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Sequence stratigraphic interpretation of Middle–Late Miocene successions of OMAH–1 well Offshore Niger Delta, Nigeria

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Original Research

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Abstract:

Sequence stratigraphic analysis provides indications of depositional systems and specific cycles of sedimentation. Such studies are useful for the prediction of quality and geometry of reservoir systems. Ditch cuttings and Well log data recovered from the Middle-Late Miocene "OMAH-1 Well", Offshore Niger Delta, Nigeria were analysed in order to have a proper understanding of rock units' relationships with chronostratigraphy and depositional environment-significant forms. Results of paleobathymetry of the deposits using benthic foraminifera ranged from coastal deltaic to shallow marine (shallow inner neritic, inner neritic and middle neritic) settings. Two foraminiferal zones and four palynological zones indicative of Middle–Late Miocene age was identified. Four (4) sequence boundaries (SBs) were identified and dated: SB 1 at 7250 ft. dated 10.6 Ma, SB 2 at 6530 ft. dated 10.35 Ma, SB 3 at 4400 ft. dated 8.5 Ma and SB 4 at 2210 ft. dated 6.7 Ma. Three (3) maximum flooding surfaces (MFS) were also identified viz: MFS 1 dated 10.4 Ma at 6910 ft., MFS 2 dated 9.5 Ma at 5150 ft. and MFS 3 dated 7.4 Ma at 2930 ft. These surfaces were used to subdivide the stratigraphic column in the well section into five depositional sequences (Sequence I-V) characterized by Lowstand systems tract, Transgressive systems tract and Highstand systems Tract. The depositional sequences identified have quality reservoirs and source rocks with high potential for hydrocarbon generation.

Keywords: Niger Delta; Chronostratigraphy; Paleobathymetry; Sedimentary cycle; Sequence stratigraphy

1. Introduction

Sequence stratigraphy is a stratigraphic technique that utilizes unconformities and their correlative conformities to arrange sedimentary successions into temporally and spatially confined sequences (Vail et al., 1991; Emery and Myers, 1996; Onyekuru et al., 2023). This method was developed by the now famous Exxon research group in the 1980s championed by the likes of Baum and Vail (1988), Posamentier et al. (1988), with inputs from many other scholars that are not related to the Exxon research group (Galloway, 1989; Emery and Myers, 1996). Sequence stratigraphic method was specifically designed to provide proper understanding of sedimentary successions for hydrocarbon exploration. It uses biofacies data to identify key stratigraphic surfaces, system tracts and depositional sequences. This is generally achieved using the abundance and diversity of microfossils, which are integrated with other data such as well logs and paleobathymetric data. The integration of biofacies (micropalaeontological and palynological data) with other datasets in stratigraphic analysis has been discovered to be of significant advantage in sequence stratigraphic studies (Catuneanu, 2006). Integrated study of well logs, core samples and thin sections from oil producing fields in Late Turonian-Early Coniacian sediments in Southern Iraq was used for sequence stratigraphic interpretation (Mohammed et al., 2022). The study identified two 3rd-order sequences and key bounding stratigraphic surfaces that were linked to global sea-level fluctuations. In the Cenomanian-Turonian deposits of Sinai, Farouk et al. (2022) identified certain benthic invertebrates that were linked to regional depositional cycles and sea-level fluctuations.

The Niger Delta basin in Nigeria, is comprised of a series of independent depocentres representing depositional units through time (Stacher, 1995). The entire sedimentary wedge in the Niger Delta was deposited sequentially in five major depobelts (depocentres), each separated from the other by a distance of about 30 – 60 km. The youngest depobelt is positioned offshore, while the oldest is situated farthest inland. According to Evamy et al. (1978), syn-sedimentary growth faults disrupted the equilibrium and caused sedimentation in the depobelts to rely on the rate of sediment supply and subsidence. The "escalator regression" model was developed by Knox and Omatsola (1989) to explain the sedimentation processes in depobelts. When the rate of sediment supply and the rate of subsidence were virtually in balance, the Agbada Formation sediments were deposited in the majority of depobelts (Reijers et al., 1997). The Benin Formation's continental sands migrated quickly across each depobelt to sustain base level fluctuations when the rate of subsidence decreased, resulting in a reduction in the space available for sediments deposition (Reijers et al., 1997; GhasemShirazi et al., 2014; Anyanwu et al., 2021). The lithostratigraphic units in the delta basin are therefore strongly diachronous and cannot be easily correlated using marine biostratigraphic methods because the deposition of sediments in the Niger Delta basin was done across timelines and ranged in depositional environments from marine through paralic to continental (Reijers et al., 1997; Anyanwu et al., 2022b). Sequence stratigraphy will therefore present the most accurate correlation results, the reason it was applied in the study of the successions in OMAH-1 Well.

Research on the Niger Delta's sequence stratigraphic subdivision is still in its early stages (Stacher, 1995; Reijers, 2011; Onyekuru et al., 2021). It is anticipated that the use of this cutting-edge and trustworthy approach in the OMAH-1 WELL would significantly advance knowledge of the structure, stratigraphy, connectivity of reservoirs, and architecture of the Niger Delta basin. Armentrout et al. (1999) in their now classical paper demonstrated that the different system tracts such as lowstand system tracts (LSTs), transgressive system tracts (TSTs) and highstand system tracts (HSTs), and key bounding surfaces, can be documented by studying biofacies configurations in terms of abundance and diversity, lithologic information as well as palaeobathymetric data of foraminiferas. Petters (1979) working on the foraminiferal species of Parable-1 well erected and described three (3) biozones that were dated Late Oligocene–Miocene based on *Globorotalia opima nana* and *Globorotalia opima opima* to define Late Oligocene, *Globorotaliafoshi peripheronda* was used to define early middle Miocene and Pliocene.

Onyekuru et al. (2012) performed a sequence stratigraphic analysis in the "XB Field," the Central Swamp depobelt of the Niger Delta basin, utilizing well logs and biostratigraphic data from six wells. They discovered sequences that were deposited in the Neritic to Bathyal paleoenvironments and have good reservoir seal characteristics. A combination analysis of seismic, well log, and biostratigraphic data allowed for the sequence stratigraphic interpretation of the "Beta-24 well" in the Northern depobelt of the Niger Delta basin (Ukpong and Anyanwu, 2018c). Similarly, Ukpong et al. (2018) integrated well logs and biostratigraphic information for sequence stratigraphic analysis of B-24 well, Niger Delta basin. In a more recent study, Ukpong and Ekhalialu (2021) used well logs and foraminifera information recovered from ditch cuttings from two wells in the Niger Delta for sequence stratigraphic interpretation.

