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High Resolution Biostratigraphic, Sequence Stratigraphic and Paleoenvironmental Analyses of Motun-1 Well, Niger Delta, Nigeria

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Abstract
High resolution biostratigraphy of Motun -1 well from offshore Niger Delta was undertaken to determine the age and depositional setting of the stratigraphic succession in the well. The study involved integrated foraminiferal, calcareous nannofossil and palynological analysis using standard preparation techniques of wet sieving, smearing and pipette method as well as Hydrofluoric (HF) and Hydrochloric (HCl) acids maceration techniques respectively. This was complimented by the sedimentological description of samples. The samples yielded exclusively benthic foraminiferal fauna with moderate diversity consisting of eleven species belonging to seven genera of calcareous benthic and three (3) species belonging to three genera of arenaceous benthic foraminifera. They include *Bolivina, Lenticulina, Quinqueloculina, Cristellaria, Ammobaculites,* and *Textularia*. The recorded calcareous nannofossil consists of nine genera and 27 species, including *Helicosphaera ampiaperta, Sphenolitus heteromorphus, Pontosphaera multipora,* and *Cyclicargolithus floridanus*. The palynological data consists of highly diversified assemblages dominated by pollen, comprising 42 species and seven species of spores and subordinate amount of dinocysts (one species). They include *Monoporites annulatus, Zonocostites ramonae, Magnastriatites howardi, Belskipolis elegans, Crassoretitriletes vanraadshooveni,* and *Leiospheridia sp*. The well is dated early to middle Miocene (NN4 –NN5) based on the occurrence of marker species *Helicosphaera ampliaperta* and *Sphenolithus heteromophus* which corresponds *Echitricolporites –Crassoretitriletes vanraashooveni* zone (P680-P720). One maximum flooding surface identified on the bases of maximum diversity and abundance of calcareous nannofossil assemblage composition is placed at the 7680 ft depth and dated 16 Ma. The environment of deposition fluctuated between middle neritic and inner neritic to littoral, including coastal deltaic settings based on deductions from sedimentological and foraminiferal data.

Introduction
The Niger Delta is the most important hydrocarbon province in the West African continental margin (Fig.1), holding roughly 34 billion barrels of oil in addition to its huge gas resource. Significant research in the basin started in the late 50s following the first discovery of commercial quantities of petroleum in the basin. A number of studies on the stratigraphy of the basin have been undertaken by both multinational oil companies and other authors all jeered towards elucidating on the geology of the basin [e.g. 1, 2,3,4,5,6,7]. However, much of the research findings in the basin have been kept secret by the oil companies for proprietary reason.Considering the complex stratigraphic nature of the Niger Delta occasioned by the occurrence of numerous synsedimentary faulting and related structural elements [5], the need for thorough biostratigraphic correlations from well to well cannot be overemphasized [8]. Small stratigraphic traps are usually smaller than the depth resolutions of seismic data interpretations.

High Resolution Biostratigraphy and sequence stratigraphic studies involve the integration of micropaleontology (foraminifera), nannopaleontology (calcareous nannofossil) and palynology (palynomorphs) with or without lithostratigraphic analysis. Such study permits better characterisation of stratigraphic section into narrow time slices thereby facilitating reliable correlation within sedimentary basins on reservoir scale [9]. High resolution biostratigraphy complemented with detailed sedimentological evaluation and supporting stratigraphic analyses such as stable isotopes, cyclostratigraphy allows for the assessment of the completeness of a stratigraphic boundary as well as highlighting any minor change in sediment accumulation rate and mark the presence of possible non-depositional hiatuses in the succession [9]. The interpretation of depositional environment is vital to the reconstruction of the burial history as well as in sequence stratigraphic studies [10]. High resolution biostratigraphic studies in the basin are rare. It is in the consideration of the aforementioned that this study seeks to establish biostratigraphy and depositional environments of a section of the strata penetrated by Motun -1 well through integrated sedimentological, micropaleontological and palynological analysis.

