Sequence Stratigraphic Framework and Depositional Architecture of Yowi Field, Shallow Offshore, Niger Delta, Nigeria

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Authors' contributions

This work was carried out by author PSM under the supervision of author MIO. Author PSM designed the study, wrote the protocol, and the first draft of the manuscript. Author PSM managed the literature searches, performed the analysis and author MIO managed and reviewed the experimental process. Both authors read and approved the final manuscript.

Original Research Article

ABSTRACT

Sequence stratigraphic analysis carried out in Yowi Field by integrating both well logs and biostratigraphic data revealed six depositional sequences within the Agbada Formation of about 7000 ft thick. Three systems tracts identified include highstand systems tract, transgressive systems tract and lowstand systems tracts. The highstand systems tract is majorly stacked regressive 4th - order shoreface sands that occurred in five parasequence sets, whereas the transgressive systems tract is a transgressive unit with both source rock and sealing potentials. The lowstand systems tract shows a boxcar log motif and is identified to be probably channel or barrier bar sand. Major shale units (maximum flooding surfaces) with regional significance mapped are

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designated MFS_1 to MFS_7, and tied to intervals with significant biostratigraphic records. This division is relevant to identifying genetic depositional units that contain one or more paleontologically distinct transgressive shale horizons. Six genetic sequences occurred in the field. The transgressive shales represent interruptions in the overall regressive sequence that is related to sea-level rise. Seven of these shales have been mapped and five of them correspond to five of the eleven genetic megasequences that occur delta wide. The ages of the sediments penetrated in the wells were inferred to range from Late middle Miocene to Pliocene using paleontological data. A predominantly marine and deltaic sequences strongly influenced by clastic output from the continent is inferred from both well log and paleontological data analysis. Paleowater depth is interpreted to fluctuate considerably and deposition occurred within a variety of littoral and neritic environments ranging from nearshore barrier sand complexes to fully marine outer shelf mudstones. The sediments are rapidly deposited within the shallow marine realm and reworked into longitudinal bars by wave action, strong longshore drift and tidal effects. The dominant depositional trend observed in the study area shows progradation.

1. INTRODUCTION

Sequence stratigraphy is the study of sedimentary rock relationships within a chronostratigraphic or geologic-time framework. It is the basis for the identification of stratal surfaces, regional unconformities and their correlative conformities [1,2,3,4]. The division of depositional packages into genetic units is well understood through the concept of sequence stratigraphy. This technique is a relatively new concept developed from the traditional stratigraphy that has helped to enhance the understanding of sedimentary processes and deposits in most basins of the world [5,6,7]. The cyclical nature of stratigraphic successions (better explained by sequence stratigraphic concept) is useful in the determination of reservoir architectures, and helps to predict the occurrence of reservoir rocks both at the regional and reservoir scales of investigation. Establishing a sequence stratigraphic framework for all the oil fields/depobelts in the Niger Delta is imperative, and will form a basis for establishing a regional sequence stratigraphic framework of the basin, and will be relevant to improved exploration techniques and the discovery of unidentified resources.

Most exploited traps in the Niger Delta sedimentary basin are structural in origin. Huge hydrocarbon deposits are located within the rollover anticlines associated with the synsedimentary growth faults. The quest for improved production has called for techniques more appropriate for new discoveries. The Yowi field area is located within the shallow water of between 10 and 30 ft deep.

The field has been on production for the past one decade, and currently experiences a high decline in oil production. It is imperative to improve reserves through the identification of the various depositional elements occurring within sequences that help to entrap hydrocarbon. Most stratigraphic elements that have potentials for hydrocarbon accumulation are in the fourth-order/fifth-order scale occurring as parasequences and parasequence sets. This study will identify these parasequences within third-order sequences. The Yowi field from its present and paleogeographic location occurs in a zone where the development of parasequences is significant. Parasequences are well developed within shallow marine – shoreface environments.

Adopting sequence stratigraphic technique to the study of the subsurface of the Yowi Field will be relevant to improved reserve, discovery of bye-passed hydrocarbon within thin beds and subtle stratigraphic traps; and the establishment of a sequence stratigraphic framework for the field. The study provides the best approach to studying offshore deposits which is the region of exploration interest in Nigeria for the past few decades.

1.1 Study Location and Area Geology

The Yowi Field lies in the shallow offshore depobelt in the eastern part of the Niger Delta sedimentary basin (Fig. 1a). It is located between latitude $4°38'$ – $4°32'$N, and longitude $8°18'$ and $8°35'$E, about 3km from the coast and about 30 km from the Cameroon border. The field covers an area extent of approximately 60 sq.km. The

first four exploratory wells were drilled in 1997, after which a total of 49 development /production wells have been drilled at two selected sites as at July 2010.

The Niger Delta basin is located on the continental margin of the Gulf of Guinea in the equatorial West Africa (Fig. 1a). It ranks among the world's most prolific petroleum province with about 5% of the world's oil and gas reserves [6].

Several works carried out in the Niger Delta have revealed the tectonic history, sedimentology, stratigraphy, depositional environments and the petroleum potential of the basin [8,9,10,11,12,13, 14]. The major structural elements delimiting the Niger Delta basin into two segments are the Benin Hinge Line (BHL) – an extension of the Chain Fracture on the west running from the Gulf of Guinea area through the Dahomey basin to the continent; the Charcot Fracture zone (CFZ) running through the centre of the basin to the Benue Trough, and the Calabar hinge Line (CHL) in the east, trending NW-SE into the Gulf of Guinea along the Cameroun Volcanic line. The Charcot Fracture running through the centre of the basin has been used to demarcate the basin into western and eastern Niger Delta, and the basin has been reported to be shallower at the flanks and deepest towards the centre [11,14]. In fact, one of the deepest well ever drilled in Nigeria is located within the centre of the basin, but at such depth (about 18707 ftMD/17961 ftTVD) the Akata Formation was not penetrated. But the Akata Formation is suspected in the Yowi oil field, eastern Niger delta at a depth shallower than 14000 ft (wells A2P2, A9P2).

