High-Resolution Biostratigraphic Characterization of the Early Miocene Agbada Formation: Sequence Stratigraphic Implications for Reservoir Continuity in The Niger Delta Basin

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***Abstract*: The paper represents a detailed biostratigraphic and sedimentological investigation of Well HI-001 in the Niger Delta Basin by use of composite cutting samples comprising of fifteen ditch cuts, which cover the depth ranges of 2780 m to 3980 m. The main agenda was to answer the biochronological age and paleoenvironmental evolution of the stratigraphic section in resolving the existing gap between the site-specific correlation in the Early Miocene depobelts. The characterization of the lithostratinology has defined seven different units that alternate between shaly sands, sandy shales, and separate clay layers that show a typical example of a paralic sequence of the Agbada Formation. Sixty-five (65) species of foraminiferar were identified, including 16 planktons and 49 benthic foraminiferar. Even though the sampling resolution was limited to 30-meter composite intervals, the recovery of the Praeorbulina evolutionary lineage of Praeorbulina curva, Praeorbulina glomerosa, and the First Appearance Datum of Orbulina suturalis clearly places the studied section as either Early or Middle Miocene (Burdigalian or Langhian). This coincides with N8-N9 planktonic zones of Blow (1969), which is the critical period in the region of the accumulation of hydrocarbons. Paleobathymetric assessment of benthic index species Spiroplectammina wrightii, Bulimina buchiana and Lenticulina spp would indicate a deepening-upward succession of Coastal Deltaic, Inner Neritic and Outer Neritic environments. High-energy depositional environment caused by periodic marine incursion is confirmed by the prevalence of the quartz (>80 interpret of the sedimentological record) and the occurrence of authigenic glauconite and shell fragments. A separate Lowland Systems Tract (LST) is defined by coarse grained channel sands, superimposed by a Transgressive Systems Tract (TST) as defined by glauconitic sands with the surface being a Maximum Flooding Surface (MFS) in the calcareous shales of Unit 4. Essentially, the results are closely related to the geographical tendencies in the Greater Ughelli Depobelt regarded as the reflection of the stratigraphic setting that was captured within the Oloibiri and Ughelli fields. This makes Well HI-001 a dependable source of information on the Early Miocene period. The paper determines that although the Unit 1 sands have great reservoir potential, the structural complexities and rate of facies change inherent to this depobelt would necessitate very strict biostratigraphic control that would be useful in predicting the continuity of laterality and integrity of seals.**

***Keywords*: Niger Delta, Biostratigraphy, Early Miocene, Praeorbulina, Greater Ughelli Depobelt, Hydrocarbon Exploration, Sequence Stratigraphy, Reservoir Continuity.**

1. Introduction

A. Background of the Study

Niger Delta Basin is internationally known to be one of the most prolific hydrocarbon provinces, being one of the largest deltaic systems in the world. It is typified by a regressive series of thick and regressive clastic sediments, which occurs in an active wave-dominated and tide-controlled deltaic system. The basin itself has been geologically investigated with high intensity since the start of commercial oil production in the late 1950s. The accurate reconstructions of paleo environments and accurate age dating of sedimentary packages are crucial to the success of the exploration and exploitation of hydrocarbons in this region.

It is also like none other because of its huge thickness and complicated style of formation, which is caused by the gravity tectonics of the underlying Akata Formation shales. It has led to a sequence of depobelts which are clear sedimentary wedges that have advanced southward over time. Although the gross lithostratigraphy of the basin has been well documented (Short and Stauble, 1967; Doust and Omatsola, 1990), there are still certain problems regarding the reservoir correlations in complicated fault block areas. The large-scale growth faults and rollover anticlines prevail in the structural style of the Niger Delta and form compartmentalized reservoirs. In the Miocene sequences, facies shift rapidly over both short lateral distances, and lithostratigraphic correlation is no longer adequate and can be highly dangerous. This is complicated by the occurrence of several stacking patterns in which localized patterns of channel sands can be confused with large scale shoreface offices unless stringent time constraints are observable.

Microfossils, specifically Foraminifera are the main instrument that is used in solving these complexities. Foraminifera are single-celled protists the fossil record of which also stretches back to the Cambrian up to the Recent. The various test compositions such as organic, agglutinated and calcareous at the same time and their high evolutionary rates render them the most valuable in biostratigraphy (Bolli and Saunders, 1985). The interactions between eustatic changes of the sea level and local eustonics have been able to produce a complicated stratigraphic structure in the Niger Delta. Planktonic foraminifera are used to provide the chronological framework (biozones) through the rapid increase in growth rate and global distribution whereas benthic foraminifera can be used to provide the substantial information of the bottom-water conditions (paleobathymetry), dissolved oxygen and the rate of sediment supply (Petters, 1982).

B. *Statement of the Problem and Research Gap*

Although the Niger Delta region has a long history of exploration, to the best of knowledge, there is a paucity of published information on the biostratigraphic nature of the Early Miocene transition of particular wells in the open literature. Much of the high-resolution data is proprietary to International Oil Companies (IOCs), leaving independent researchers and academic institutions with limited access to reference sections. Consequently, there is a scarcity of independent verification of the regional biozonation schemes applied to specific blocks.