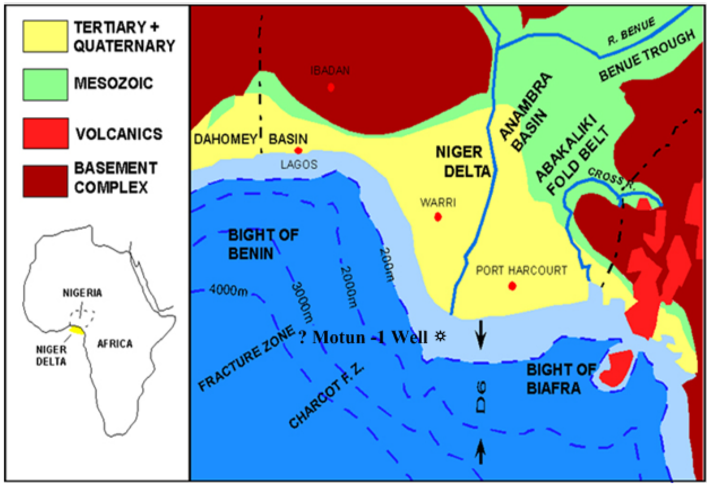


Figure 1: Geological map of Niger Delta, modified after [11].

Geology and stratigraphy of the Niger Delta

Motun-1 well is located in the Niger Delta Basin which covers an area of about 100,000 square kilometres on the continental margin of Gulf of Guinea on the west coast of central Africa (Fig. 1). The basin is a regressive clastic wedge which represents the third phase of sedimentation in the Benue Trough. Globally, it contains the 12th largest known occurrence of recoverable hydrocarbons, with ultimate recovery currently estimated at nearly 40 billion barrels of oil and with a conservative estimate of gas reserves staggering 40 trillion cubic feet of gas [12]. The origin of the Benue Trough in which the Niger delta is located has been related to the breakup of the Gwandana Supercontinent and the concomitant opening of the South Atlantic Ocean in Late Jurassic to Early Cetaceous times, with the failed arm of the rift triple junction being regarded as the Benue Trough aulacogen [13,14]. The development of the Niger Delta Basin started in the Eocene regression after the rift –filled stage and the Santonian tectonic inversion. Synsedimentary faulting and clay diapirism played a major role in the development of delta [3]. Deep wells in the basin show a tripartite lithostratigraphic unit that reflects the regressive character of the sequences.

The basal Akata Formation consists of dark grey marine shales and silts with rare streaks of sand of probable turbidites (potential reservoirs in deep water) flow origin. It is estimated to be 6,400 m thick in the central part of this clastic wedge [11]. Marine planktonic foraminifera suggest a shallow marine shelf depositional setting ranging from Paleocene to Recent in age [11]. The lithologies of the overlying parallic Agbada Formation consist largely of alternating sands, silts and shales with progressive upward changes in grain size and bed thickness. The strata are generally interpreted to have formed in fluvial-deltaic environments [15]. Its maximum thickness is roughly 3,900 m and ranges in age from Eocene to Pleistocene [11]. The last sediment to be deposited is the continental Benin Formation which consists of predominantly massive sands with intercalations of shale lenses. The sands are yellowish brown to white, fine to coarse-grained [16].

Materials and method

Twenty (20) ditch samples collected at 30 ft intervals from Motun -01 well in the Niger Delta Basin were used for the study. The samples came from the intervals 4470 to 5070 ft. Samples were first studied under light reflecting stereoscopic microscope to determine their textural attributes of mineralogical composition, colour, grain size, sorting, and roundness. This was followed by preparation of sample for foraminifera, nannofossils and palynology.

Preparation of samples for foraminifera followed the standard practice. A standard weight (30 g of dried sample) was soaked for four hours in kerosene, followed by soaking in soapy water overnight. The disaggregated sample was then washed under a shower of water over a 63 micron mesh sieve. The washed residue was then dried over a hot plate at 40 ^{o}C and sieved into three fractions (coarse, medium and fine) prior to picking. All the foraminifera, ostracod shell fragments and other biota seen were picked from a gridded picking tray and counted under light reflecting binocular microscope. The specimens picked were stored in depth-labelled slide provided with a cover slip for analysis.

Precisely 2 g of uncontaminated, mud free, dry sample was weighed and prepared for nannofossil analysis using the pipette straw method. The dried sample was gently crushed using mortar and pestle. Crushed sample was dispersed in distilled water in a tube. A disposable glass pipette was employed to pipette the suspension onto a 22 x 40 mm cover slip at a slightly hot temperature of 60-70^{0}C. The dried cover slip was then mounted on a glass slide using already heated Canada balsam as the mounting medium and then cured under UV light.