Sedimentation in the eastern Niger Delta is controlled by several factors which include; sediment supply by the Calabar and Benue Rivers, (Fig. 1b) the weathering of the Cretaceous Oban Massif (Fig. 1b) and the Cameroon Mountain, and the activity of the active volcanic line of the Cameroon Mountain.In the eastern delta, sedimentation was interrupted by cutting-and-filling events [5], resulting in the Agbada, Elekelewu, Soku and Afam channels. During the Pliocene, catastrophic gravity events, possibly related to contemporaneous activity along the Cameroon volcanic line formed the Qua Iboe Channel in the south-eastern offshore area. In the southeastern offshore Niger Delta,

the fossiliferous Agbada Formation underlying the Benin sand is divisible into four members: the D-1 sand, the Qua Iboe Shale member, the Rubble beds and the Biafra Member (Fig. 1c; 7). The D-1 sand is an alternating sequence of regressive sands occurring within shales (QISM). The top and base of the QISM are unconformable and formed excellent stratigraphic element necessary for hydrocarbon entrapment. The Rubble beds (RB), Miocene-Pliocene conglomeratic beds underlie the QISM. It is underlain by the Biafra member. Farther south in the Equatorial Guinea, the lower portion of the Biafra member is represented by the Isongo Formation, which thickens towards the offshore area (Fig. 1c). The D-1 member has been encountered in the Ubit, Enang and Okwok oil fields in the offshore area operated by ExxonMobil. It thins towards the shallow offshore and is absent in the Yowi oilfield where average water depth is about 24 ft. The general trend of the QISM shows the thickest sediment offshore and thins out towards the onshore area (Fig. 1c).

Three key subsurface lithostratigraphic units identified include the Akata Formation, Agbada and the Benin Formation. A proposal to upgrade the three traditional Formations to Group status has been raised in the work of [14]. With this proposal, several other sub-formational units (Members) assume a Formation status. In the Eastern Niger Delta, the Qua Iboe Shale member is classified as Formation in that proposal, to include the Biafra Sand, Rubble Bed and the Qua Iboe Clay as constituent Members in the Qua Iboe Formation (Fig. 1b). A total of about 39372 feet (12,000 metres) thick successions of overall regressive, offlapping sediments com-posed of three diachronous siliciclastic units (deep-marine pro-delta Akata Group, the shallow-marine delta-front Agbada Group and the continental, delta-top Benin Group) (Fig. 1b) have been reported for the basin [14]. The Akata shale is assumed to be the major source rock, overlain by the Agbada Formation which hosts most of the exploited petroleum accumulations (Fig. 1b). The Benin sand is the youngest continental clastics overlying the Agbada Formation. Though the thickness of sediments in the basin is estimated at 39,372 feet (12000 metres), most wells drilled in the Niger Delta have not gone beyond 19686 feet (6000 metres).The deepest well drilled recently towards the centre of the basin attained up to 18,706.9 feet (5701.6 metres) (Measured Depth).
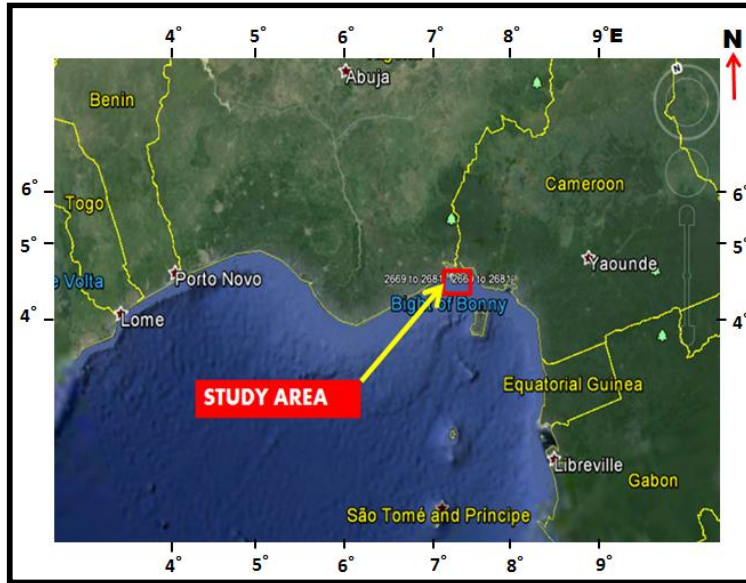
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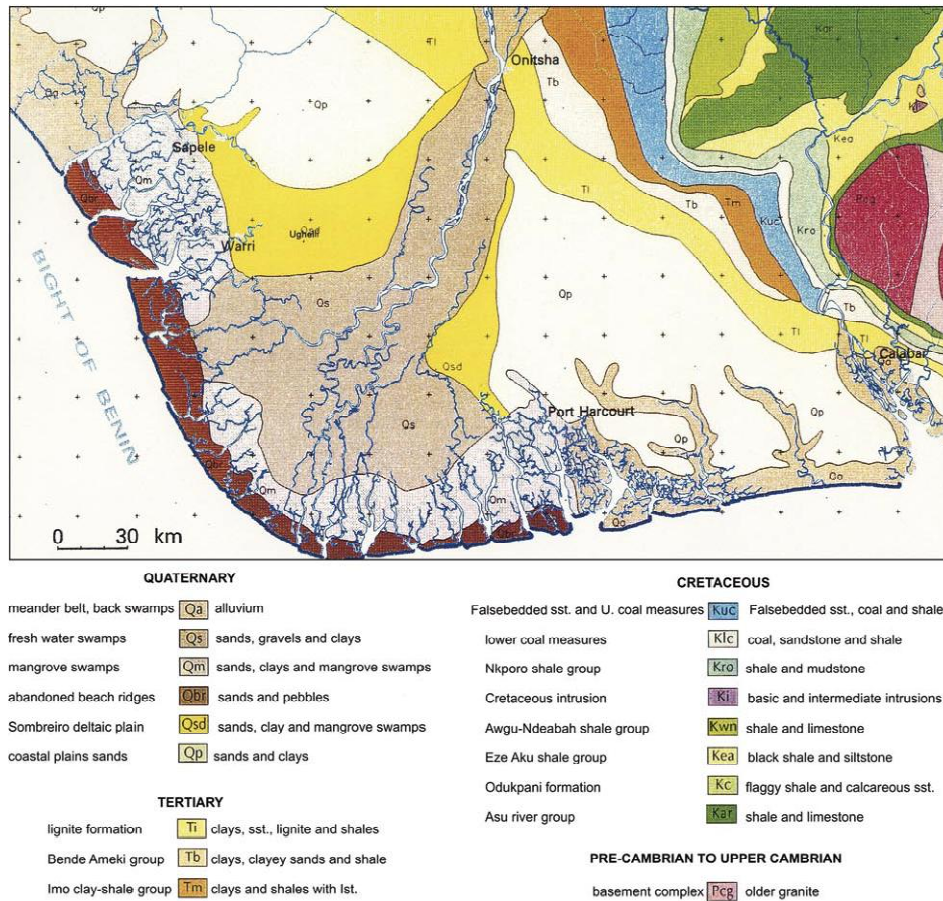**Fig. 1a. Map of Niger Delta showing the study area**