Furthermore, there is often a lack of rigorous integration between lithofacies analysis and micropaleontological data in independent academic studies. Many studies focus on one discipline to the exclusion of the other, leading to disjointed interpretations of reservoir geometry. Specifically, the distinction between "shale" as a lithology and "Maximum Flooding Surface" as a chronostratigraphic event is often blurred in purely lithological reports.

The specific problem this study addresses is the stratigraphic uncertainty associated with the 2780 m – 3980 m interval of Well HI-001. In the absence of accurate biostratigraphic control, it is hard to tell whether the sand bodies of this period are lateral channel sands or isolated shoreface sands. In addition, it is important to establish an accurate apex of the Early and Middle Miocene to regional correlate. This paper seals this void by combining the Praeorbulina-Orbulina bioseries a used global marker event with more detailed lithologic information to present a robust chronostratigraphic chronicle of the well that can be directly compared to the well-known regional trends of the Greater Ughelli Depobelt.

C. *Aim and Objectives*

This study was mainly focused on determining the age, deposition environment, and stratigraphic sequence of the strata that Well HI-001 penetrated. The specific objectives are:

1. *Taxonomic Classification*: In order to determine and categorize planktonic and benthic assemblages formed by foraminiferal, in the ditch cuttings to a species level, it was necessary to identify and differentiate between autochthonous and allochthonous assemblages.
2. *Geochronology*: To ascertain the exact geologic age of the strata according to index planktonic foraminifera and conventional biozonation scale (Blow, 1969) in particular, the N8-N9 transition.
3. *Paleoenvironmental Reconstruction*: To determine the paleobathymetric history and the depositional environments based on the benthic biofacies ratios (P/B ratios) and sedimentological features.the regional distribution.
4. *Sequence Stratigraphy*: To explain the systems tracts (LST, TST, HST) and locate such important stratigraphic surfaces (MFS, SB) in order to construct a predictive model of the sand body geometry.
5. *Hydrocarbon Evaluation*: To assess how such results apply to the reservoir quality, seal quality and source rock potential in the region.

2. Geologic Setting and Literature Review

A. *Tectonic Evolution and Basin Architecture*

Niger Delta is at the crossroad of the Benue Trough and South Atlantic Ocean that developed due to the division of the African and South American tectonic plates during the Late Jurassic period to the Early Cretaceous (Whiteman, 1982). Development of the basin started with the rift phase, which was followed by the Proto-Niger Delta that was deposited during the Paleocene. Nigeria, due to mass supply of sediment by the Benue and Niger Rivers water, which drain a large portion of the West African shield, started its modern Niger Delta prograding in the Eocene.

The geometry of the basin has three significant structural characteristics in the Benin Hinge Line, to the northwest, Calabar Hinge Line to the east, and the fall of the continental margin to the south (Doust & Omatsola, 1990). The delta is separated into depobelt, or megastructures, reflecting consecutive stages in the development of the delta, the Eocene into the Recent. There are depobelts that are referred to as Northern Delta, Greater Ughelli, Coastal Swamp, and Offshore depobelts. They are bounded by large growth faults—syndepositional listric normal faults that flatten with depth into the Akata shales. These faults control sedimentation patterns, often resulting in expanded sedimentary sections on the downthrown block (rollover anticlines) which form the primary traps for hydrocarbons.

B. *Stratigraphic Architecture*

The Cenozoic stratigraphic succession of the Niger Delta is defined by three diachronous lithostratigraphic units. These units are not layer-cake formations but rather time-transgressive facies belts that migrated seaward over time (Short & Stauble, 1967; Avbovbo, 1978):

- *The Akata Formation (Paleocene – Recent)*: This is the basal unit, composed primarily of marine prodelta shales. It is characterized by dark grey, overpressured shales containing planktonic foraminifera and localized turbidite sands. The Akata Formation is the primary source rock for the Niger Delta petroleum system (Ekweozor & Daukoru, 1994), rich in amorphous organic matter derived from terrestrial and marine sources. It reaches thicknesses of up to 7,000 meters in the distal parts of the delta.
- *The Agbada Formation (Eocene – Recent)*: Overlying the Akata is the Agbada Formation, the major hydrocarbon-bearing unit. It consists of a paralic sequence of alternating sands and shales deposited in a transitional environment. The sandstones represent deltaic distributary channels, barrier bars, and shoreface deposits, while the shales represent flooding surfaces and lagoonal deposits. The thickness varies from 300 to 4,500 meters. The high sand-to-shale ratio in the upper section decreases with depth as the formation transitions into the underlying Akata shales. This is the formation penetrated by Well HI-001.
- *The Benin Formation (Oligocene – Recent)*: The topmost unit consists of massive, continental fluviatile sands with minor clay intercalations. It is a freshwater-bearing formation with thicknesses up to 2,000 meters and serves as the regional overburden, providing the necessary pressure for hydrocarbon maturation in the underlying units.