The application of biostratigraphy in a sequence stratigraphic framework will provide a first-rate tool for the analysis and interpretation of sediment packages in marine basins and the identification of key stratigraphic surfaces and systems tracts. This present study is aimed at carrying

Figure 1. Map of the Niger Delta showing the location of OMAH-1 well.

out a sequence stratigraphic interpretation of the Middle-Late Miocene sediments in OMAH-1 well in the offshore Niger Delta, Nigeria in order to have a proper understanding of rock units' relationships with chronostratigraphy using depositional environment significant forms. OMAH-1 well that is under investigation is precisely located at Latitude 4° 20′ N and Longitude 5° 10′ E, Offshore Niger Delta (Fig. 1). The well was drilled by Chevron Nigeria Plc. as part of its hydrocarbon exploration ventures. The ditch cuttings used for this study were recovered from depth intervals of 1580 – 8350 ft. at a ninety feet (90 ft.) sampling interval.

2. Niger Delta stratigraphy

While oil exploration and production activities have documented the stratigraphy of the Niger Delta clastic wedge, most of these stratigraphic schemes have remained the exclusive property of the major oil firms operating concessions in the Niger Delta Basin. Short and Stauble (1967) detailed the stratigraphic development of the Tertiary Niger Delta and the nearby Cretaceous deposits, but many other researchers, including Evamy et al. (1978), Doust and Omatsola (1990), and Tuttle et al. (1999), have described the petroleum geology of the region. While Oomkens (1974), Allen (1965) and Anyanwu et al. (2022a) described the primary depositional habitats, sedimentation, physiography and geochemistry of the present Niger Delta, Stacher (1995) constructed a hydrocarbon habitat model for the Niger Delta based on sequence stratigraphic approaches. The three main lithostratigraphic units (Fig. 2) identified in the Niger Delta's subsurface (Akata, Agbada, and Benin Formations) are generally accepted to be decreasing in age basinward, reflecting the overall regression of depositional conditions inside the delta clastic wedge (Reijers et al., 1997; Anyanwu et al., 2022b). Southern Nigeria has stratigraphic comparable units to these three formations (Short and Stauble, 1967). The formations were deposited in marine, deltaic, and river environments (Weber and Daukoru, 1975; Weber, 1986), and they show a gross coarsening-upward progradational clastic wedge (Short and Stauble, 1967). About 80 kilometers east of Port Harcourt, in the Akata 1 Well, the Akata Formation's type section was established (Short and Stauble, 1967). In the Akata 1 well, a total of 11,121 feet (3, 680 meters) were drilled before running into the Akata Formation's base. The deepest occurrence of deltaic sandstone strata (7,180 feet in Akata well) marks the apex of the formation. In the middle of the clastic wedge, the formation is thought to be 21,000 feet thick (Doust and Omatsola, 1989). Dark gray silts and shales make up the lithologies, with occasional sand streaks that are thought to be turbidites (Doust and Omatsola, 1989). Up to 50% of the

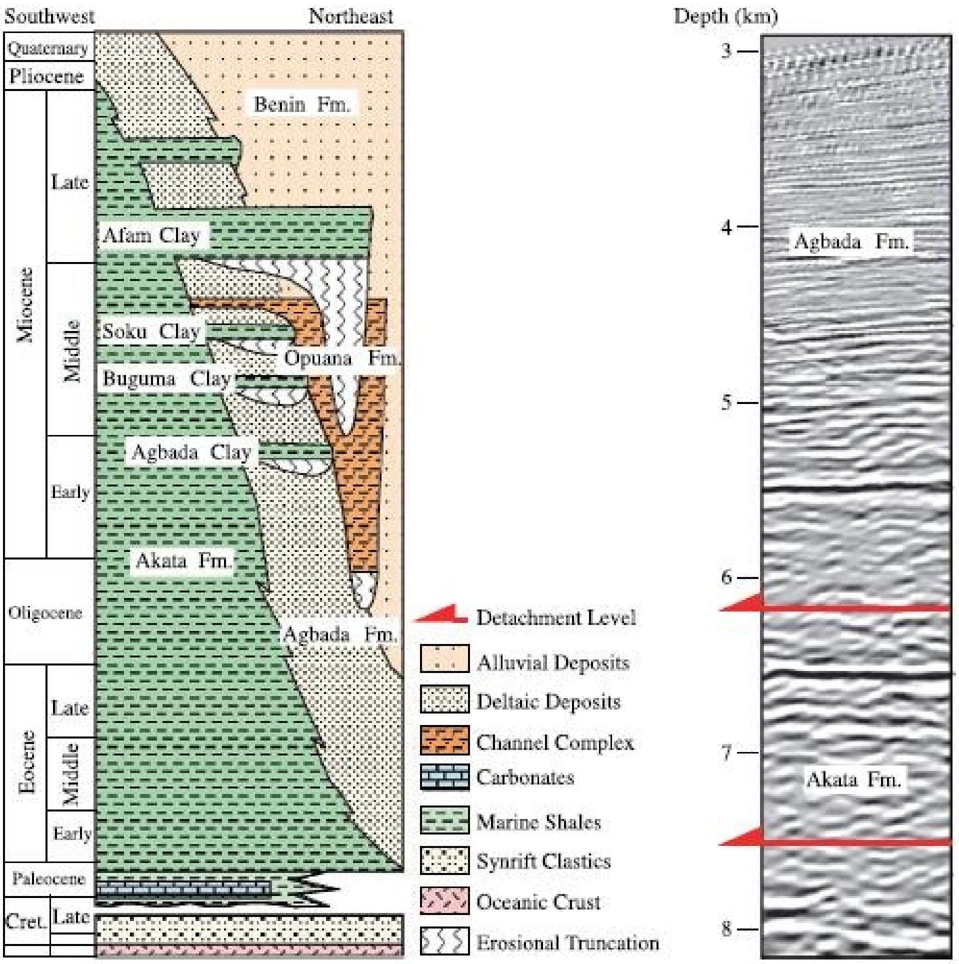

Figure 2. Schematic representation of the stratigraphic framework of the Niger Delta and variable thickness seismic display of the primary units (Corredor et al., 2005).

microfauna assemblage is made up of marine planktonic foraminifera, which suggest shallow marine shelf deposits that range in age from Paleocene to Recent (Doust and Omatsola, 1989). The shales that formed during the early developmental stages of Niger Delta progradation, are thickest along the axis of the Benue and Bida Troughs.

The Imo Shale is a Formation of shales that is exposed onshore in northeastern Niger Delta. Along the continental slope, this formation and its components can also be found offshore as shale diapirs. These marine shales are often underpressured when firmly buried. According to Stacher (1995), the Akata shales are deepwater lowstand deposits. The transition zone contains a lot of plant remnants and micas as the formation grades upwards into the Agbada Formation (Doust and Omatsola, 1989).

The Agbada 2 well, which was dug about 11 km to the north-northwest of Port Harcourt, defines the Agbada Formation (Short and Stauble, 1967). The formation's base, which was the top of the Akata Formation in the Akata 1 well, was not penetrated by the well, which went down a total of 9500 feet. The formation's maximum thickness is roughly 13,000 feet, and it can be found throughout the Niger Delta clastic wedge. It is known as the Ogwashi-Asaba Formation where it emerges in southern Nigeria (between Ogwashi and Asaba) (Doust and Omatsola, 1989). The lithology is made up of alternating sands, silts, and shales that are grouped within successions of ten to one hundred feet that are marked by gradually increasing changes in grain size and bed thickness. It is believed that fluvial-deltaic conditions are where the strata developed. The formation is Eocene to Pleistocene in age.