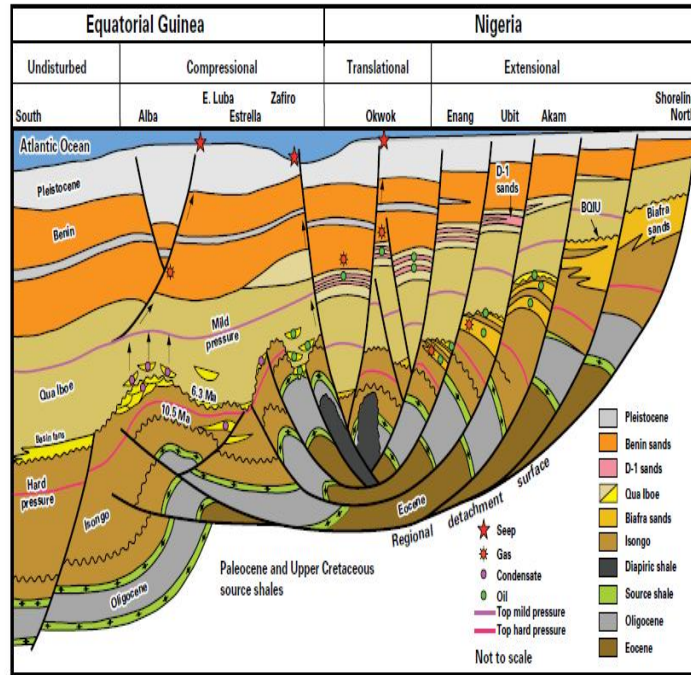**Fig. 1b. Geological map of the Niger Delta and surroundings, after [5]**

Fig. 1c. Play concept diagram for Nigeria's golden rectangle [15]

2. METHODS AND DATASETS

Two important models are adopted in this research in identifying sequences in the field. The Vail [1] and Galloway models [16]. Vail considers unconformity surface (sequence boundary) as a criterion in subdividing sedimentary fills within a basin into sequences (depositional sequences). Sequence boundaries develop when the rate of sea level fall is a maximum or when relative sea level begins to fall at some specific break in slope, thereby initiating the incision of valleys by head-ward erosion [17]. Galloway's model uses the flooding surfaces as a means of identifying genetic sequences. Applying the Galloway model is significant to establishing the continuity of key regional marker shales within the field. Two deep wells (A2P2 & A9P2) were used for the sequence stratigraphic interpretations with biostratigraphic information from well A9P2. We also correlated five representative wells across the field to establish the continuity of key marker horizons that fall within sequences.

2.1 Datasets

The datasets used for this study include; well logs and biostratigraphic data (nannofossils and palynological information inclusive).

2.1.1 Well logs

Most subsurface investigations in the Niger Delta are based on logs technique beside other geophysical data. Well logs provide essential information and interpretation of the subsurface geology of the area penetrated by boreholes, thus facilitating correlation between different areas. It provides information on the nature of the strata penetrated, the shape of the structure, physical data of the rocks, the depth at which these rocks are encountered, the porosity and permeability of the rock, type of fluid contained in the rock, temperature, etc. The well log data provided for this study include: Gamma Ray log, Neutron Log (NPHI), Bulk density Log (RHOB), Sonic Log, and Resistivity Log (ILD). Basically, the gamma ray log motif was used to identify lithology and the gross depositional setting of the study area. Other log types (Neutron, Density, etc.) were not used since they do not have direct relevance to the objectives of the investigation.

Gamma-ray log is an indicator of lithology. On a typical gamma-ray log, the logging tool measures natural gamma radiation of the rock formation. Higher gamma-ray counts indicate the presence of shale, because shale

constituents, including clay minerals, K-feldspar, and organic material, emit natural gamma radiation. With the exception of arkoses (K-feldspar rich), sandstones contain fewer or none of these components and therefore emit less radiation and lower gamma-ray count. Since clay content generally decreases with increasing grain-size of sands, gamma ray log measures continuous gain-size profiles in sandstone-shale sequences. The minimum gamma ray trend on the gamma ray log is taken as sand baseline, which is about 30°API in the Yowi Field. The maximum gamma ray trend corresponds to the shale baseline, about 120ºAPI. Quantitatively, gamma ray log is used to estimate shale volume. Other usefulness of GR log include; delineation of reservoir boundaries, depositional environments of sand bodies, well correlation to establish the continuity of geological units, establishment of the thickness of sand bodies, etc.

2.1.2 Biostratigraphic data

Micropaleontology was primarily used to identify the biostratigraphic successions and with support provided by other disciplines including palynology, and calcareous nannoplankton (nannofossils). Biostratigraphic report of samples from well A9P1/A2P2 provides broad constraints on the age and depositional environments of the Agbada Formation in the field. Biostratigraphy plays an important role in the identification of sequences, systems tracts and age determination of marker units /rock bodies in the study area. This was used to map and interpret the first appearance or extinction of a fossil species in the rock record, and also to establish useful markers for biostratigraphic correlation.

3. RESULTS

3.1 Lithofacies Interpretation

Lithologic correlation of five wells across the field revealed eight laterally extensive and continuous sand horizons (Fig. 2). Wells A2P2 and A6P1 occurred on the Eastern part of the field, whereas wells A8P1, A9P2, and A9P3 occurred on the western flank. Top and base of key sand units are used for correlation base on gamma ray trends (Fig. 2). Each depositional stack (parasequence) is unique to guide sand body correlation thereby complementing the traditional lithostratigraphic correlation. High gamma ray (with a cut-off of 75° API value and above) corresponding to the shale base line indicates shale lithology, whereas clean sand intervals

have gamma ray values corresponding to the sand base line (25° API). The top and base of key marker shales form the base and top of suspected sand bodies. The sands are better developed towards the Yowi East than in the West (Fig. 2) with a large lateral extent. The gross thickness of the reservoir ranges from 111 ft to 345 ft with a layer-cake architecture and large lateral extent. Significantly, well correlation helps to establish the stratigraphic framework of the reservoirs and can be used in building 3-D petrophysical, dynamic modeling, and flow unit demarcation.