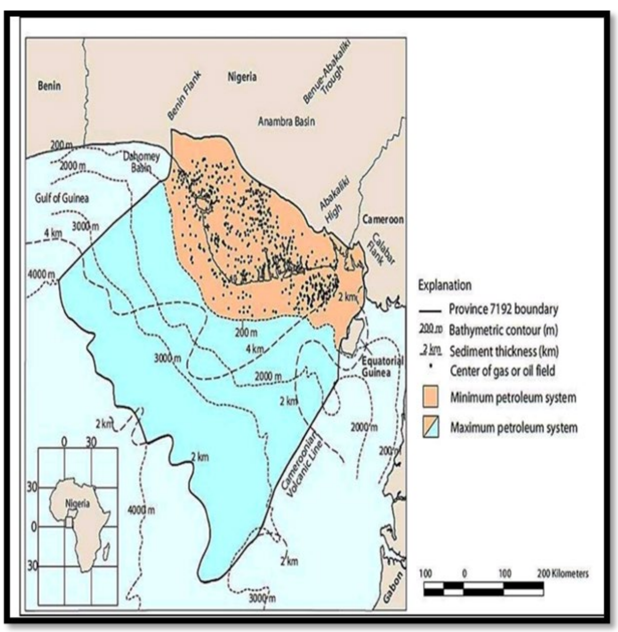

Fig. 1. Map of the Niger Delta Province showing the maximum petroleum system boundary, structural elements, and depobelts. The location of the Greater Ughelli Depobelt is highlighted, illustrating the regional context for Well HI-001. (Adapted from Doust & Omatsola, 1990)

C. *Biostratigraphic Framework of the Region*

Previous studies by Petters (1982) and Ozumba (1995) have established biozonation schemes for the Niger Delta based on the global cycle charts of Blow (1969) and Bolli and Saunders (1985). The Early to Middle Miocene is a critical interval marked by the diversification of planktonic foraminifera, specifically the Orbulinid lineage.

- *Planktonic Markers*: The base of the Middle Miocene is globally recognized by the evolutionary transition from *Globigerinoides* to *Praeorbulina* and finally to *Orbulina*. The First Appearance Datum (FAD) of *Orbulina suturalis* is a definitive marker for the Langhian stage (Zone N9). This burst of evolution is linked to an occurrence of global warming and the rise in sea-level (Miocene Climatic Optimum) and is therefore a good correlation tool.
- *Benthic Markers*: To distinguish neritic habitats in the Niger Delta the benthic assemblages of the Uvigerina sub-peregrina zone and the Spiroplectammina wrightii zone are employed. The replacement of arenaceous (glued by glutaraldehyde) types by calcareous types is usually a sign of a change in the environment of marginal to an open marine environment (Brasier, 1980). These shifts should be known to determine the Shale Baseline on wireline logs.

3. Materials and Methods

A. *Sample Collection and Processing*

Fifteen (15) composite ditch cutting samples of Well HI-001 were then used in the study. Although the well goes to a considerable depth, the samples were mixed at 30-meter levels.

- *Justification for Compositing*: Cavings and mixing are common in the ditch cutting analysis especially when carrying out rotary drilling. Sub-sampling at 30m intervals will be used to and make sure that enough material is present to retrieve a statistically significant sample of microfossils, and to smooth-out small lithological discontinuities which otherwise would bias the interpretation. This is the norm of regional scoping studies, but the fact remains that sub-seismic stratigraphic details (below 10m) can be brushed out.
- *Interval*: The depth range (a depth range of 2780m to 3980m) of the section studied is covered.

1) *Laboratory Preparation Protocol*

The process of separating the micropaleontological material of the rocks to single out the microfossils was done using standard techniques of micropaleontological preparation.

1. *Visual Inspection*: A preliminary lithologic characterization was carried out to document the attributes of texture, color and grain size and fossil type. To determine whether or not the location was influenced by the ocean, a 10 percent dilute Hydrochloric Acid (HCl) test was conducted to identify the evidence of calcareous material (calcite

cement or shell fragments).

2. *Weighing and Soaking*: Each sample weighed some 15g of the sample. The samples were moistened in an enamel bowl. Anhydrous sodium carbonate (Na_2CO_3) was also added in the solution and then it was boiled on a hot plate using a teaspoon during 30 minutes.
   - *Chemical Function:* The sodium carbonate is a defloating agents (dispersing agent). It raises the solution pH neutralizing the electrical charges of the clay particles, and this causes them to repel. This disrupts the indurated clay matrix without necessarily being crushed which may destroy the delicate foraminiferal tests.

