Downhole Occurrence of FDO Hedbergellamonmouthensis at 4020ft.
First Downhole Occurrence of FDO Heterohelixglobulosa at 4020ft.

Diagnostic features

a) The upper boundary of this zone is defined by the FDO of Hedbergellaholmdelensis at 3,930ft.
b) Interval characterised by diverse planktic and benthic foraminiferal assemblages dominated by species of Hedbergella, Heterohelix, and Praebulimina, suggesting a Maastrichtian age for this interval.
c) Recorded planktic species include the following: Globotruncanahavanensis, Hedbergellaholmdelensis, H. monmouthensis, H. delrioensis, H. planispira, Heterohelixglobulosa, H. reussi, H. striata, and Heterohelix pulchra.
d) Calcareous benthic foraminiferal assemblage over this interval includes: Praebulimina fang, P. laddi, P. prolixa, Buliminella quadrilobata, Hanzawaiamantaensis, Cibicides harperi, Lnticulinastephensoni, Sphaeroidinabullodes, Trifarinaangulosa, and Uvigerina peregrina.
e) Associated arenaceous species that characterised this interval include Haplophragmoidesexcavata, Trochamminatexana, Haplophragmoideshausa, Haplophragmoidesbauchensis, and Ammobaculitessubcretacea.

f) The observed increase in abundance and diversity of foraminiferal species at depths 4,020ft and 5,100ft could be a condensed section and is probably associated with 67.5 Ma MFS and 69.5 Ma MFS, respectively (Enge *et al*. 2016).
g) The lower boundary of this zone is not reached at the last sample analysed, tentatively placed at the Terminal Depth at 6,180ft.

Table 1: Foraminifera Biozonation of AT-4 Well



3.2.3 Paleoenvironmental Indication

The analysed interval shows a progressive deepening of the depositional environment from the base (6180 ft) upward to a depth of 4,020 ft, followed by shallowing upward again to the topmost depth (2,880 ft). The high shale percentage (70–90) in association with glauconite, pyrite, and mica flakes over the interval 5460 ft–3420 ft suggests a low-energy, anoxic marine depositional condition. This is confirmed by the moderately abundant and diverse foraminiferal fauna recovered within the interval. These include Hanzawaiamantaensis, Gyroidinabulloides, Cyclamminasp., Karreriellasp., Trifarinaangulosa, Sphaeroidinabulloides, Cibicidesharperi, Uvigerina peregrina, Nodasariasp., Buliminellaquadrilobata, Saccamminacomplanata, Praebulimina fang, Lenticulinastephensoni, and Fisurinasp. This benthic foraminiferal association suggests sediment deposition in the Middle to Outer Neritic (Fadiya and Ojoawo, 2015). The paleoenvironment deepened to Upper Bathyal at a depth of 4020ft, where foraminiferal abundance and diversity were recorded, including planktic species.

Intervals 6180 – 5640ft and 3180 – 2880ft were predominantly sandy with common shell fragments and carbonaceous detritus in association with shallow water arenaceous foraminiferal species such as Trochamminatexana, Haplophragmoidesexcavata, Haplophragmoidesbauchensis, Haplophragmoideshausa, Trochamminasp. and Arenaceous indeterminate, indicating high-energy Inner Neritic to Coastal Deltaic environmental settings (Peters, 1982).

Interval 1 (2880-3930FT) Outer Neritic Environment
Description: Shallow to moderate depth marine environment, characterised by a mix of coastal and open ocean influences, characterised by low abundance of planktonic foraminifera, high diversity of benthonic foraminifera.

Interval 2 (3930-5460ft) Middle –Upper Bathyal Environment
Description: Moderate to deep marine environment, with increasing open ocean influence and decreasing coastal effects, characterised by a high abundance of planktonic foraminifera and diverse benthonic foraminifera.

Interval 3 (5460-6180ft) Upper Bathyal – Lower Bathyal Environment

Description: Deep marine environment, characterised by low light, high pressure, and limited coastal influence, with the absence of planktonic organisms, which might be a result of some environmental factors such as temperature, Salinity change, pH, and food scarcity.

3.3Sequence Stratigraphy

The well log sequence stratigraphic analysis technique proposed by Vail and Wornardt (1991) has been adopted in this study. Armentrout et. al. (1990) method was also adopted in recognising chronostratigraphic surfaces using patterns of foraminiferal abundance and diversity. Foraminiferal density and diversity lows and peaks have been used for defining candidates for sequence boundary and condensed section, respectively (Figure 5). Furthermore, identifiable systematic variations in foraminiferal abundance and diversity, as well as the paleo bathymetric curve for the studied section of the well, have aided the recognition of systems tracts.