Greater sand development is observed towards the eastern part of the field, whereas thick shales are noticed for wells in the west (Fig. 2). Thicker sand units are observed in reservoir N4, N5 and N5.2 (Fig. 2) occurring towards the middle to the lower parts of the well section. The upper section shows thin continuous sand horizons. These two sections may represent sediments deposited within both the coastal plains and the deltaic front environments. The upper section (possibly coastal plain) may be associated with more channels (amalgamated) whereas deltaic front with thick sand accumulations is characterized by thick continuous shoreline regressive deposits. From the perspective of facies models, layer-caked shore-parallel facies have been assumed to form homogenous, uniform reservoirs with high production capacities. Wave-influenced coastline deposits possess distinct facies with homogenous beach and shoreface sands accumulating on the updrift side of the river mouth with significantly more heterogeneous facies on the downdrift side. The heterogeneous unit is noticed towards the lower parts of the reservoirs (N4, N5, and N5.2) in wells A2P2 and A9P2 (Fig. 6). Well log interpretation shows that, predominantly the formation is made up of sand and shale occurring in alternate sequences especially within the Agbada Formation. The QIS base (Qua Iboe Shale) on the well log (Fig. 2) occurring at about 1850 ft represents the regional unconformity separating the onset of paralic sedimentation from the overlying continental Benin Formation. The Qua Iboe Shale (QIS) forms the regional marker shale delimiting the continental sediments of the Benin Formation from the paralic Agbada sequence.

3.2 Recognition of Systems Tracts

Systems tracts are three-dimensional assemblages of lithofacies that are genetically linked by sedimentary processes and

environments, and are bounded by discrete, recognizable surfaces [18]. Systems tracts are arranged laterally and vertically in a predictable manner, within the majority of clastic depositional sequences. Sequences are subdivided into systems tracts based on types of bounding surfaces, position within a sequence, parasequence set-stacking patterns, geometry, and facies associations [19]. Sequence stratigraphy and parasequence stacking patterns exert a strong control on recovery at large scale architecture because they determine the distribution of laterally extensive, parasequence and sequence bounding surfaces and hence the degree of hydraulic communication between successive shoreface-shelf sandstones [20,21] while the facies and facies association within each parasequence, are key factors controlling
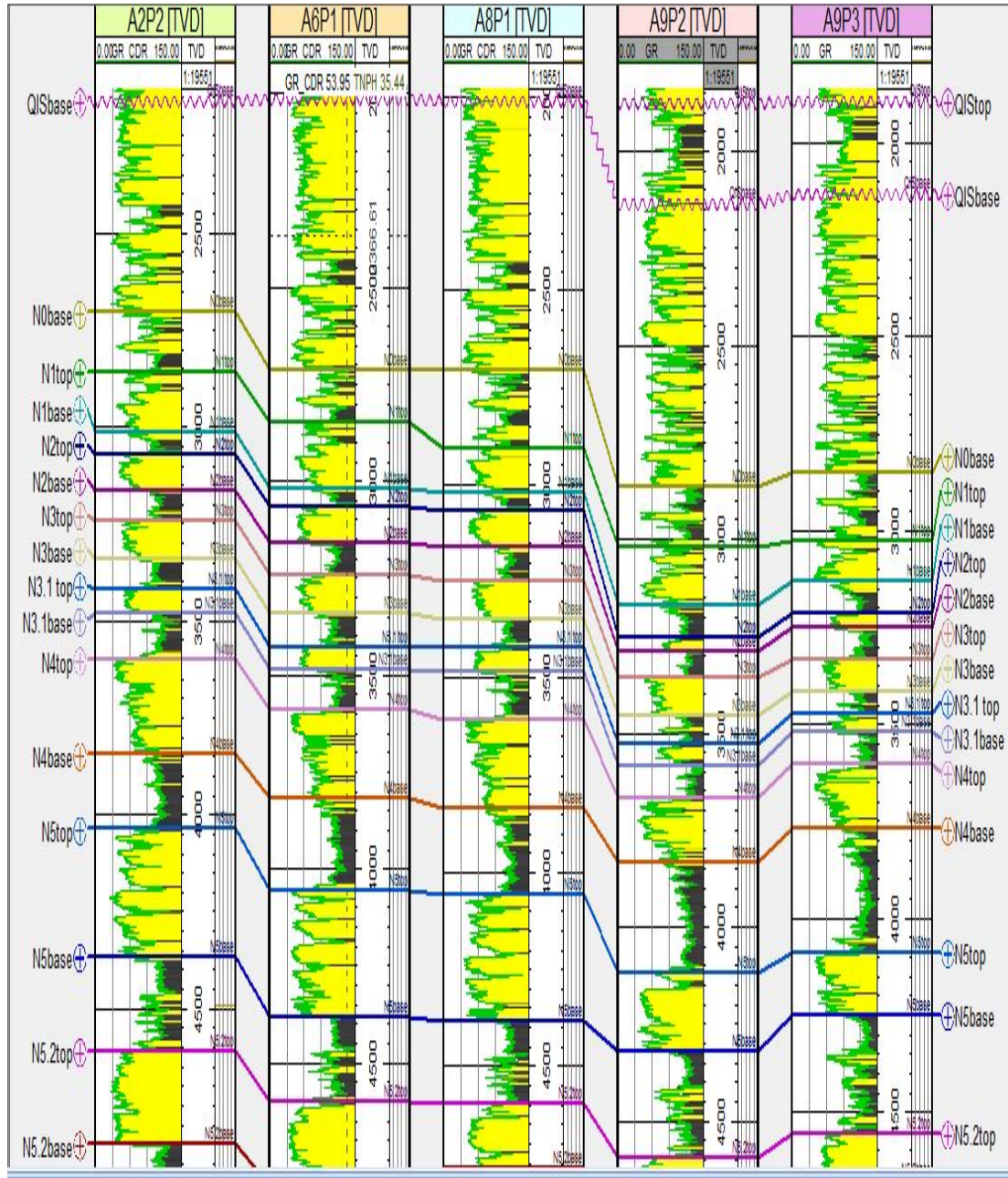

Fig. 2. Litho-correlation of Key sand units across the field

fluid flow during production, and control the smaller scale distribution of petrophysical properties such as permeability and porosity. Three systems tracts identified based on log stacking patterns include; highstand systems tracts (HST), transgressive systems tracts (TST) and lowstand systems tracts (LST).