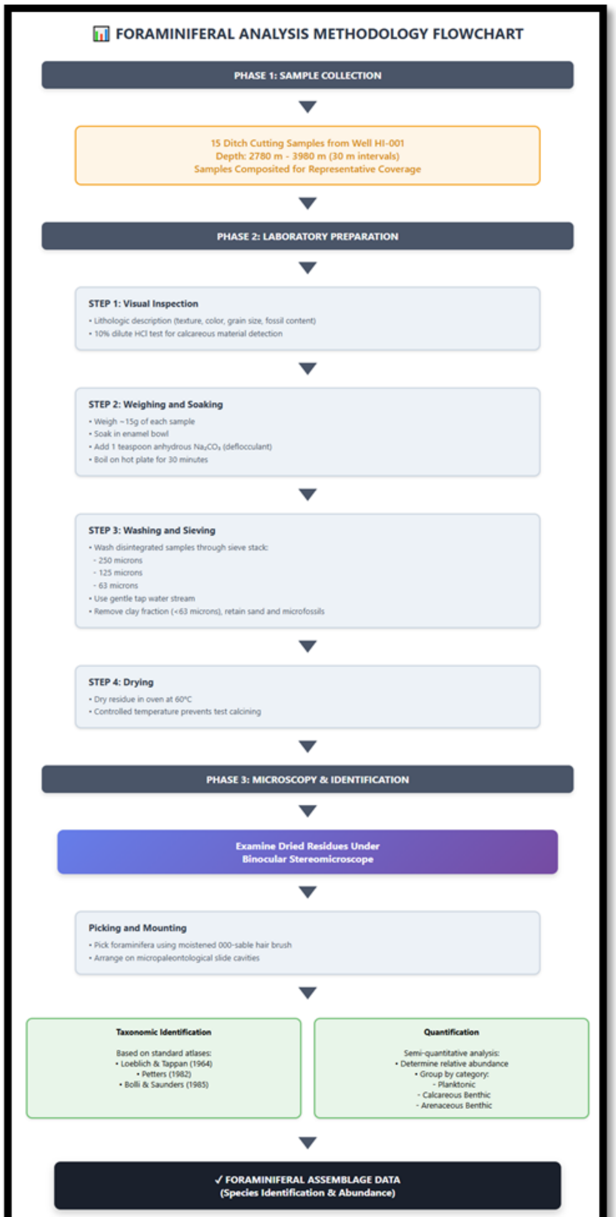

Fig. 2. Methodology Workflow Chart outlining the processes in collecting the sample, preparation in the laboratories (washing/sieving) to microscopic identification and data assembly. The chart puts the critical control point of Low Temperature Drying as the control point to maintain test integrity

3. *Washing and Sieving*: The broken samples were rinsed using a series of standard micropaleontological sieves (63 microns, 125 microns and 250 microns) in a light flow of running water. This left the clay fraction (less than 63 microns) behind and left the sand and microfossils.

4. *Drying*: The leftover contained in the sieves was dried in an oven with a set temperature of 60o C.
   - *Significance:* This is very important low temperature. An increase in temperature may cause the swift engorgement of the fluids in the foraminiferal chambers resulting in a calcifying or exfoliating process in the tests. The calcined tests fault and go opaque and brittle, eliminating the diagnostic characteristics of pores and apertures to identify the species at the species level.

B. *Microscopy and Identification*

The remaining dried pieces were examined using the binocular stereomicroscope in different magnifications (x10 to x40). The Foraminifera were selected with a wetted 000-sable hair brush and placed on the micropaleontology slide cavities to store forever and be used as a reference.

- *Taxonomic Identification*: This was identified by means of the generic and species descriptions of Loeblich and Tappan (1964), Petters (1982) and Bolli and Saunders (1985) atlases. Special consideration was given to the shape of aperture, layout of the chamber and texture on the wall.
- *Quantification*: To establish the relative abundance of the species semi-quantitative analysis was done. To provide a solution to the predilection of assemblages to the paleoenvironment, the assemblages were classified as Planktonic, Calcareous Benthic, and Arenaceous Benthic.

4. Results

A. *Lithostratigraphic Description*

The lithologic analysis of the section between 2780 m and 3980 m shows an Agbada Succession. The part consists of a mixture of siltstone, sandstone and shale. Seven (7) informal lithostratigraphic units were defined on the basis of sand-shale ratios, additional textural features of the rocks and accessory minerals.

- *Unit 1 (2780 m – 2900 m)*: The period is marked by coarse grained, sub-angular sandstones and slight intercalations of grey shale. The sands are quite uniformly sorted and show a blocky log motif character (based on the profile of grain size). There are ferruginous materials, which are manifested as oxidizing conditions or in diagenetic change, as reddish-brown stains.
- *Unit 2 (2900 m – 3150 m)*: This unit consists mainly of dark grey fissile shales and full of mica flakes. The

fissility is so large that it means it is very compressed in a deeper water habitat. This thick interval is dominated by shale implying that there was a relative quiescence and low energy.

- *Unit 3 (3150 m – 3300 m)*: This unit has a heterolithic sandy shale and clayey sand (mixed lithology). Sands are fine grained indicating that less energy is deposited than Unit 1. The profile is serrated, which means that it changes quickly in the amount of sediment supplied or the amount of energy.
- *Unit 4 (3300 m – 3500 m)*: Predominantly shale. Most importantly, the shale is calcareous, which is highly reactive to HCl. This calcareous character is associated with a foraminiferal abundance peak, which makes it stand out of the shales of Unit 2 (non-calcareous).
- *Unit 5 (3500 m – 3650 m)*: A shaly sand unit. The sands are also glauconitic in nature, but they are greenish in color. Glauconite is a diagnostic mineral in the marine environment where a slow-sedimentation rate usually occurs and mostly related to events of transgression.