Preparation of samples for palynological analysis followed the standard procedures described by [17]. which involved sample maceration Hydrochloric (HCl) and Hydrofluoric (HF) acids to remove carbonates and siliceous components, sieving through 10 micron sieve. This was followed by separation of palynomorphs from residue using zinc bromide solution prior to mounting grains on glass slides. The analysis involved identification, sorting, naming and counting of forms in each sample using relevant published albums as guide [18]. Quantitative analysis involved documentation of the total abundance of form per sample, absolute abundance of each species, etc. The assemblages present in each sample were recorded in Excel spreadsheet prior to being presented in assemblage distribution chart using Stratabug software on a scale of 1:2500.

Result and interpretation

Sedimentological examination reveal the stractigraphic section from the depth interval 4470 to 5070 ft were composed mainly of shaly sand and shale. The colour varies from light grey to brownish grey. The sediments are fine, medium or coarse grained, poorly sorted, subangular to angular.

Foraminifera

The foraminiferal recovery is poor as the upper section of the studied interval did not yield any foraminifera fauna (Fig. 2). The analysis indicates that some of the samples were moderately diverse in benthic micro faunal and micro accessory with few agglutinated (arenaceous) foraminifera The recorded assemblage composition is comprised of both calcareous benthonic fauna comprised of 11 species distributed within seven (7) genera and a few arenaceous taxa (three species belonging to three genera) with the former dominating the assemblage. There is a general absence of planktic species. The recovered calcareous benthic foraminifera taxa include *Bolivina, Lenticulina, Quinqueloculina* and *Cristellaria* while the arenaceous forms are *Ammobaculites, Spiroplectommina* and *Textularia* (Fig. 4) with restricted occurrence of the latter group to only a single horizon (4920 ft). The calcareous tests display wider temporal distribution occurring from the 4770 ft to the last sampled depth of 5040ft. The absence of foraminiferal in the upper part of the well may be attributed to lack of preservation or ecological exclusion. Other fauna recorded in association with foraminifera include echinoid remains, bivalve shells and gastropods.

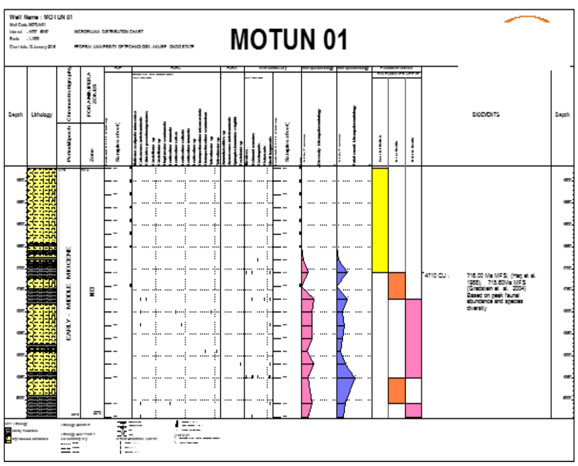


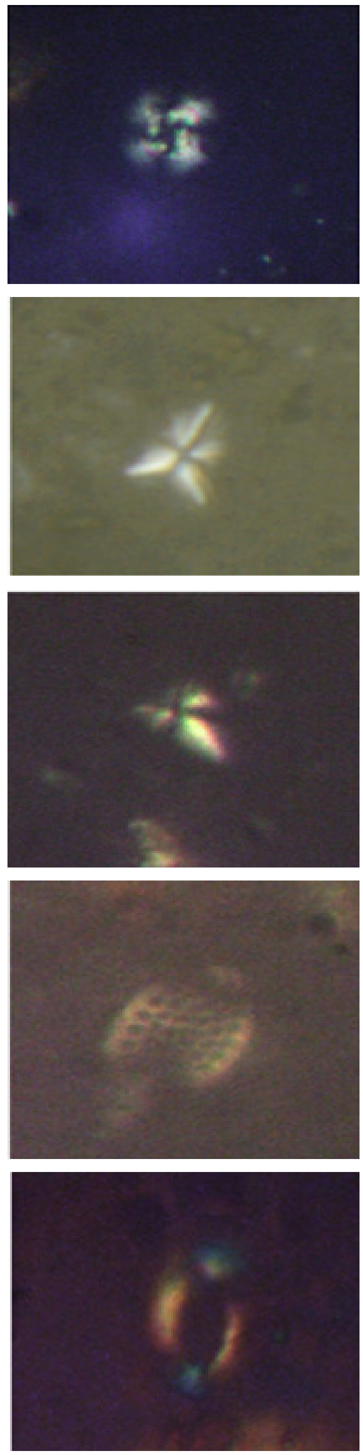
Figure.2: Stratigraphic distribution of foraminiferal assemblages recorded in Motun -1 well.