3.2.1 Highstand Systems Tract (HST)

The HST in sequences 1 to 6 each consist of a progradational parasequences and parasequence sets (Fig. 3a to 3d). It consists of coarsening-upward successions of marine sandstones overlain by alternating marine mudstones/shale beds. The shoreface sandstones displayed typically gradational base with sharp upper contacts (Fig. 3a-3d; Fig. 6) separated by marine mudstones. Coarsening upward successions generally depict deposits resulting from falling sea level and constitute widespread, normal regressive systems tracts in the field. More repetitive units (parasequence sets) are observed in the upper sequences (sequence 5, 6 and 7) as shown in Fig. 3a, 3b and 3c. The highstand systems tract is bounded at the base by the maximum flooding surface and at the top by the overlying sequence boundary (Fig. 3a, 3b, 3c and 3d). The best potential reservoirs of the highstand stage tend to be associated with the shoreline to shoreface depositional systems, which concentrate the largest amounts of sand, with the highest sand/mud ratio (Fig. 2). These reservoirs are meters to tens of meters thick {345feet thick (105.15 metres) of N5 sand}, and display very good lateral continuity along strike in the field (Fig. 2; Fig. 3a – 3d). Both strandplains (open shorelines) and deltas (river-mouth settings) prograde and downlap the maximum flooding surface, which marks the lower boundary of the highstand normal regressive package. Highstand sands are highly productive and occupy the first terrace on the creaming curve where there is a rapid increase in production with potential for greater exploration/exploitation success in any sedimentary basin. The HST forms the dominant systems tract that stacked into parasequences and parasequence sets (Table 1; Fig. 3a – 3d) in the field. Sequence 7 contains eight consegative HST that stacked into parasequence set (Fig. 3a). This stacked HST is common to younger sequences, and may indicate rapid sedimentation of younger sediments onto the shelf.

3.2.2 Transgressive Systems Tract (TST)

Transgressive systems tracts are bounded at the base by the first major marine flooding surface and at the top by the maximum flooding surface (MFS). It is a deposit that results from transgression which indicates the landward migration of the shoreline. The transgressive systems tract comprises a well-developed backstepping succession of marine mudstones and heteroliths. Transgression occurs when accommodation is created more rapidly than it is consumed by sedimentation. That is, when the rates of base-level rise outpaces sedimentation rate at the shoreline. The TST is observed in sequence 2, 4, 5, 6 and 7 (Table 1). The transgressive sands form reservoirs with fair to good quality.

3.2.3 Lowstand Systems Tract

Lowstand Systems Tract (LST) – A component unit of a sequence defined by a correlative conformity (CC) and its correlative surfaces as the lower boundary and a maximum regressive surface (MRS) and its correlative surfaces as the upper boundary [2].

In this study, lowstand systems tract (LST), transgressive systems tract (TST) and highstand systems tract (HST) are used to partition sequences. The lowstand systems tract forms when there is a significant sea level fall and results in extensive subaerial exposure and/or widespread fluvial incision (incised valley). Lowstand systems tract is bounded at the base by a sequence boundary and above by the first major marine flooding surface (transgressive surface). It shows an aggradational depositional trend (Fig. 3b). All processes of aggradation or erosion are linked to the shifting balance between environmental energy flux and sediment supply (i.e., aggradation occurs only where sediment supply outpaces energy flux, and erosion occurs only where energy outpaces sediment load), [22]. With high rate of sediment supply as noticed in sequence 2, 5 and 7 in the Yowi Field, there is the likelihood of potential unconformity traps and buried channels in the field. The LST forms excellent reservoirs and constitutes the first exploitation phase in the field. The LST type common in the field may be due to fluvial incision and also deepwater/slope turbidite sands especially within the Akata Formation.
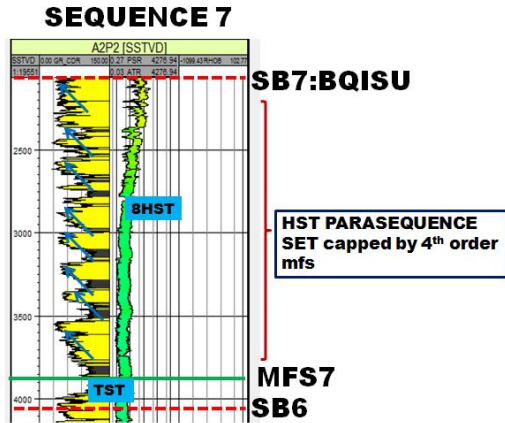
Fig. 3a. Sequences and systems tracts in the study area
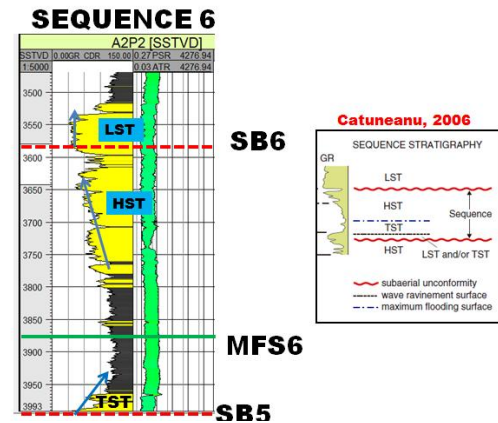

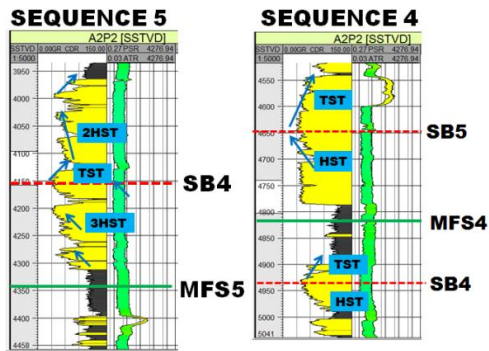Fig. 3b. Sequences and systems tracts in the study area