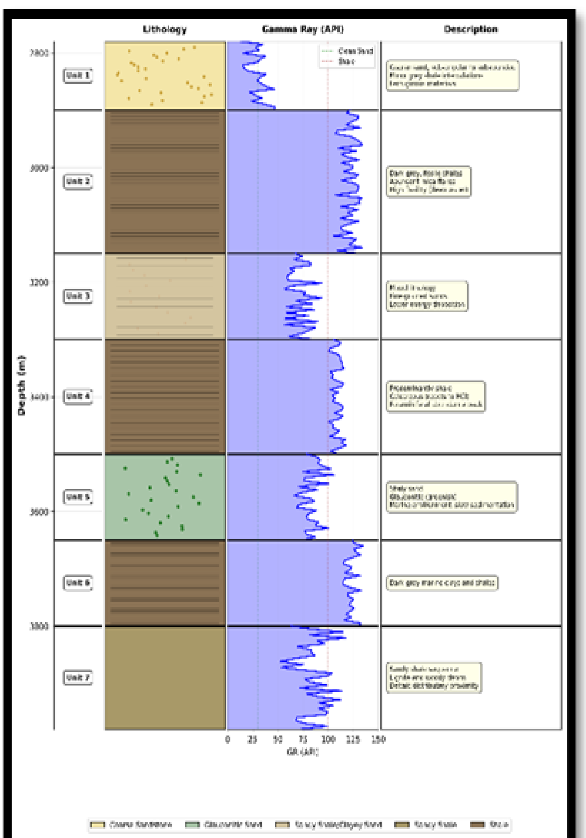

Fig. 3. Graphical Sedimentary Log of Well HI-001 (2780 m -3980 m). The song displays vertical distribution of the grain size (Lithology) and the Gamma Ray profile interpretation. Observation of the change in the blocky sands of Unit 1 (Low Gamma) into the marine shales of Unit 4 and 6 (High Gamma)

- *Unit 6 (3650 m – 3800 m)*: Dark marine grey and shales. These resemble Unit 2 except that they do not contain as high a content of mica and thus they appear bigger than fissile.
- *Unit 7 (3800 m – 3980 m)*: A lignite and woody debris sandy shale sequence. Carbonaceous material of the basins signifies that there was a carbonaceous source near a deltaic outlet or that there were major contributions of terrestrial materials into the basin.

B. *Foraminiferal Assemblage*

This analysis provided a moderate to diverse recovery of 65 foraminiferal species. The assemblage is predominated by benthic forms (75 percent) and contains a large planktonic component (25 percent) which enable the assemblage can be dated with high confidence.

1) *Planktonic Foraminifera*

Renowned sixteen (16) planktons were harvested. All the assemblage is typified by significant stratigraphic markers that are important on Miocene biostratigraphy. The *Praeorbulina* lineage was particularly well-preserved:

- *Praeorbulina glomerosa:* Characterized by a spherical test with multiple apertures along the sutures.
- *Praeorbulina curva:* The ancestral form with a less enveloping final chamber.
- *Orbulina suturalis:* The descendant form where the final chamber almost completely envelopes the earlier ones.

  Other planktonics included *Globigerinoides quadrilobatus*, *Globigerina falconensis*, *Pullenia bulloides*, and *Paragloborotalia obesa*.

The co-occurrence of *Globigerinoides* spp. and the *Praeorbulina* lineage is the most significant biostratigraphic signal in the well, marking the transition from the Early Miocene to the Middle Miocene.

2) *Benthic Foraminifera*

Forty-nine (49) benthic species were identified, split between calcareous (39 species) and arenaceous (10 species) forms.

- Dominant Calcareous Species: *Brizalina dilatata*, *Lenticulina* spp., *Bolivina tenuicostata*, *Quinqueloculina seminulum*, *Dentalina leguminiformis*, *Valvulina flexilis*, *Planulina wuellerstorti*, and *Bulimina exilis*.
- Dominant Arenaceous Species: *Haplophragmoides bradyi*, *Bathysiphon* sp., *Karreriella bradyi*, and *Cyclammina* sp.

Ecologically, the presence of *Heterostegina* sp. and *Amphistegina* sp. was noted in the shallower sections, while *Cyclammina* and *Bathysiphon* became more prevalent in the shaly, deeper intervals.

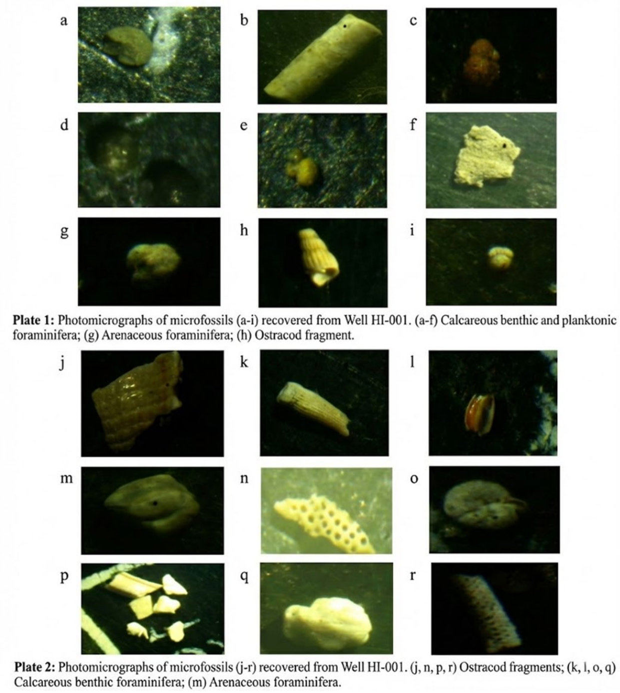

Fig. 4. Photomicrographs of Microfossils

5. Discussion

A. Biostratigraphic Age Determination

The age of the studied interval is determined based on the evolutionary lineage of the *Globigerinoides-Praeorbulina-Orbulina* bioseries. This lineage is one of the most reliable biochronological markers in tropical/subtropical Neogene stratigraphy (Blow, 1969; Bolli & Saunders, 1985).