Foraminifera Biostratigraphy

Planktic foraminifera are particularly useful as biostratigraphic markers. Their absence in this study did not permit erection of foraminiferal chronostratigraphic zones. Foraminifera data is used here for paleoecological inferences. However, the calcareous nannofossil zones identified in the succession can be correlated to the N8 standard Planktic Foraminifera Zone of [19].

Nannofossils

Detailed identification of forms (to species level where possible) is made of all taxa encountered in each slide. Three traverses were studied in each slide. The cascading counting method [20] is employed in determining relative abundance and diversity of the assemblages. The result of nannofossil analysis is presented in Figs. 3&4.



Cyclicargolithus floridanus

Phenolithus abies

Spherolithus heteromorphus

Pontosphaera multipora

Helicosphaera ampliaperta

Figure 3: *Photomocrographs of some calcareous nannofossils recorded in Motun- 1 well.*

A total count of 308 specimens was recorded comprising 27 species and belonging to nine genera. The stratigraphic distribution of the assemblage compositions is variable. The common genera include *Casidiscus, Discoaster, Helicosphaera, Sphenolitus*, *Pontosphaera*, and *Coccolithus* (Figs. 3 &4). Species richnesss fluctuates between 0 and 13. The highest species richness (13) occurs as double peaks at 4770 and 4680 ft with the latter peak coinciding with the highest abundance.

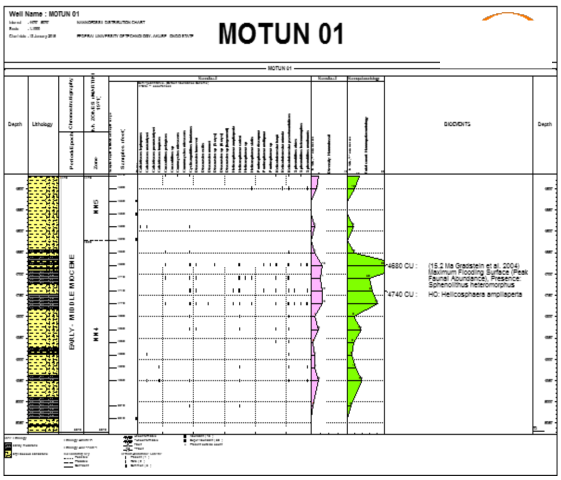


Figure 4: Assemblage distribution chart of calcareous nannofossils recorded in Motun 01 well.

Calcareous Nannofossil Biostratigraphy of Motun-1 well

Calcareous nannofossil analysis was carried out on twenty (20) ditch cutting samples of the Motun-01 well at 30 feet depth intervals. The studies interval had few abundant and diverse calcareous nannofossils. Standard nannofossil zonation schemes of [21] and Okada and [22] which are regarded as the standard framework for the calcareous nannofossils biostratigraphic calibrations of low-latitude Cenozoic marine sediments based on were applied for the analyses. The highest nannofossil abundance and diversity peaks were dated based on peak faunal abundance as well as important marker species such as *Sphenolithus heteromorphus* and *Helicosphaera ampliaperta* (Plate 1). The entire well is believed to penetrate the ?NN5 and NN4 zone [21] which suggest Early to Middle Miocene age for the sequence. The details of the results are discussed below and shown graphically in Fig. 5.

On the basis of first and last stratigraphic occurrences (tops and bases respectively) of these bioevents as well as their relative abundance, two zones are defined as described below using [21] scheme:

Stratigraphical interval 4470 – 4620ft
Age Middle Miocene
Nannofossil Zone: ?NN5

Remark

Interval is virtually barren of calcareous nannofossils but the recovery of Sphenolithus heteromophus indicates the ?NN5 zone

Stratigraphical interval:4620 – 5070 ft
Age: Early - Middle Miocene
Nannofossil Zone: NN4

Remark

Interval is fairly rich in calcareous nannofossils in most part. The presence of *Helicosphaera ampliaperta* indicates the NN4 zone of [21]. The nannofossil peaks recognized suggest the 16.0 Ma MFS (15.20 Ma MFS, [19] based on the records of the diagnostic species and the foraminiferal data. As a result of the absence of the co-occurrence of the FDO of *Sphenolithus belemnos* and the LDO of *Sphenolithus heteromorphus* of the analyzed section, the base of the interval is tentatively placed at the terminal depth (TD) of the well.