Benin Formation is on top of the Agbada Formation. The Niger Delta clastic wedge's uppermost lithostratigraphic units are found in the overlying Benin Formation. From the Benin-Onitsha region in the north to beyond the current coastline in the south, it has been discovered to be exposed (Short and Stauble, 1967). Elele 1 Well, which was dug about 38 km to the north-northwest of Port Harcourt, serves as its type section (Short and Stauble, 1967). The formation's base descends to a depth of 4600 feet, and its top is the most recent delta top surface that is subaerobically exposed. The Agbada Formation's youngest marine shale serves as the basis. During the progradation of the delta, non-marine sand was largely deposited in alluvial or upper coastal plain settings, making up the shallow portions of the formation (Doust and Omatsola, 1989). Although a scarcity of faunal remains prevents precise age dating, the formation's age is thought to span from the Oligocene to the Recent (Short and Stauble, 1967).

3. Methods

Sixty-eight samples (1580 – 8350 ft.) from OMAH-1 well were subjected to detailed identification and description of lithology, palynoflora and fauna contents. The samples selected for foraminiferal and palynomorph analyses were first treated with sodium carbonate and sodium hexametaphosphate, to increase the solubility of organic matter in aqueous solutions and for clay deflocculant, respectively (Armstrong and Brasier, 2005; Ukpong et al., 2017) before other sample preparation methods were carried out. Prepared slides were thereafter analysed for palynological and foraminiferal constituents using the appropriate microscopes. All species (pollen, spores, dinoflagellate cyst, fungal remains, algae, and foraminiferal linings) and foraminifera present were recorded in the analysis sheets, which enhanced the paleontological, palynoecological groupings and paleoenvironmental reconstruction process.

The identification of foraminiferas was carried out using the published reference schemes of Fayose (1970), Petters (1982), Bolli and Saunders (1985) while palynomorphs were identified by using published reference schemes of Germeraad et al. (1968), Clarke and Frederiksen (1968) and by comparison to local (in-house) palynological catalogues of Shell (1980).

Sample lithology or lithofacies assemblages (characteristics ascertained using hand lens and bionocular microscopy), gamma-ray log, and biostratigraphic data were employed in the interpretation of environment of deposition (EOD) and the reconstruction of sequence stratigraphic framework for OMAH-1 Well. Well log signatures were used to demarcate the entire succession into distinct stacking patterns (progradational, aggradational or retrogradational) that depict the different EODs and systems tracts. Higher gamma-ray readings were used to compliment the interpretation of zones with abundant biofacies as maximum flooding (MFS) surfaces (Vail and Wornardt, 1990), while sequence boundaries (SB) were interpreted from well logs at depths with abrupt fall in gamma–ray counts and high resistivity kicks, which are usually related to sharp lithological changes, and correspondingly barren biofacies data (Onyekuru et al., 2012). These sequence stratigraphic surfaces (MFS and SB) and the interpreted biozones were picked based on the identification (or absence) of stratigraphically significant planktic foraminiferal index species. The Standard biozonal scheme of Blow (1979) and Bolli and Saunders (1985) were used for foraminiferal biozonation, while the biozones scheme of Evamy et al. (1978) was used to zone the palynomorphs. Paleobathymetric study was done using significant forms. Benthic foraminifera were used for this purpose. As bottom dwellers, they provided information about the conditions at the sea floor especially paleodepth because certain benthic foraminiferas are restricted to particular bathymetric ranges (Petters, 1995), as such proved very useful for the bathymetric zonation and paleobathymetric interpretation of the studied well (Fig. 3). Also, different species of calcareous and agglutinating benthic foraminifera which are diagnostic of normal saline waters of the continental shelve environment were used in the study, while transitions from estuarine (marginal marine environment) to the open neritic setting was analysed by an increase in the abundance and diversity of calcareous foraminifera. The paleoenvironmental/paleobathymetric study of OMAH-1 well was based on the qualitative evaluation of the paleoenvironmental ranges of selected depositional environment-significant benthic foraminiferas (Adegoke et al., 1976; Murray, 1991). Thereafter, all the interpreted parameters (data sheets, that display identified forms), paleobathymetry, lithology, well log and systems tracts were used as input data into the