The sequence stratigraphic framework proposed here has been correlated with the Global Cycle Chart of Haq et al (1988). The correlation has been guided by chronostratigraphically significant bioevents recorded over the studied section. The proposed sequence stratigraphic framework for AT-4 is summarised in Table 2, and the sequence stratigraphic events are briefly highlighted below:

The interval shows three distinct sequences constituting the High System Tracts (HST) and Transgressive System Tracts (TST), characterised by different lithology and paleoenvironment trending patterns.

Sequence 1: 6180 – 5970ft

Bio-event 1: 6180 – 5970ft: Highstand Systems Tract (HST)

The interval is characterised by a high sandy unit and recorded very sparse foraminifera abundance and diversity, showing a shallowing-upward paleoenvironmental trend. The Sequence Boundary (SB) at the top of this sequence is picked at 5970 ft, characterised by low foraminifera abundance and a diversity peak. Based on stratigraphy position, this sequence Boundary is correlated with the 69.5 Ma event of Haq *et al*. (1988).

Sequence 2:5970 – 5100ft

Two system tracts characterise this interval.

Bio-event 1: 5970- 4470 ft, Transgressive Systems Tract (TST)

This depth is characterised by TST with high shale percentage, increasing upward foraminifera abundance and diversity, showing a deepening-upward paleoenvironmental trend. The interval terminated in a condensed section marked by foraminifera abundance/diversity maxima at 5100 ft. The maximum flooding surface (MFS) marked at the top of the TST is picked within the condensed section and is believed to be related to the?69.5 Ma flooding event based on correlation with the Global Cycle Chart of Haq *et al.* (1988). This age is assigned based on its stratigraphic association with the First Downhole Occurrence (FDO) of the planktic foraminiferal species, Hedbergellamonmouthensis, at 4020ft.

Bio-event 2: 5100 ft – 4470 ft: Highstand Systems Tract (HST)

The interval is characterised by HST, a sandy unit, with dressing-upward foraminifera characterised by a shallowing-upward paleoenvironmental trend. Stratigraphic position is directly above the Maximum Flooding Surface (MFS).

The Sequence Boundary (SB) at the top of this sequence is picked at 4470ft, characterised by low foraminiferal abundance and a diversity peak. The Sequence Boundary is correlated with the 68.0 Ma Sequence Boundary of Haq *et al*. (1988).

Sequence 3: 4470 – 2880ft

This sequence is characterised by two system tracts.

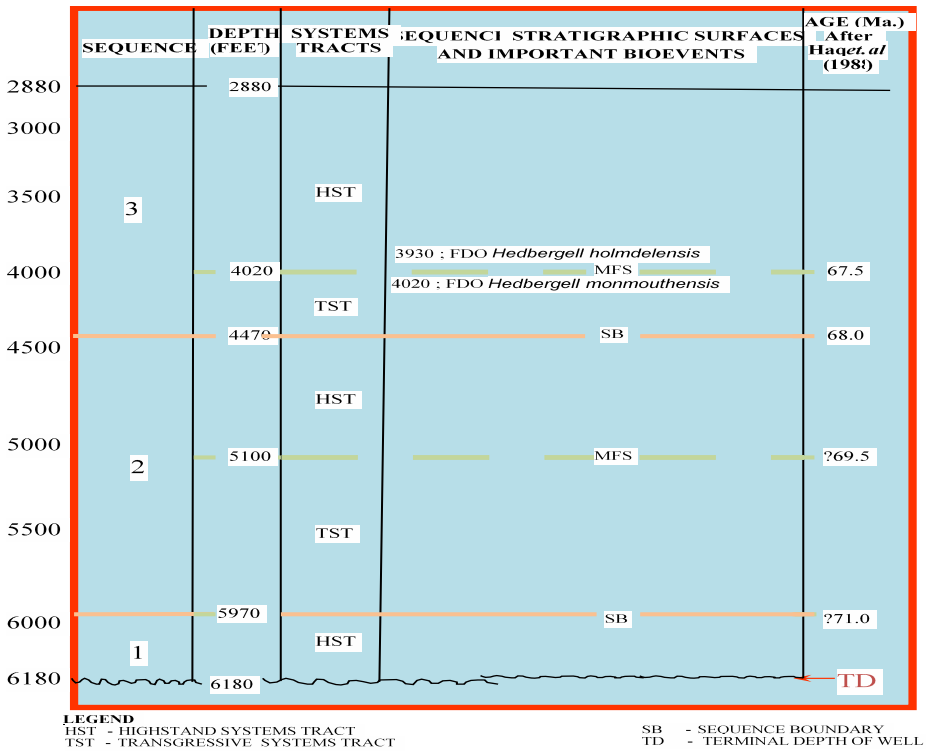
Bio-event 1: 4470 – 4020ft: Transgressive Systems Tract (TST)

This interval is a high-shaly unit with increasing species and a deepening-upward paleoenvironmental trend. The interval terminated at the condensed section (MFS)picked at 4020 ft, characterised by foraminiferal abundance/diversity maxima. The MFS is believed to be related to the 67.5Ma flooding event based on correlation with the Global Cycle Chart of Haq et al. (1985). This age is assigned based on its stratigraphic association with the First Downhole Occurrence (FDO) of the planktic foraminiferal species, Hedbergellamonmouthensis and Hedbergellaholmdelensis at 4020ft and 3930ft, respectively.