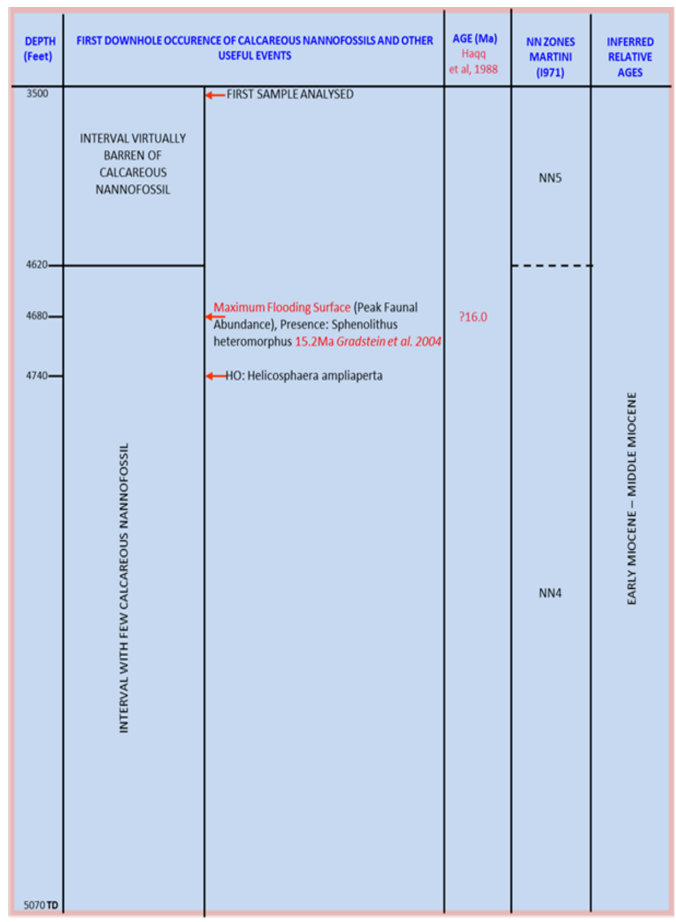


Figure 5: Summary of calcareous nannofossil biostratigraphy of Motun-1 well.

Palynostratigraphy of the Motun-1 well

Ten (10) ditch cutting samples composited at 60 ft intervals were analyzed for the palynomorph content. The palynomorphs recovered were moderately abundant, diverse and well preserved. A total sum of fifty six (56) palynomorphs species were identified comprising dominantly of pollen grains with over 40 taxa, spores (5 taxa) and marine element dinoflagellate cysts (1 taxa as minor constituents. The assemblage is dominated by terrestrial forms such as *Zonocostites ramonae, Monoporites annulatus, Laevigatosporites sp., Verrucatosporites sp., Retitricolporites sp., Acrostichum aureum* with few counts of dinoflagellate cysts *Leiosphaeridia sp*. (Figs. 6&7). The palynomorph sequences (Fig.8) of Motun-1 well fall within the Pan-Tropical *Echitricolporites spinosus zone-Crassoretitriletes vanraadshooveni zone* of [18] and is correlated to the P720-P680 subzones of [2]. Which indicates Early to Middle Miocene age for the studied interval.

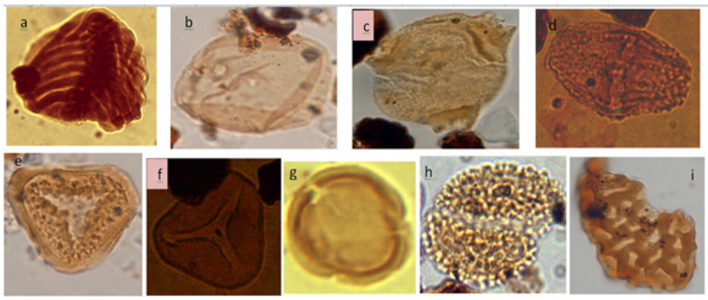


Figure 6: Photomicrographs of some of the palynomorphs retrived from Motun-1well. a, Magnatritites howardi, b. Monoporites annulatus, c. Retibrevitricolporites obodoensis, d. Beskipolis elegans, e. polypodiaceiosporites sp., f. Acrostichum aureum, g. Zonocostites ramonae, h. Racemonocolpites hians, i. Crassoretitriletes vanraashooveni