- *The Praeorbulina Event*: The recovery of *Praeorbulina curva* and *Praeorbulina glomerosa* is significant. In the standard Blow Zonation, the First Appearance Datum (FAD) of *Praeorbulina curva* marks the base of Zone N8 (Early Miocene). This species evolved from *Globigerinoides bisphericus* and represents a distinct morphological shift towards a spherical test.
- *The Orbulina Datum*: The presence of *Orbulina suturalis* is critical. The changing point of the Early Miocene (Burdigalian) to the Middle Miocene (Langhian) is the evolutionary transition of Praeorbulina glomerosa to Orbulina suturalis. This is an occurrence that establishes the foundation of Zone N9.

Therefore, the stratigraphic interval between well HI- 001 of 2780 m to 3980 m date may be safely dated to Early Miocene to early Middle Miocene This is associated with N8 N9 planktonic zones. Evidence of this Miocene designation is by the presence of Globigerinoides quadrilobatus and Globigerina falconensis. The survivance of the isolated Globigerinoides ruber into the shallow depth (3080 ft) could be explained by caving due to the overriding Pliocene/ Pleistocene sections or contamination since G. ruber are typically of more recent formation.

B. Paleobathymetry and Paleoenvironmental Reconstruction

By using the fusion of the foraminiferal biofacies data with the sedimentological data, the depositional environments may be reconstructed. The environment swings between Coastal Deltaic and Outer Neritic, which is a manifestation of the eco-cyclic progradation and retrogradation of the delta.

1) Inner Neritic to Coastal Deltaic (Shallower Intervals)

The intermittent sands and higher areas (Unit 1 and Unit 7) have low species diversity and can include Ammonia species (in rare cases), Quinqueloculina seminulum and arenaceous species, such as Haplophragmoides. The comparison of the sedimentologic data of lignite, woody debris, and sub-angular pieces of quartz grains proves the high-energy, deltaic plain to inner neritic environment (0 30m of water depth). The occurrence of Amphistegina suggests the existence of warm shallow clear waters, probably accompanied by reefal or carbonate deposition effects in the delta front, or may be some re-working of shelf margin material.

2) Middle to Outer Neritic (Deeper Intervals)

The lower regions (in particular Unit 2, 4 and 6) are richer and more numerous in planktonic foraminifera (25% total population). Deepening of waters is typical in the increase in planktonic/ benthic (P/B) ratio.

- *Diagnostic Benthics*: Spiroplectammina wrightii, Bulimina buchiana, Bolivina interjucta, Uvigerina spp., and Planulina wuellerstorti presence shows the presence of an Outer Neritic environment (100m - 200m water depth).
- Oxygenation Indicators: *Bulimina and Bulivina are infaunal species that can be found in the prodelta slope of lower oxygen content in the muddy substrates. The characteristic morphology of Bolivina tenuicostata (slender, costate) frequently associates with these low-oxygen bottom waters and this helps in preserving the organic matter (potential source rock).*
- *Glauconite Significance*: The glauconite aspect of Unit 5 is a terrific indicator that there was a marine transgression. The authigenic mineral known as glauconite is deposited at the sediment-water interface under reduced oxygen environments at times when the sedimentation of the continental shelf is low (condensed sections). It is observable when marine floods occur, as opposed to shaly intervals.

C. Regional Comparison

One of the most important parts of proving the stratigraphy of Well HI-001 is the comparison of the trends observed with the existing models in the region. The lithostratigraphic and biostratigraphic indicators of Well HI-001 are extremely aligned with the patterns as shown in the Greater Ughelli Depobelt.

Particularly, the stratigraphic text resembles that of the typical Oloibiri and Ughelli Fields. A hallmark paralic sequence is present here in the Early Miocene of the Greater Ughelli Depobelt where a zone of regionally extensive flood surface is commonly used to characterize the transition between the Burdigalian and Langhian (N8/N9) boundary sequences that follow in this well as in the transition between Unit 4 and Unit 5.

Research conducted by Evamy et al. (1978) and Ozumba (1995) in the Greater Ughelli Depobelt has recorded the prolific occurrence of the Praeorbulina/Orbulina lineage as one of the significant correlation markers of the equivalent shale D-Marker. The Praeorbulina glomerosa has emerged in Well HI-001 giving a powerful tie-point to the regional markers. Furthermore, the alternation of "blocky" channel sands and "serrated" heterolithic shoreface sands observed in Units 1 and 3 respectively is typical of the structural traps found in the Oloibiri field, suggesting that Well HI-001 penetrates a similar macro-structure, likely a rollover anticline crest or flank. This regional consistency validates the biostratigraphic dating and suggests that the reservoir properties encountered in Unit 1 may share the high connectivity and porosity characteristics of the proven reservoirs in the Ughelli sector.