Bio-event 2: 4020 ft- 2880ft, Highstand Systems Tract (HST)

The interval 4020 ft- 2880ft is characterised by a high sandy unit with decreasing species abundance and diversity and shallowing-upward paleoenvironmental trend. The Sequence Boundary (SB) marking the top of this HST is probably shallower than the top of the analysed section (2880ft) of this well.

Table 2: Sequence stratigraphic model of AT-4 well



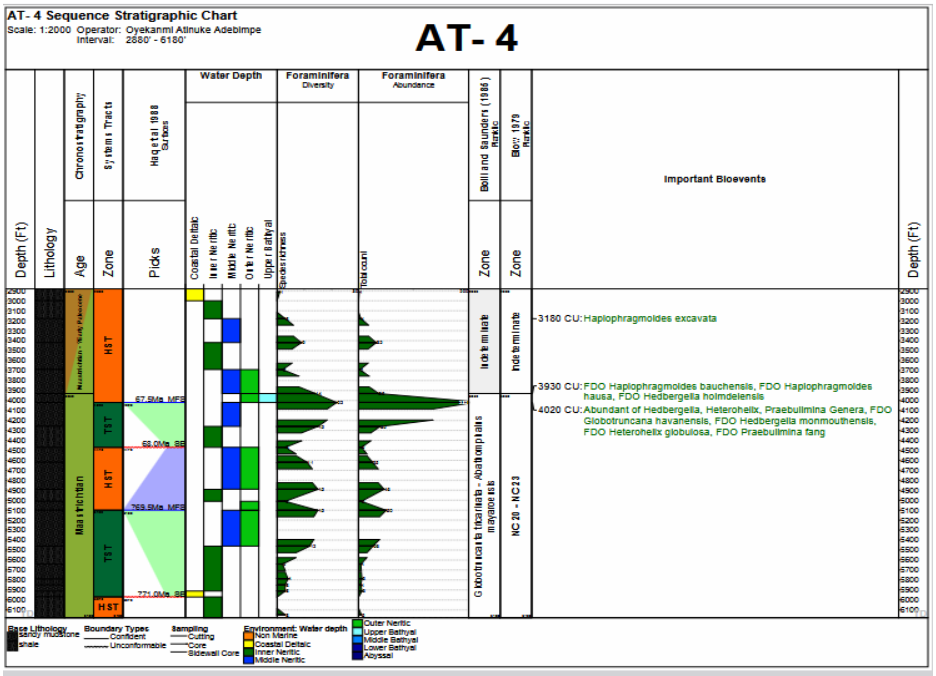


Figure 5: Sequence stratigraphic chart for AT-4 Well

IV. Conclusions

The biofacies analysis of the AT-4 well in the eastern Dahomey Basin, Southwestern Nigeria, provides significant insights into the foraminiferal assemblages, depositional environments, and sequence stratigraphy of the studied interval (2880–6180 ft). The study reveals that the interval was deposited during the Maastrichtian age, with an estimated numerical age ranging from 67.5 to 71.0 million years ago. This age determination is based on the presence of key planktic and benthic foraminiferal species, such as Hedbergellaholmdelensis, Hedbergellamonmouthensis, Hedbergelladelrioensis, Haplophragmoidesexcavata, and Trochamminatexana,

which are well-documented in the Nigerian sedimentary basins and globally recognised for their chronostratigraphic significance.

The foraminiferal assemblages indicate a variety of depositional environments, ranging from marginal marine (fluvio-marine) to shallow inner neritic, middle neritic, outer neritic, and upper bathyal settings. The presence of arenaceous foraminifera, such as Haplophragmoides spp., and Trochamminaspp., in the lower and upper intervals suggests high-energy, shallow-water environments, likely associated with coastal deltaic settings. In contrast, the middle intervals, characterised by calcareous benthic foraminifera such as Hanzawaiamantaensis, Cibicidesharperi, and Uvigerina peregrina, indicate deeper, low-energy, anoxic marine conditions, typical of middle to outer neritic environments. The presence of planktic foraminifera, particularly in the middle section (around 4020 ft), further supports an open marine environment, with the highest foraminiferal abundance and diversity suggesting a condensed section associated with maximum flooding surfaces (MFS).