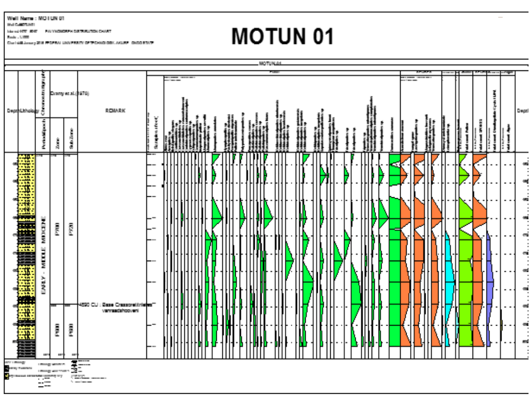


Figure 7: Stratigraphical distribution of palynological assemblages of Motun-1 well.

Biozonation

Subzone recognized

Subzone: P720

Interval: 4470-4890 feet
Age: Middle Miocene

Remark

The subzone (P720) is characterized by moderate abundance of *Racemonocolporites hians, Retitricolporites sp., Tricolporites sp., Belskipollis elegans, Crassoretitriletes vanraadshooveni, Verrucatosporites rotundiporus, Monoporites annulatus, Zonocostites ramonae, Acrosticulum aureum* and the different forms were moderately abundant and diverse in which the base of the subzone is marked by first occurrence of *Crassoretitriletes vanraadshooveni at* 4890 ft (Figs 7 and 8)

Subzone: P680

Interval: 4890-5070 feet
Age: Early Miocene

Remark

The subzone (P680) is characterized with moderate abundance of *Triporites sp., Alnus vera, Psilatricolporites sp., Retitricolporites irregularis* and with few or scanty dinoflagellate cysts. The base of P680 was not encountered as as it lies below the last sampled depth.

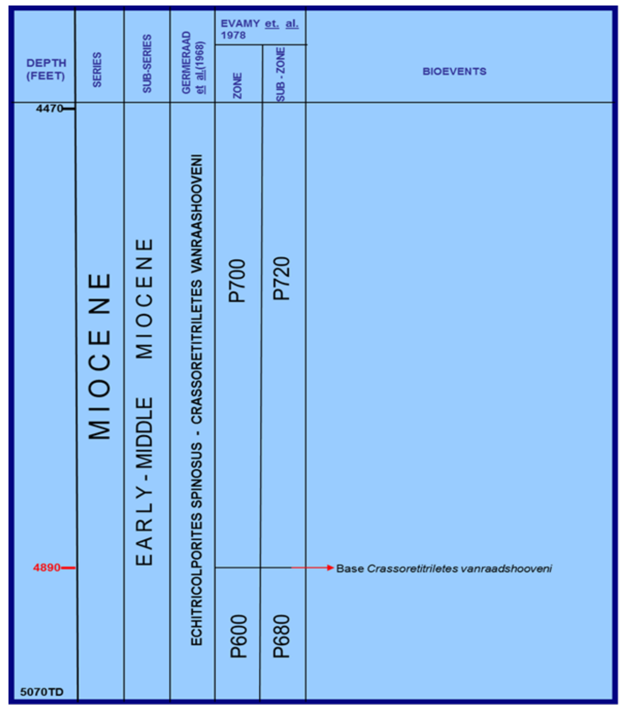


Figure 8: Palynological Zones recognized in Motun-1 well

Table 2: Condensed section as correlated to Global Cycle Chart of [23] and Gradstein et al. 2004

Maximum flooding surface /condensed section Age (Ma),	Suspected Interval (ft)	Dating criteria
After Haq et al. (1987) and Gradstein et al. (2004)		
CN: ?16.00 Ma MFS; (Haq et al. 1988); 15.60Ma MFS [19]	4680-4710	Based on Peak Faunal Abundance, Presence: *Sphenolithus heteromorphus*
Foraminifera: 16.00 Ma MFS; (Haq et al. 1988); 15.60Ma MFS [19]	4680-4710	Based on Peak Faunal Abundance and Species Diversity

Depositional paleoenvironment and sequence stratigraphy of Motun-01 Well.