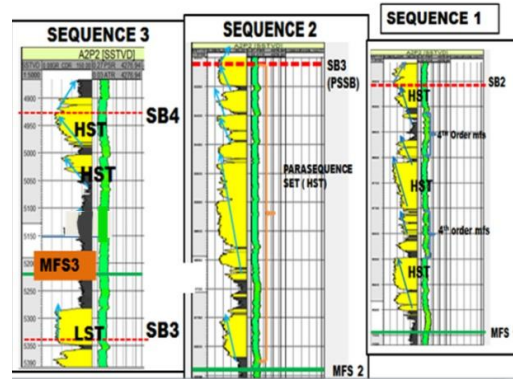Fig. 3c. Sequences and systems tracts in the study area

Fig. 3d. Sequences and systems tracts in the study area

Table 1. Systems Tracts and Sequences (Well A2P2)

Sequences	Depth interval (ft.)	SB depth (FT)	Thickness (FT)	System tracts
1	? – 6470	Base not seen		MFS1, 4HST
2	6470-5380	6470 – SB2	1090	MFS2, 5HST, TST
3	5380-4960	5380 – SB3	420	LST, MFS3, 2TST, 3HST
4	4960-4650	4960 – SB4	310	TST, MFS4,HST
5	4650-4000	4650 – SB5	650	TST, MFS5, 6HST
6	4000-3550	4000 – SB6	450	TST, MFS6, HST
7	3550-1973	3550 – SB7	1577	TST, MFS7, 8HST
		1973 – SB8		BQISU

3.3 Recognition of Sequences

A sequence is the primary unit of sequence stratigraphy. It is subdivided into component units called systems tracts. The stacking patterns of systems tracts couple within distinct chronostratigraphic surfaces (sequence boundaries and maximum flooding surfaces) (Fig. 4) forms the major criteria for the recognition of a sequence either depositional or genetic stratigraphic sequence. Two dominant depositional trends observed on the well log are regression and transgression. Regression is indicated with a shallowing upward trend,

whereas a deepening upward represents transgressive process (Fig. 4). Using the regressive-transgressive approach of mapping sequences, six depositional sequences are clearly observed in Fig. 4. Two key chronosurfaces that aided the sequence stratigraphic correlation in Fig. 4 include; sequence boundary and maximum flooding surfaces (MFS). Lithologic correlation of five wells that cut across the field has helped to establish the continuity of key horizons (Fig. 2) and corroborated by sequence stratigraphic correlation in Fig. 4. Two deepest wells (A2P2 and A9P2) are used as representative wells for sequence stratigraphic interpretation (Fig. 4).
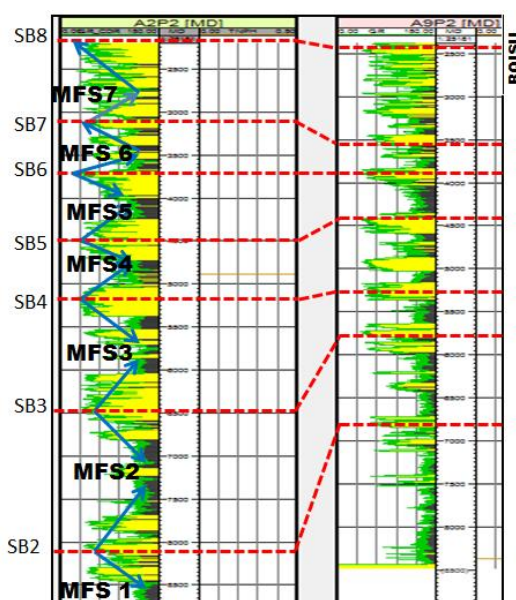
Fig. 4. Stacking patterns and key surfaces identified on wells A2P2 and A9P2
NOTE: BQISU – Base Qua Iboe Shale Unconformity; SB – Sequence Boundary; MFS – Maximum Flooding Surface

3.3.1 Sequence 1

Sequence 1 is the oldest penetrated by the two deepest wells (A2P2 and A9P2) on both the eastern and western flanks of the field (Fig. 4). The base (SB1) of this sequence is not seen. Only wells A2P2 and A9P2 penetrated the top boundary of this sequence (Fig. 2). The top sequence boundary (SB2) is at 6470 ft in well A2P2 (Table 1), and contains MFS1, a major flooding surface older than P780/N5-N6 (possibly Middle Miocene) (Table 2; Fig. 5). Three major sand bodies and two 4th-order marine flooding surfaces occur in this sequence. The sand

bodies comprise of three Highstand Systems Tracts (Table 1; Fig. 3a-3d) occurring above the maximum flooding surface (MFS1). The Highstand Systems Tracts are capped by 4th-order marine flooding surfaces, showing an abrupt change/increase in water depth. They display a coarsening upward (progradational parasequence) trends with thicknesses of about 85 ft, 102 and 123 ft. Other sand bodies may occur below this shale to form a complete depositional sequence.

3.3.2 Sequence 2

This occurs between SB2 and SB3 from 66470 ft and 5380 ft. The top boundary (SB3) is possibly a parasequence set boundary (Fig. 4b). Six sand bodies comprising of Transgressive Systems Tract (TST) and HST occur in this section. The TST unit is overlain by MFS2, whereas the five parasequence sets of the highstand systems tract downlap the MFS2. Some marine flooding surfaces cap the repeated HST showing abrupt increase in water depth. The log pattern of the TST shows a thickening upward transgressive parasequence, while the HST shows a regressive shallowing upward trend. The thickness of this sequence is 1090 ft on the eastern flank (Table 1). This sequence is not penetrated by wells A6P1, A8P1 (Fig. 3a- 3d) and most of the wells except A2P2 and A9P2.

3.3.3 Sequence 3

Sequence 3 lies between sequence 2 and 4 with a thickness of 420 ft in well A2P2, between 4960 ft and 5380 ft. This sequence contains one transgressive parasequence set of two TST; one highstand parasequence set with three HST and one LST underlain by a sequence boundary. The TST displays a retrogradational trend and downlaps the lowstand sand. The thickness of both the TST and LST forming the N5.2 sand/reservoir is about 262.53 ft and thicker in well A2P2 than in well A9P2 (Fig. 2, 3a). This may be as a result of decrease in regressive force/ sand development marking the onset of transgression. The channel fill size decreases as we move in the basinward direction.