The sequence stratigraphic analysis reveals three distinct sequences within the studied interval, each characterised by transgressive and highstand systems tracts. The lowermost sequence (6180–5970 ft) is interpreted as a highstand systems tract (HST), marked by a high sandy unit and sparse foraminiferal recovery, indicating a shallowing-upward trend. The middle sequence (5970–4470 ft) includes a transgressive systems tract (TST) with increasing foraminiferal abundance and diversity, culminating in a condensed section at 5100 ft, interpreted as the maximum flooding surface (MFS). This is followed by a highstand systems tract (HST) with decreasing foraminiferal abundance and diversity, indicating a shallowing-upward trend. The uppermost sequence (4470–2880 ft) also shows a transgressive systems tract (TST) with increasing foraminiferal abundance and diversity, peaking at 4020 ft, interpreted as another MFS, followed by a highstand systems tract (HST) with decreasing foraminiferal recovery.

The alternating foraminiferal discovery in terms of abundance and diversity is an indication of the seasonal climatic/sea-level changes and oxygenation fluctuation attributed to the Dahomey Basin in the Gulf of Guinea, as supported by the litho/bio/sequence stratigraphy. The absence of carbonate rocks in the offshore sequence of the Basin also supported the few discoveries of foraminiferal species.

APPENDIX A

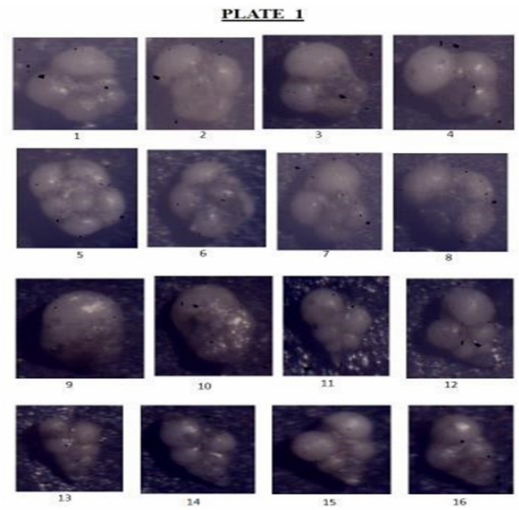
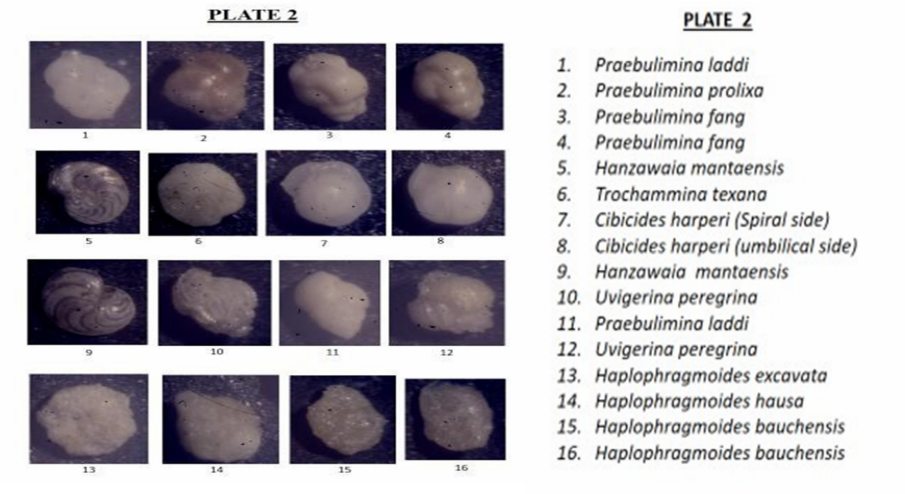


PLATE 1

1. *Hedbergella monmouthensis (Spiral side)*
2. *Hedbergella monmouthensis (umbilical side)*
3. *Hedbegella delrioensis (Spiral side)*
4. *Hedbergella delrioensis (umbilical side)*
5. *Hedbergella holmdelensis (Spiral side)*
6. *Hedbergella holmdelensis (umbilical side)*
7. *Hedbergella delrioensis (Spiral side)*
8. *Hedbergella delrioensis (umbilical side)*
9. *Globotruncana havanensis (Spiral side)*
10. *Globotruncana havanensis (umbilical side)*
11. *Heterohelix reussi*
12. *Heterohelix reussi*
13. *Heterohelix globulosa*
14. *Heterohelix striata*
15. *Heteroheix striata*
16. *Heterohelix globulosa*

APPENDIX B



Authors Contributions

O.A.: conceptualisation, data generation, interpretation, writing and reviewing of manuscript
A.O.: data interpretation, writing of manuscript

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