The interpretation of the depositional environment is based on the integration of sedimentological characteristics of ditch samples and interpretation of micropaleontological data. The lithology of the well consists of alternations of sandstone and shale with the proportion of sand becoming more dominant towards the upper part of the well. The lithologic characteristics indicate that the well penetrated Agbada Formation. The shales are brownish grey to grey, fine to medium grained while the sandstones are light grey to brownish grey, fine to coarse grained, moderately to poorly sorted, quartzose sandstones with subangular to angular grains.

Based on the sedimentological and foraminiferal data, the studied stratigraphic sequences of Motun -1 well have sediments deposited in marine environment that ranged from coastal deltaic to Middle Neritic with the influence of inner neritic at some horizon. The upper part of the studied section (4470 – 4740 ft) was deposited in the coastal deltaic environment (4470 - 4680ft) and deepening to the inner Neritic (4710 – 4740 ft). The lower section of the studied interval is predominantly Middle Neritic (40 -100 m water depth within the shelf) to inner neritic settings (0 -40 m). The occurrence of diversified calcareous benthic foraminiferal fauna such as *Hopkinsina semionata, Valvulineria spp, Bolivina scabrata miocenica, Lenticulina inornata, Lenticulina calcar* and *Quinqueloculina microcostata* suggests deposition in inner to middle neritic environment. The occurrence of *Hopkinsina semionata* amongst other deep water calcareous foraminiferal fauna from the Niger Delta was used by [10] to deduce middle neritic environment. Miliolids such as Quinqueloculina are adapted to normal salinity shelf environments and their occurrence is indicative of shallow marine to intermediate environments [24]. According to [24] the dominance of of Bolivina and Lenticulina in an assemblage suggests middle neritic environment. The dominance of calcareous fauna over arenaceous benthics as well as the absence of planktic taxa also supports this deduction. Similarly, [25] used the common association of *Bolivina sp., Lenticulina sp.*, and *Cibicide sp*., to infer middle neritic environment and stated that Lenticulina inornata is a good indicator of middle neritic environment as well as oxygenated bottom water condition.

Following the procedures for sequence stratigraphic interpretation outlined by [26], a combination of deductions on depositional environment from foraminifera data and log characters, interpretation of condensed sections from nannofossil abundance and diversity peaks as well as age dating of well sequence from biostratigraphic data was employed to erect a tentative sequence stratigraphic interpretation framework for the well since lithologic log profile was unavailable. Condensed sections are considered as thin marine stratigraphic units consisting of pelagic to hemipelagic sediments typified by very low sedimentation rates which are most areally extensive at the time of maximum regional transgression. The most landward surface within a depositional system is associated with a condensed section seaward.

The maximum flooding surface (MFS) is the surface corresponding to the time of maximum flooding [27]. It separates rocks formed during transgressive conditions from those deposited during the following overall regression. It also marked by a land-ward distribution of diverse, open marine, cosmopolitan, often abundant, planktons and deep water benthos. The MFS is a key stratigraphic surface while the surface itself is commonly a condensed horizon. Therefore, nannofossil abundance, diversity patterns and foraminifera data calibrated with chronostratigraphically important bioevents facilitated the recognition of a condensed section. This is correlated with the Global cycle chart of [23] and is believed to be associated with the 15.0Ma maximum flooding surface (Table 2). The condensed section associated with the maximum flooding surface comprises a biostratigraphically distinctive event usually with abundant planktonic fossils. It thus has the greatest potential for being dated and correlated across a basin (and possibly globally). It is, therefore, a more correlatable event than the sequence boundary, which sometimes is difficult to date or even recognize biostratigraphically. The depths selected as condensed sections were confirmed by tying them with nannofossil abundance and diversity peaks.

Conclusion

Sedimentological and biostratigraphic study of Motun 1 well from Niger Delta indicates that well penetrated Agbada Formation typified by the sand-shale intercalations. The studied successions yielded exclusively low diversity benthonic foraminifera taxa including Bolivina, Lenticulina, Quinquelloculina, Ammobaculites and Textularia. The abundance and high diversity of the recorded calcareous nannofossils and palynomorphs allowed the age of the well to be constrained to early to middle Miocene with the identification of one maximum flooding zone at 7680 ft and dated 16.0 Ma by correlation to standard eustatic sea level chats. The sediments were deposited in environments ranging from littoral through inner to middle neritic settings based on deductions from sedimentological and foraminifera data.

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