3.3.4 Sequence 4

Sequence 4 occurs between SB4 and SB5. The thickness is about 310 ft between the intervals of 4650 to 4960 ft. It contains one TST, HST and MFS4 (Fig. 3a-3d; Table 1).

3.3.5 Sequence 5, 6 & 7

These sequences (5, 6 and 7) are thicker than the sequence below them. SB6 is a possible parasequence set boundary, bounding six stacked successive prograding highstands (Fig. 3a). Sequence 7 is the thickest unit of about 1577ft thick (Table 1); occurring between 3550ft and 1973 ft. 1973 ft (SB8) is actually the BQISU (Base Qua Iboe Shale Unconformity). It has series of stacked highstand systems tracts (8HST; Fig. 4a). In these younger sequences there are sets of fourth order highstand parasequences capped by marine flooding surfaces. These parasequences stack to form the systems tracts that are correlated across the field (Fig. 3a-3d). The dominant trend noted in the field is the shallowing upward, which represents a progradational phase of delta outbuilding in a lower coastal plain setting.

3.4 Biostratigraphic Interpretation

This supplied information on the paleoenvironments of deposition and the age of the formation. Biostratigraphic information used in this study include; foraminiferal, palynology and nannoplanktonic data. They aided the identification of maximum flooding surfaces, age determination and paleoenvironmental reconstruction.

3.4.1 Maximum Flooding Surface (MFS)

Maximum flooding surfaces are indicative of regional development of a condensed section consisting of hemipelagic or pelagic sediments. They form during base-level rise, when depositional trends change from coastal retrogradation to progradation. Seven major shales designated MFS1 to MFS7 are significant and have a field-wide continuity (Fig. 5). Integration of biofacies plots and well log confirmed the candidate MFS (Fig. 5). Intervals with high abundance and diversities of fauna and flora coincide with intervals with thick shale units on the well log, and sequence boundaries fall within the low gamma ray intervals as well as sections on the biofacies plot that is barren or with low abundance and diversities of fauna (Fig. 5). Five of these shales coincide with the regional biostratigraphic markers (Table 2) with good seal and source rock potentials. The youngest is the Qua Iboe Shale occurring between 1873 ft and 2000 ft across the field. This unit corresponds to the P870 zone on the Niger Delta Chronostratigraphic chart reported in the work of [14].

3.4.2 Age & Depositional Environments

Paleontological study was carried out on well A9P2. The well was drilled to TD at 8500ftmd (7971fttvd). The outcome of the analysis revealed the age and possible paleoenvironments of sedimentary sequences in the field (Tables 3-5). Micropaleontological data revealed certain index fauna that are indicative of the age and environments of the sequences. Generally, the thick Agbada unit is composed of Late Miocene (Tortonian) sediments between the intervals of 1873 ft to 7000 ft. The highest occurrence of calcareous benthonic foraminifera (*Ammonia beccarii*) at 2250 ft; planktonic foraminifera including *Globigerina praebulloides* (P13 – N17) at 2500ft, a single specimen of the local index taxon *Marginulina costata* at 3350ft, 6550ft, and the first downhole appearance of the local index taxon *Globigerina triloba* (N4 – N23) at 2550 ft is consistent with a Tortonian age assignment (Table 4). The mixed assemblages of calcareous planktonic and benthonic foraminifera with sporadic ostracods recovered between 2550 ft and 4050 ft are all interpreted as sediments of Late Miocene (Tortonian) age. The index fossil taxa, *Lenticulina cultrata* and the planktonic index taxon *Globigerina triloba* are consistently present at and below 6150ft. These records support a Late Miocene (Tortonian) age interpretation. The highest occurrences of *Globorotalia pseudopima* (N17 – N23), *Globoquadrina venezuelana* (P18 – N19) and *Lenticulina calcar* were all noted at 7250 ft; while the highest occurrences of *Nodosaria cf. multicostata*, *L. sumatraensis*, *Uvigerina capayana* and *Brizalina nitida* were all recorded at 7350 ft. These foraminiferal assemblages are consistent with a Tortonian age assignment and are associated with outer shelf or deeper marine conditions. The highest occurrences of *Globigerinoides ruber* (at 8000 ft) and both *Cibicidoides miocenica* and *Nodosaria multicosta* at 8050ft have been recorded just above the Early Miocene section (8100 ft). The age below Tortonian have been established for the interval 8100 ft – 8500 ft based on the co-occurrence of two index nannoplantonic taxa, *Helicosphaera ampliaperta* (NN2 – NN4) and *Sphenolithus heteromorphus* (NN4 – NN5) (Table 3). The highest occurrence of the index flora *Racemonocolpites hians* at 8200 ft, rare occurrence of *Nummulipollis neogenicus* at 4100–4300 ft, and the peak of

Echiperiporites estelae at 6120 ft suggests an age between early Late Miocene and/or not older than P820 or probably Middle Miocene (Table 5).

3.5 Sequences and Sequence Boundaries

Six major depositional sequences have been inferred in the Yowi Field. They are separated by sequence boundaries, which form in response to falls in base level [23]. Sequence boundaries are laterally continuous, correlatable over at least the basin scale, and appear within the limits of chronostratigraphic resolution to be synchronous in many basins around the world [1]. A sequence is bounded by nondepositional unconformities and their correlative conformities typically defined to be marked by a basinward shift in facies including abnormal subaerial exposure [24]. The basinward shift in facies is interpreted to form in response to a relative fall in sea level. Many flooding surfaces can exist within a sequence but a sequence deposited during the same cycle of relative changes of sea-level is bounded by a sequence boundary. There are at least eight (8) sequence boundaries identified in the Yowi Field. The criterion for the identification possible sequence boundaries included basically changes in parasequence stacking pattern from progradational to retrogradational (Figs. 7, 8, 9, 10 and 11). Because sequence boundaries form in response to base level fall, siliciclastic sequence boundaries are often marked by