D. Sequence Stratigraphic Interpretation

By synthesizing the lithologic, biostratigraphic, and regional data, a sequence stratigraphic model for Well HI-001 is proposed. The succession (Units 7 → 1) broadly represents a regressive sequence overall (shallowing upward), typical of a prograding delta, but punctuated by higher-order cycles.

1) Lowstand Systems Tract (LST) Candidates

- *Unit 1 (2780m – 2900m)*: The coarse grain size, sub-angular nature, and "blocky" log motif suggest rapid deposition in a high-energy environment. In a distal setting, this often corresponds to a Lowstand Systems Tract where sea level falls, forcing rivers to cut into the shelf and deposit coarse sediments further basinward (basinward shift of facies). Unit 1 was probably an Incised Valley Fill; or a Prograding Wedge complex which straddles a Sequence Boundary (SB). The angular lower part of this unit of sand indicates an erosion contact.

2) Transgressive Systems Tract (TST)

- Unit 5 (3500 m – 3650 m) & Unit 4 (3300m – 3500m):
    - *Interpretation:* Unit 5 contains glauconitic sands. The formation process of glauconites is time consuming and scarcity of sediment input, people would expect to be a typical part of a TST when the supply of the sediment is cut off or trapped landward as the sea level increases.
    - *Key Surface:* The change in Unit 4 characterized by the calcareous shale and the highest activity of the planktonic foraminifera (Orbulina/Praeorbulina) is the Maximum Flooding Surface (MFS). This is the section that is condensed having the prevailing effect of pelagic deposition as against clastic input. This is a crucial correlation marker because the response to gamma rays would be high here (because of the concentration of Uranium in organic matter).

3) 3. Highstand Systems Tract (HST)

- Unit 3 (3150 m – 3300 m) → Unit 2 (2900m – 3150m):
    - *Interpretation:* Following the maximum flooding, the delta begins to prograde (move seaward) again. Unit 2 (Fissile Shale) represents the pro-delta shales of the early HST. As the system shallows, we transition into Unit 3 (Sandy Shale/Heterolithic), representing the distal delta front.
    - *Sequence Context:* These units represent the aggradational to progradational phase ("filling the accommodation space") before the subsequent sea level fall that deposited Unit 1.

E. Implications for Hydrocarbon Exploration

Table 1
Potential hydrocarbon pay zones and risk analysis

Zone Rank	Unit(s)	Pay Potential	Rationale
Primary Target	Unit 1 (2780–2900 m)	High	Reservoir: Coarse-grained, sub-angular sandstones indicate high porosity and permeability. Correlates with Oloibiri-type channel sands. Seal: Unit 2 acts as a bottom seal. If a shale sits above Unit 1, this is a classic boxcar reservoir. Risk: Oxidation (ferruginous materials) suggests meteoric water flushing, which might have degraded hydrocarbons (biodegradation) if the trap is shallow.
Secondary Target	Unit 3 (3150–3300 m)	Moderate	Reservoir: Fine-grained sands/clayey sands. Permeability will be lower than Unit 1. Seal: Excellent top seal provided by the thick Unit 2 (Fissile Shale). Trap Style: Ideally situated for stratigraphic traps where sands pinch out into the Unit 2 shales.
Source/Seal	Unit 2 & 4	None (Non-Reservoir)	These are seal and source rocks. Unit 4 (Calcareous Shale) is particularly important as a regional seal/MFS.
High Risk	Unit 5 & 7	Low	Unit 5 (Glauconitic): often tight due to clay/glauconite pore-filling. High water saturation is common (conductive minerals). Unit 7 (Lignitic): While sands exist, the abundant woody debris and "sandy shale" texture imply poor sorting and heterogeneity.

The findings of this study have direct applications to the petroleum systems of the Niger Delta:

1) Reservoir Continuity and Geometry:

The identification of Outer Neritic environments in the deeper sections of Well HI-001 suggests that sand bodies found here are likely to be slope-channel complexes or turbidites rather than continuous shoreface sands. Sands deposited in the Outer Neritic zone (lowstand systems tracts) often have excellent sorting but may be compartmentalized. The "Interbedded shaly sands" described in the lithology likely represent the heterolithic facies of the Agbada Formation (Thin

Bed Pay), which can form complex reservoirs requiring high-resolution seismic to map. Conversely, the LST sands of Unit 1, correlating with the regional Ughelli trends, are likely more laterally continuous along the axis of the incised valley but confined laterally.

2) Source Rock Potential:

The Outer Neritic to Upper Bathyal shales identified by the abundance of *Uvigerina* and *Bolivina* are excellent candidates for source rocks. These environments preserve organic matter due to lower oxygenation. Type II/III kerogen is also likely to be present in the Dark grey, fissile shales, of Unit 2 and Unit 6 and bring about the charge of hydrocarbons in the basin.

3) C. Seal Integrity:

Those units of the thick shale (Unit 2, 4, 6) that are rich in planktonic foraminifera serve as seals on the region. Geologists are able to calculate these seals in comparison with the rest of the field wells using the biostratigraphic dating (N8-N9). If these seals are laterally extensive (which Outer Neritic shales typically are), they reduce the risk of hydrocarbon leakage. However, the presence of glauconite (Unit 5) can sometimes be misleading on Gamma Ray logs ("Hot Sands") and should be carefully evaluated to distinguish it from shale seals.