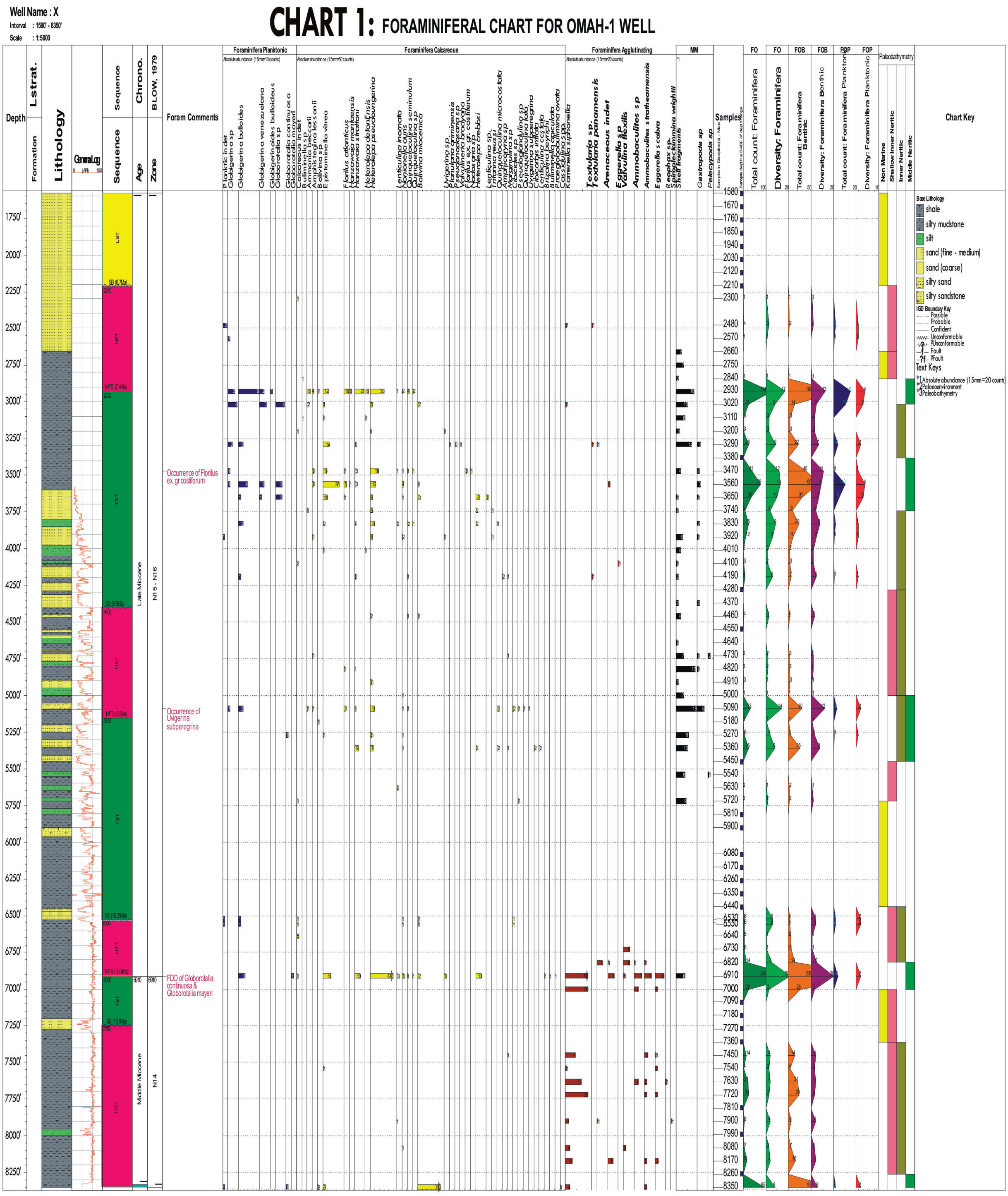

Figure 3. Stratigraphy and foraminiferal distribution chart of OMAH-1 well.

STRATABUGS 2.0 software, to generate distribution charts. The charts would show the identified foraminifera and palynomorph species arranged according to species' stratigraphic appearances and disappearances against increasing depths, with interpreted systems tracts inserted by the side of the studied OMAH-1 well. The marker species were plotted separately from other species to facilitate the picking of palynological and foraminiferal zonal boundaries.

4. Results and discussion

4.1 Microfossils of OMAH-1 well

The sixty-eight samples recovered from the depth range of 1580 – 8350 ft. and subjected to detailed lithologic, palynoflora and fauna contents revealed abundant and diverse microfossils (pollen, spores, algae, foraminifers). Foraminiferas were dominated by calcareous benthics including *Epistominella vitrea, Lenticilina inornata, Florilus atlanticus, Heterolipa pseudoungrina, Hanzawaia mantaensis, Amphisterinalessoni, Florilus* ex. *gr. Costiferum, Quin-*

queloculina seminulum, Uvigerina subperegra, Quinquiloculina microcostata, Hanzawaia strattoni, Ammonia baccarii and Heteroleppa cressi.
Arenaceous forms observed within the sections included *Textularia panamensis, Karriella siphonella, Valvulineria bradyana and calcareous indet*, with some occurrences of planktics including *Globigerina bulloides, Globorotalia mayeri, Globorotalia continuosa and planktic indets*.
Calcareous benthics recovered in the samples included *Bolivina miocenica, Brizalina beyrichi, Heterolepa crebbis, Heterolepa pseudoungrriris, Hanzawaia strattoni, Buliminella apiculeta, Epistominella vitrea, Lenticulina inornata, Praeglobobulimina ovata* among others. Also, the arenaceous taxa observed within the zones of study included *Ammobacculites strathearnensis, Valvulineria flexilis, Karreriella siphonella, Sygerella scrabarow, Textularia panamensis* (Fig. 3).

The palynomorph assemblages were dominated by land and fresh water-derived sporomorphs particularly *Monoporites annulatus, Zonocostites ramonae, Perchidermitites diderexi, Sterisporites sp, Retitricolpories irregularies, Psilastephanocoporites laevigatus* and freshwater algae-*Botriococus braunnii* (Fig. 4).

4.2 Biozonation of OMAH-1 well

The foraminiferal and palynological zonation schemes of Shell (1980) and Bolli and Saunders (1985) were used to zone the entire succession in OMAH-1 Well.
The results revealed that two foraminiferal biozones were penetrated in the analysed sections of the well including N16-N15 and N14.

N16-N15 zone

The top of this zone was not penetrated in the analysed interval of 1580 – 5090 ft. due to non-recovery of diagnostic

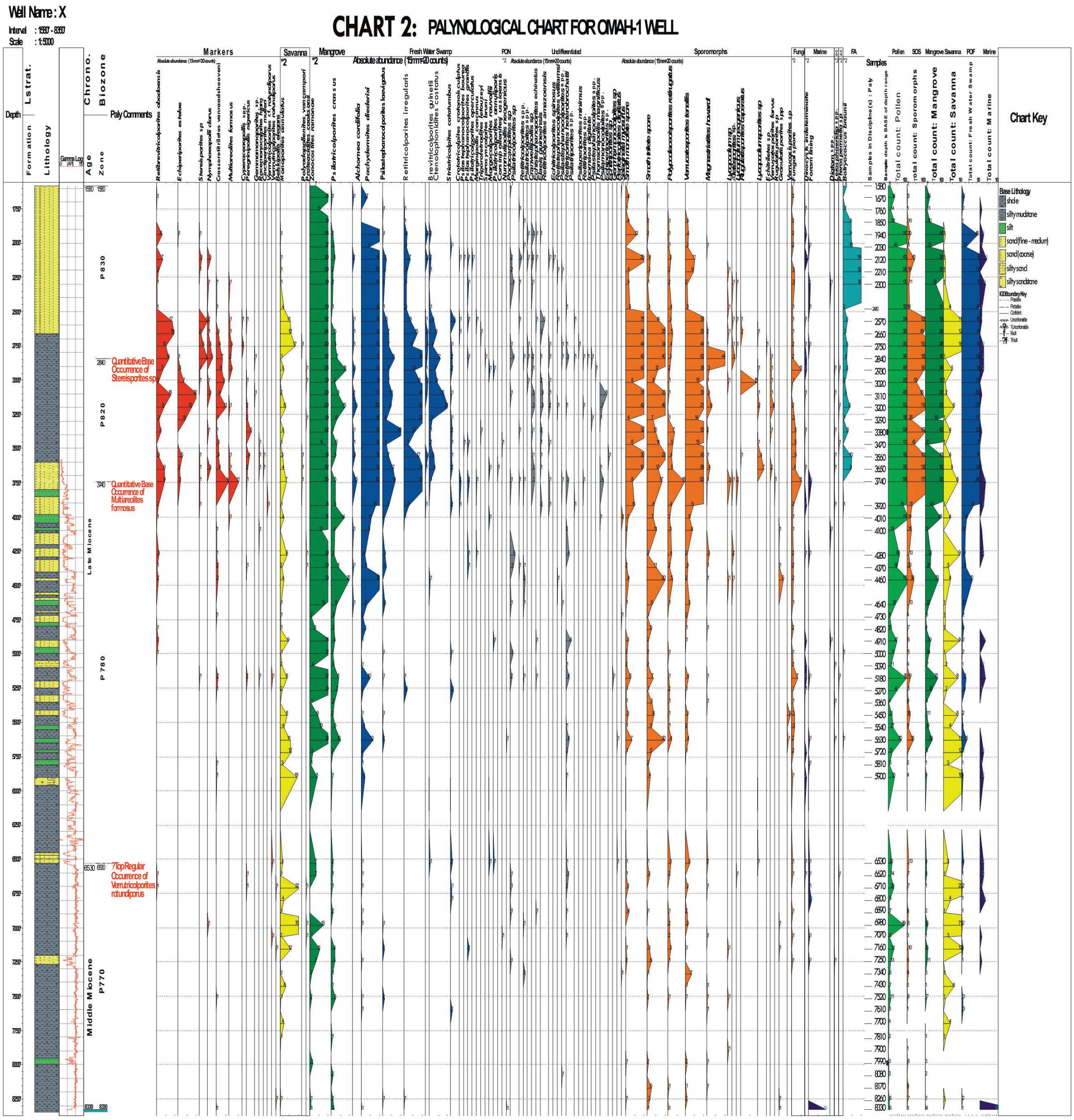

Figure 4. Stratigraphy and palynological distribution chart of OMAH-1 well.

Table 1. Foraminiferal biostratigraphic summary of OMAH-1 well.

Depth	Biozone	Age	Event
1580 – 5090	N15-N16	Late Miocene	7.4 Ma MFS at 2930 ft., occurrence of *Florilus ex. gr. costiferum* at 3470 ft., occurrence of *Uvigerina subperigina* at 5090 ft., associated with 9.5 Ma and 10.4 Ma MFSs
5090 – 8350	N14	Middle Miocene	FDO: *Glorobotalia mayeri* and *Glorobotalia continuosa* at 6910 ft.

taxa. However, the occurrence of *Florilus* ex. *gr costiferrum and Uvigerina subperigina* at 5090 ft. depth is an indication of the penetration of the N16 Zone. These taxa occur within the N16 zone of Bolli and Saunders (1985). The boundary between the N16 and N15 could not be delineated due to non-recovery of diagnostic taxa such as *Globorotalia aeostaensis* within the interval. This resulted in the designation of this interval as composite zone (N16-N15) zone (Table 1).

N14 zone

The First Down Hole occurrence (FDO) of *Globorotalia mayeri* and *Globorotalia continuosa* at 6910 ft. depth was used to delineate this zone ((Bolli and Saunders, 1985);Table 1). The base of this biostratigraphic zone was not penetrated as age diagnostic taxon such as *Hastigerina prasiphonifera* which marks the penetration of N13 zone was not encountered till the total depth of the well (Fig. 3).

The use of the zonation scheme of Evamy et al. (1978) for the palynological zonation of OMAH-1 well established four zones (Table 2):

1. P830 zone (1580 – 2840 ft.): The top of this zone was not penetrated but the base indicated by *Stereisporites sp* was recovered at the depth of 2840 ft.

2. P820 zone (2840 – 3740 ft.): The quantitative base of *Stereisporites sp* at the depth of 280 ft. forms the top of this zone and the quantitative base was encountered by occurrence of *Multiareolites formosus* at the depth of 3740 ft.

3. P780 zone (3740 – 6530 ft.): The quantitative base occurrence of *Multiareolites formosus* at 3740 ft. depth formed the top and the regular occurrence of *Verrutricolporites rotundiporus* at 6530 ft. depth formed the base.

4. P770 zone (6530 – 8350 ft.): The regular occurrence of *Verrutricolporites rotundiporus* at 6530 ft. depth formed the top. The base was not encountered till the total depth of the well (Fig. 4).

4.3 Paleobathymetry and environment of deposition (EOD) of sediments in OMAH-1 well

Lithostratigraphic study of OMAH-1 well showed that the lithology is dominated by coarse sand, shale and siltstone (Figs. 3 and 4). The shales are generally greyish in colour, fissile and laminated. These characteristics connote sedimentations in environments that are devoid of oxygen (Onyekuru and Iwuagwu, 2010). The preservation of primary lamination in the dark grey shales is suggestive of the absence of mud-eating benthos. Their formation in the Cretaceous is usually considered to have been related to warm climate and consequent stagnant oceans (Francis and Frakes, 1993; Onyekuru et al., 2023). It can therefore be interpreted from lithofacies analysis that the shales in OMAH-1 well were deposited in stagnant marine EOD (Table 3).

The result of paleobathymetric analysis revealed increase in biological activities from surface-water to bottom. This was deduced from reduced abundance of planktonic fauna which encouraged the production of benthic assemblages, thereby reducing the planktonic/benthonic ratio of the sediments in the seafloor (Fig. 5; (Leckie and Olson, 2003; Ukpong and Anyanwu, 2018a)). The results also suggested

Table 2. Summary of palynological analysis of OMAH-1well (1580 – 8350 ft.).

Interval (ft)	P-Zone	Age	Key Events
1580 – 2840	P830	Late Miocene	Top: Not encountered. Base: Quantitative base of *Stereisporites* sp at 2840 ft.
2840 – 3740	P820		Top: Quantitative base of *Stereisporites* sp at 2840 ft. Base :Quantitative base occurrence of *Multiareolites formosus* at 3740 ft.
3740 – 6530	P780	Middle-Late Miocene	Top: Quantitative base occurrence of *Multiareolites formosus* at 3740 ft. Base :?Top regular occurrence of *Verrutricolporites rotundiporus* at 6530 ft.
6530 – 8350	?P770	Middle Miocene	Top :?Top regular occurrence of *Verrutricolporites rotundiporus* at 6530 ft.

Table 3. Interpretation of environment of deposition using lithofacies and well log signatures of OMAH-1 well.

Depth (ft.)	Depositional environment
1580 – 2650	Upper shoreface, massive channel sands with thin mudstone break.
2650 – 3600	Marginal marine shale
3600 – 6000	Alternating tidal channel sands and marginal marine shales/mudstone
6000 – 7250	Marine shale/mudstone overlain by Delta front sandstones.
7250 – 8350	Inter- distributary channel tidal sands and marine shales/mudstone

sediment deposition in Coastal Deltaic and Shallow marine (Shallow Inner Neritic, Inner Neritic and Middle Neritic) depositional environments (Fig. 3; Table 3). This interpretation was based on the preponderance of benthics in the samples. The Neritic zone is a shallow marine environment extending from mean sea level down to 200 m depth and generally corresponding to the continental shelf (Culver, 1988). Because of their proximity to land, neritic water environments receive varied amounts of sunlight, allowing both planktonic and bottom-dwelling organisms to engage in photosynthesis. They also have relatively ample nutrient levels and high levels of biological activity.