6. Summary and Conclusion

A. Summary of Findings

1. *Lithostratigraphy*: The well section is assumed to consist of a total of seven lithounits of the Agbada Formation which are the interchanging shales, shaly sands and sands that have small proportions of lignite and glauconite.
2. *Biostratigraphy*: The section yielded 65 species. The Early to Middle Miocene (N8-N9 Zones) dating of the well is based on the identification of the Praeorbulina lineage (P. curva, P. glomerosa) and orbulina suturalis.
3. *Paleoenvironment*: The depositional environment was transformed into an Outer Neritic system based on a Coastal Deltaic one. These are indicated through change of arenaceous/miliolid benthics to calcareous Bolivina/Bulimina assemblages and high planktonic diversity.
4. *Regional Context*: The stratigraphy has high affinity with the Greater Ughelli Depobelt, with predictive value on the nature of reservoirs and the geometries of traps through the nature of fields that are known so far, such as Oloibiri.
5. *Sequence Stratigraphy*: It was found that it consisted of a complete sequence cycle with a Lowstand Systems Tract (Unit 1), Transgressive Systems Tract (Units 4-5), and Highstand Systems Tract (Units 2-3).

B. Conclusion

This paper has managed to put together the chronostratigraphic and paleoenvironmental context of Well HI-001. The well went to the Early Miocene sediments that were formed in a fluvio-marine environment with great marine transgressions. Early Miocene strata in this part of the Niger Delta may be correlated using the presence of diagnostic Praeorbulina specimens in this well. The shift to deep marine shales as a result of sandy deltaic deposits implies a retrogradational stacking arrangement, presumably with a regionally rising sea-level at the time of the Burdigalian-Langhian transition.

References

[1] Adeniran, B. V. (1997). Quantitative Neogene planktic foraminiferal biostratigraphy of Western Niger Delta, Nigeria. *Nigerian Association of Petroleum Explorationists Bulletin*, 12, 54–59.
[2] Avbovbo, A. A. (1978). Tertiary lithostratigraphy of Niger Delta. *American Association of Petroleum Geologists Bulletin*, 62, 295–300.
[3] Blow, W. H. (1969). Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. In P. Bronnimann & H. H. Renz (Eds.), *Proceedings of the First International Conference on Planktonic Microfossils* (Vol. 1, pp. 199–422). E.J. Brill.
[4] Bolli, H. M., & Saunders, J. B. (1985). Oligocene to Holocene low latitude planktonic foraminifera. In H. M. Bolli, J. B. Saunders, & K. Perch-Nielsen (Eds.), *Plankton Stratigraphy* (pp. 155–257). Cambridge University Press.
[5] Brasier, M. D. (1980). *Microfossils*. Chapman and Hall.
[6] Doust, H., & Omatsola, E. (1990). Niger Delta. In J. D. Edwards & P. A. Santogrossi (Eds.), *Divergent/Passive Margin Basins* (AAPG Memoir 48, pp. 201–238). American Association of Petroleum Geologists.
[7] Ekweozor, C. M., & Daukoru, E. M. (1994). Northern delta depobelt portion of the Akata-Agbada petroleum system, Niger Delta, Nigeria. In L. B. Magoon & W. G. Dow (Eds.), *The Petroleum System—From Source to Trap* (AAPG Memoir 60, pp. 599–614).
[8] Evamy, B. D., Haremboure, J., Kamerling, P., Knaap, W. A., Molloy, F. A., & Rowlands, P. H. (1978). Hydrocarbon habitat of Tertiary Niger Delta. *AAPG Bulletin*, 62(1), 1–39.
[9] Kulke, H. (1995). *Regional Petroleum Geology of the World. Part II: Africa, America, Australia and Antarctica*. Gebruder Borntraeger, Berlin.
[10] Loeblich, A. R., Jr., & Tappan, H. (1964). Sarcodina, chiefly "Thecamoebians" and Foraminiferida. In R. C. Moore (Ed.), *Treatise on Invertebrate Paleontology, Part C, Protista 2*. Geological Society of America and University of Kansas Press.
[11] Nwachukwu, J. I., & Odjegba, D. O. (2001). Compaction and overpressure in the Niger Delta. *Journal of Petroleum Geology*, 24(4), 435–450.
[12] Ozumba, M. B. (1995). Late Miocene–Pliocene biostratigraphy of the Niger Delta. *NAPE Bulletin*, 10, 36–45.
[13] Petters, S. W. (1982). Central West African Cretaceous-Tertiary benthic foraminifera and stratigraphy. *Palaeontographica Abteilung A*, 179, 1–104.
[14] Short, K. C., & Stauble, A. J. (1967). Outline of geology of Niger Delta. *AAPG Bulletin*, 51(5), 761–779.
[15] Webber, K. J., & Daukoru, E. M. (1975). Petroleum geology of the Niger Delta. *Proceedings of the 9th World Petroleum Congress*, 2, 209–221.
[16] Whiteman, A. J. (1982). *Nigeria: Its Petroleum Geology, Resources and Potential* (Vol. 1). Graham and Trotman.