4.4 Systems tracts and sedimentary cycles

The lowstand, highstand and transgressive systems tract were identified in OMAH-1 well (Fig. 3). The systems tracts occurred at definable locations with diagnostic gamma ray log patterns in the examined base level cycles (Fig. 6; (Mitchum et al., 1993; Posamentier and Allen, 1999)). The lowstand systems tract (LST) was identified at depth intervals of 2210 to 1580 ft. and consists of sandstone units deposited in channel (continental) environment, with a high energy, oxidizing environment. This was demonstrated by the near absence of fossils which is due to dilution/environmental stress (Fig. 3). The sandstone deposits are restricted to shoreline setting within the outer shelf (fluvial or shoreface environment) that is nor-

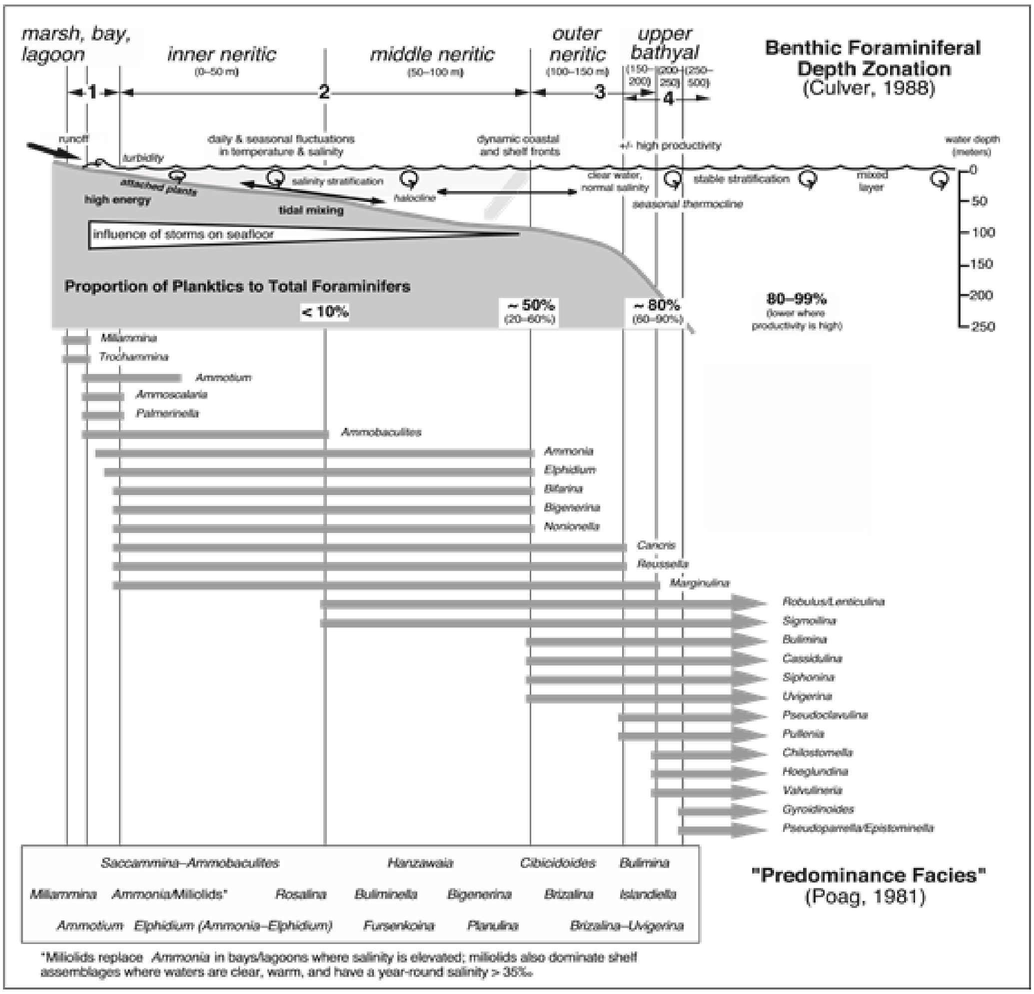

Figure 5. Benthic Foraminiferal distribution model for a typical modern ocean (Leckie and Olson, 2003); adopting the benthonic zonation of Culver (1988) and the depth distribution of the foraminiferal assemblages of Poag (1981).

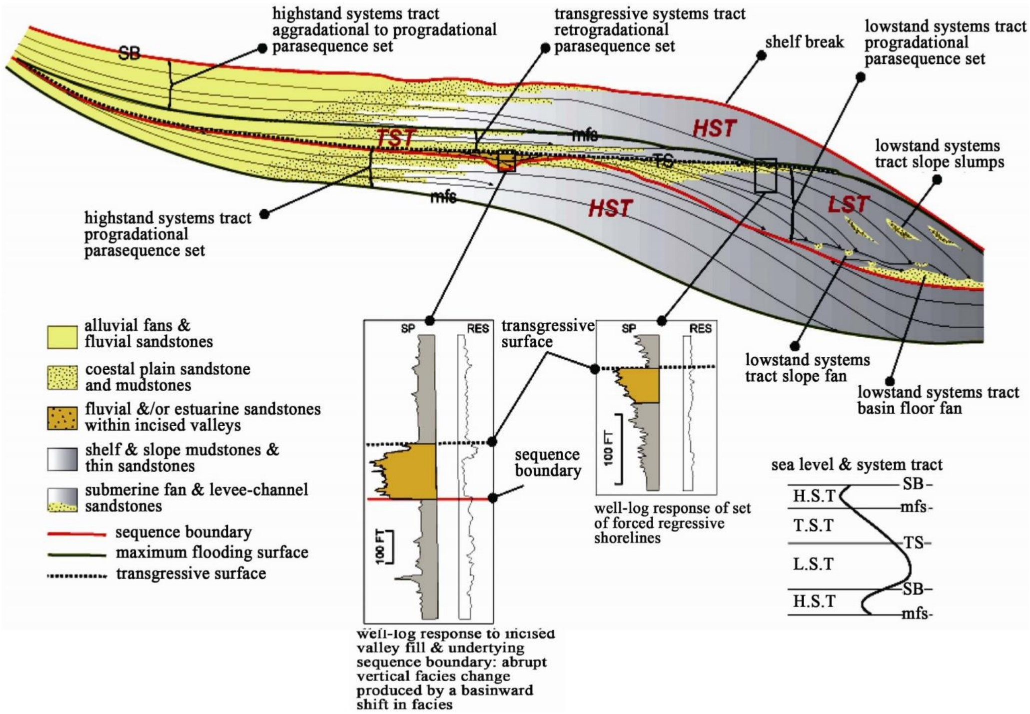

Figure 6. Key bounding surfaces and systems tract in a sequence stratigraphic model (after (Vail et al., 1977).

mally demonstrated by coarsening upward log signatures (Mitchum et al., 1993).

In a normal depositional sequence, the Highstand systems tract (HST) denotes the topmost unit (Mitchum et al., 1993). It is usually identified by an initial aggradational parasequence sets, and a progradational parasequence sets afterwards (Adegoke, 2012). In OMAH-1 well sections, the HST occurred at depth intervals of 2930 – 2210 ft.; 5150 – 4400 ft.; 6910 – 6530 ft. and 8350 – 7250 ft. (Table 4). The prograding HSTs are characterized by deposits of gravity flows, increased microfossil reworking and an upward decrease in benthic micro fauna (Armstrong and Brasier, 2005; Ukpong and Anyanwu, 2018c, 2018b).

The transgressive systems tract (TST) is referred to as the middle systems tract in the depositional sequence model. It is generated during an increasing rate of sea-level rise (Mitchum et al., 1993) and is identified by retrogradational parasequences sets. In the studied well, it was recognized at the depth intervals of 4400 – 2930 ft.; 6530 to 5150 ft.; and 7250 to 6910 ft. (Table 4). The TST units contain high quality reservoir sands like shoreline and beach deposits, which cut across the intertidal to neritic zones. The accom-

Table 4. Sequence stratigraphic summary of OMAH-1 Well.

Depth	System tract	Key surfaces
1580 – 2210	LST	-
2210	-	SB (6.7 Ma) (**Haq1988**)
2210 – 2930	HST	-
2930	-	MFS (7.4 Ma)
2930 – 4400	TST	-
4400	-	SB (8.5 Ma)
4400 – 5150	HST	-
5150	-	MFS (9.5 Ma)
5150 – 6530	TST	-
6530	-	SB (10.35 Ma)
6530 – 6910	HST	-
6910	-	MFS (10.4Ma)
6910 – 7250	TST	-
7250	-	SB (10.6Ma)
7250 – 8350	HST	-

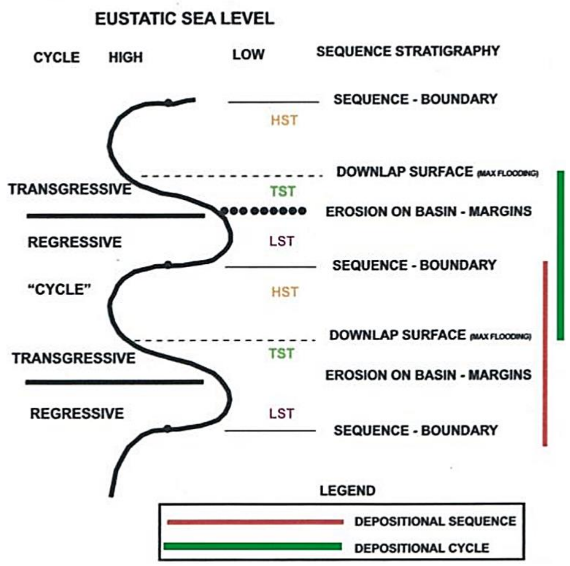

Figure 7. Relationship between cycle concept and sequence stratigraphy (Adegoke, 2012).

panying shale units are characterized by high abundance and diversity of microfossils in the well section (Fig. 3). The alternation of the depositional systems showed that the succession in the OMAH-1 well is cyclic. The main causes of cyclic depositions through time are eustatic changes and tectonic events (Farouk, 2015; Mohammed et al., 2020). Other causal mechanisms are associated with orbital climatic effects, time span, rate of sediments supply and the space available for sediments deposition (Onyekuru et al., 2023). There is a relationship between the concept of sedimentary cycle and sequence stratigraphy (Fig. 7). In the Niger Delta, eleven different sedimentary cycles have been identified and dated using regional marker shales (Fig. 8; (Reijers, 2011). Two (2) of these cycles (9 and 10) were identified in the studied OMAH-1 well. Cycle 9 (Middle Miocene-N14) was denoted by the 10.4 Ma shale marker that occurred at 6910 ft. Cycle 10 (Upper Miocene-N15-N16) was defined by 9.5 Ma and 7.4 Ma shale marker occurring at 5150 ft. and 2930 ft. respectively. These shale markers are characterized by the high abundance and diversity of microfossils and fingerprinted the maximum flooding surfaces defined in this study (Fig. 3).

4.5 Depositional sequence of OMAH-1 well

A total of five depositional sequences were recognized in this study (Sequence I- V) comprising of 3 complete and 2 incomplete sequences (Fig. 3; Table 4). A depositional sequence in this context is a stratigraphic unit containing relative conformable successions of genetically related strata bounded at its top and bottom by unconformities or their correlative conformities (Reijers, 1996; Adegoke, 2012). The depositional sequences contain the lowstand systems tract, transgressive systems tract and high stand systems tract (Fig. 3). Paleobathymetry of the sequences were inferred to be of coastal deltaic and shallow marine (shallow inner neritic, inner neritic and middle neritic) with paleodepth ranges of 0 – 100 m.

Sequence I (8350–7250 ft.)

This incomplete sequence is made up of a Highstand Systems Tract (HST: 8350 – 7250 ft.) which is comprised of an interlayering of shale and argillaceous siltstone at the 8000 ft. depth, which later graded into to shale. The HST is terminated at the top by a sequence boundary (SB: 10.6 Ma) at 7250 ft. depth, delineated by abrupt change in lithology and an erosional surface that truncated its topmost bed. This shows that the sediments accumulated during a time of decelerating rate of relative sea level rise, enabling the rate of sediment supply to exceed the rate of accommodation and as such deposited during, and shortly after the peak of relative sea level change. The HST in sequence I being the uppermost systems tract (Fig. 3) is indicative that the other accompanying systems tracts were not penetrated by OMAH-1 well.

Sequence II (7250–6530 ft.)

This complete sequence encloses a Transgressive Systems tract (TST) and Highstand Systems Tract (HST). The Transgressive System (TST: 7250 – 6910 ft.) is made up of interbedded clay, shale, mudstone. This lithology shows that the Transgressive System Tract was deposited during rising relative sea level cycle and a period of relative shore line transgression. These sediments were deposited when the rate of increase in accommodation exceeded the rate by which sediment was supplied to the basin. In this sequence, the TST thinned into a condensed section (MFS: 10.4 Ma) indicated by abundance peak of First Down Hole occurrence (FDO) *Globorotalia continuosa* and *Globorotalia mayeri* at the depth of 6910 ft. (Fig. 3). The condensed section is usually identified as shale prone, organic rich in intervals with elevated gamma-ray counts (Onyekuru et al., 2012). The HST: 6910 – 6530 ft., is made up of aggradational stacking patterns comprising of shale and sandstone units. A Sequence Boundary (SB) capped the HST at the 4400 ft. depth when the shaly siltstone changed from aggradational to retrogradational stacking pattern.

Sequence III (6530–4400 ft.)

This sequence is made up of a Transgressive Systems Tract (TST) and Highstand Systems Tract (HST). The TST: 6530 – 5150 ft., is made up of shale units interbedded with thinly bedded siltstone, coarse-medium-fine sand. The sand units are aggradational with a fining-upwards (FU) stacking pattern towards the Maximum Flooding Surface (MFS: 9.5 Ma) at 5150 ft. depth. The overlying HST (5150 – 4400 ft.) is made up of shale interbedded with silty sand. At the top of the HST is the Sequence Boundary. The wireline signature at this depth (4400 ft.) signified an erosional truncation that defined the SB (Fig. 3).

Sequence IV (4400–2210 ft.)

This sequence is made up of three system tracts namely the TST, HST, and the LST. The TST (4400 – 2930 ft.) is made up of a fining upward sequence (retrogradational) stacking pattern interbedded with shales. The 7.4 Ma MFS was defined at the top of the TST at the 2930 ft. depth. The overlying HST (2930 – 2210 ft.) is made up of two units:

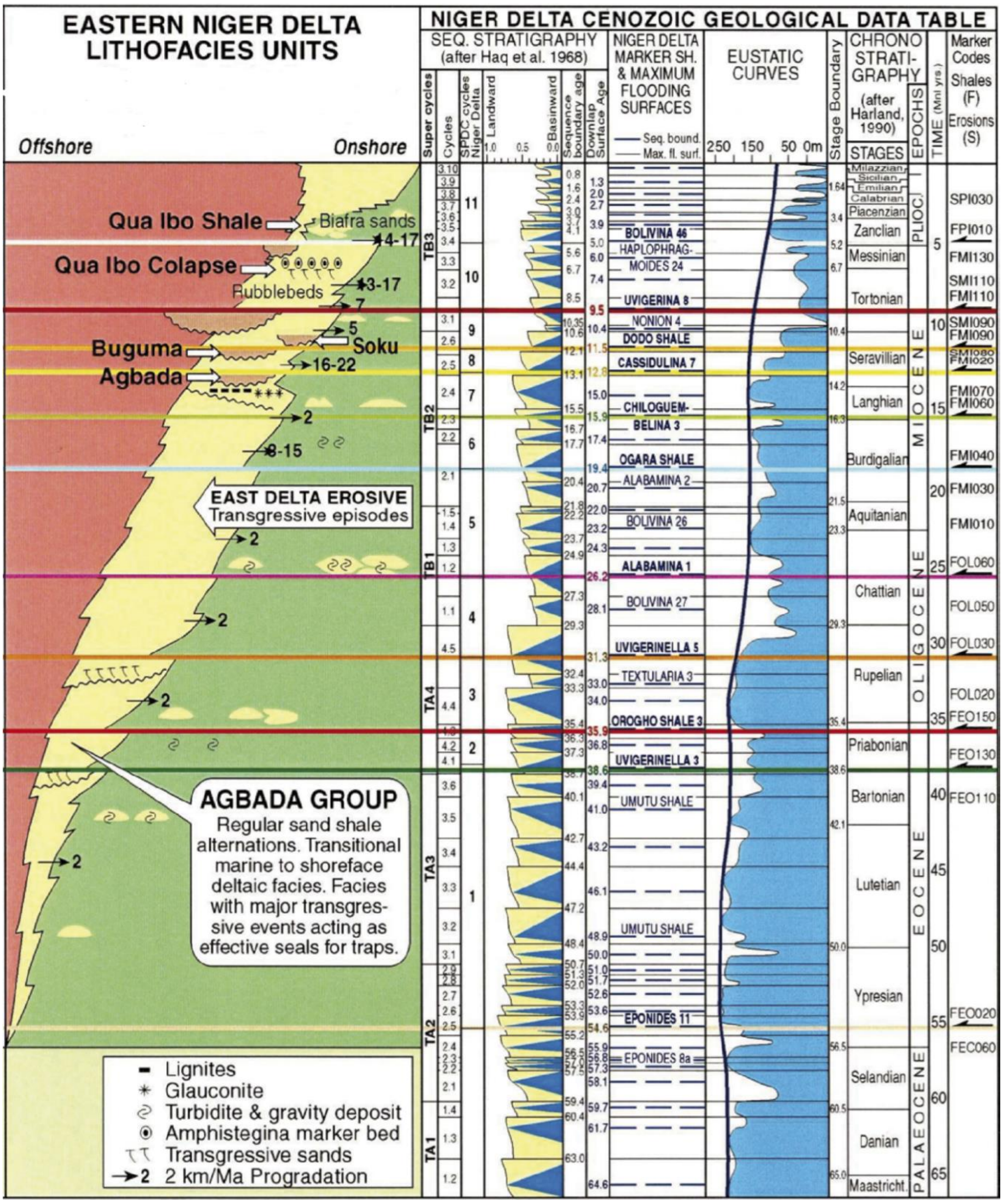

Figure 8. Stratigraphic data chart of the western and eastern segments of the Niger Delta (Reijers, 2011).

shale with sand which fines to the top into an erosional truncation that defined the Sequence Boundary (SB: 6.7 Ma) at the 2210 ft. depth. The overlying HST comprised of argillaceous siltstone with fining upward patterns to caps Sequence IV. A number of studies have indicated that the TSTs contain quality reservoir sands, and they tend to be better developed in the inner-neritic zone, where the sands are capped by hemi-pelagic shales (Mitchum et al., 1993; Adegoke, 2012).

Sequence V (2210–1580 **ft.)**

This incomplete sequence consists of an LST (2210 – 1580 ft.) with a predominantly coarsening upward package of sandstone unit of the overlying the HST (Fig. 3).

5. Summary and conclusion

Well log pattern (gamma-ray) paleobathymetry and biostratigraphic data were employed in the study of the sedimentary successions in OMAH=1 well in a sequence stratigraphic framework. A total of four Sequence Boundaries:10.6 Ma (7250 ft.), 10.35 Ma (6530 ft.), 8.5 Ma (4400 ft.), 6.7 Ma (2210 ft.)) and three maximum Flooding Surfaces (10.4 Ma (6910 ft.), 9.5 Ma (5150 ft.), 7.4 Ma (2930 ft.)) of Middle-Late Miocene age was recognized. Sequence boundaries were interpreted from the well log where evidence of abrupt fall in gamma-ray counts related to a sharp lithological change occurred and corresponding to barren biofacies data. At this point, fewer or no fossils were retrieved due to environmental stress as deposition was in a high energy environment. The higher gamma-ray

readings were used to identify maximum flooding surfaces which were further established with biostratigraphic data. Two foraminiferal zones and four palynological zones were also penetrated. Depositional environments appear to have been consistently fluvial to shallow marine (Shallow Inner Neritic, Inner Neritic and Middle Neritic).
Two of the eleven sedimentary cycles (9 and 10) in the Niger Delta were identified in the studied well. Cycle 9 (Middle Miocene-N14) was denoted by the 10.4 Ma shale marker that occurred at 6910 ft. Cycle 10 (Upper Miocene-N15-N16) was defined by 9.5 Ma and 7.4 Ma shale markers occurring at 5150 ft. and 2930 ft. respectively. These shale markers are characterized by the abundance and diversity of microfossils which corresponded to depths defined by the maximum flooding surfaces in this study. A number of studies have indicated that the TSTs contain quality reservoir sands, and they tend to be better developed in the inner-neritic zone, where the sands are capped by hemi-pelagic shales. In the OMAH-1 well, the transgressive sands of all the depositional sequences are stratigraphically positioned to serve as good reservoirs. The shale units in the TSTs are also good potential source rocks. The alternation of sands and shale units in each of the systems tracts could serve as stratigraphic traps. The identified HSTs can also serve as quality reservoirs because of the presence of a coarsening upward signatures of the sandstone units, which could be sealed by shales of the transgressive systems tracts.

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Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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