widespread fluvial incision into previously deposited subtidal strata and abnormal subaerial exposure, whereas parasequence boundaries form in response to base-level rise, parasequence boundaries are conformable over large areas and lack the incision often associated with sequence boundaries [25,24]. There are possibilities of incised valleys, barrier bar, channels and estuarine-controlled sedimentation in the Yowi Field that provides opportunity for hydrocarbon accumulation and stratigraphic traps. The sediments are mostly regressive deposits showing fast deposition of fluvial sediments into the shallow marine realm. The upper sequences display stacked regressive parasequence sets (Fig. 8). The processes and their responses show sediments supplied by river action and reworked into barrier deposits, beaches and shoreface deposits through the action of marine energy flux (wave action), longshore currents and tidal action. The fluvial influence and rapid sedimentation seems to be more active in the upper sequences (5, 6 and 7), and this accounts for the stacked prograding sand units of great thickness. The various sequence boundaries cut across the field and have potential for stratigraphic traps. Several incised valleys (IV) may be associated with the LST and channels. Depositional trends portray a highly regressive sediments basinward. This provides opportunities in adjacent areas because these sand deposits can be traced towards the deep offshore location.
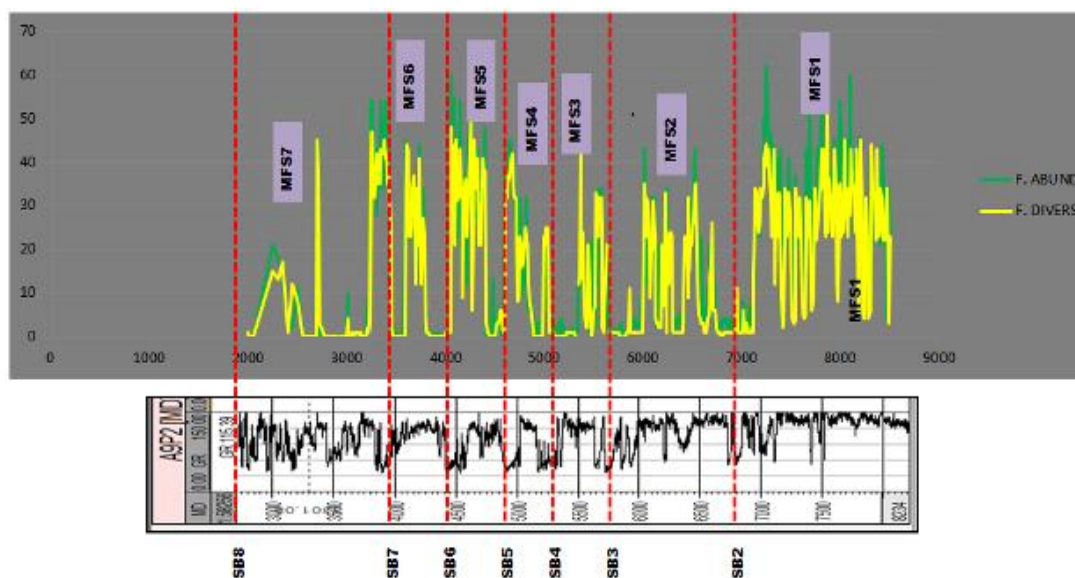

Fig. 5. Biofacies plot for abundance and diversities of foraminifera

Table 2. Microfaunal zonation of the Yowi Field

Top depth (ft)	Bottom depth (ft.)	P-Zone	Remark
1873	1973	P870	Bolivina 46
3595	3969	P850	Haplophragmoides 24
4314	4513	-	Unnamed
5050	5280	P820	Uvigerina 8
5800	6420	P780	Nonion 4
6950	7250	P770	Dodo Shale

Table 3. Nannofossils

Depth (FT.)	Index fossils	Zone	Age	Remark
2500, 7800 8000	*Discoaster quinqueramus* *Discoaster bergrenni*	NN11	Tortonian to Messinian assignment.	Age no older than Tortonian with D. quinqueramus @ 7850 ft.
8000	*Heliscosphaera statis*	NN11	Tortonian	
8100 - 8500	*Heliscosphaera ampliaperta* *Sphenolithus heteromorphus*	NN2-NN4 NN4-NN5	Early Miocene	The co-occurrence of the two taxa established E. Miocene (NN4)

Table 4. Microfaunal table

Depth (FT.)	Foraminifera	Age	Remark
2200 3166	*Ammonia beccarii* *Marginulina costata*	Upper Miocene	Tortonian age.
3228			Presence of calcareous forams & macrofossils is indicative of unit MFS4 at that level.
3443	*Eggerella scabra* *Haplophragmoides spp*		
3870	*Eggerella scabra*		
4350 – 4590	*Eggerella scabra*		
2591 - 6220			*Late Miocene (Tortonian)*
4800, 6142 - 6672	*A*gglutinated forams with common *Eggerella. scabra*	*Middle Miocene*	*Top of unit MFS1*

Table 5. Palynomorph

Depth (FT.)	Index flora/miospore	Age	Remarks
3800 – 8500	Common occurrence of *Retitricolporites spp.* Throughout the interval	Early Late Miocene	Equivalent to Retitricolpites sp common occurrence in Igbomotura-1 well by [7].
2550, 4100	*Fenestrites spinosus*	Late Miocene	Base Late Miocene marker by [26].
4100, 4300	Rare occurrence of *Nummulipollis neogenicus*	Early Late Miocene	
4100, 6600	*Verrutricolporites rotundiporus; Verrutricolporites microporus*	Early Miocene	Early Miocene marker by [26].
8200	Highest occurrence of *Racemonocolpites hians*	No younger than Late Miocene	

3.6 Significance of the Sequences

The overall depositional trend of sediments in the Yowi Field shows a prograding delta. Common depositional units that form hydrocarbon habitat occur within the Agbada Formation. The Agbada Formation occurs between 1973 ft and 8930 ft (A2P2 well) in the field. These sediments were deposited within the shoreface to shallow marine shelf environments (Fig. 6). Genetic units that form the reservoirs are barrier bar sand, beach sand, shoreface and channel deposits (Fig. 6). The barrier complexes are locally punctuated by unnamed transgressive claystone beds. The thickness of the sequences decreases with depth probably due to the intensity of both autogenic and allogenic controls as at the time of deposition of the sediments and also the effect of diagenesis (compaction). Sequence 1 is sitting on a sequence older than Middle Miocene.

4. DISCUSSION

4.1 Depositional Architecture

The Neogene sediments of the Eastern Niger Delta display distinctive shallow marine and nearshore depositional elements throughout the study area (Fig. 6 to 12). These are primarily controlled by delta progradation and deposition of sediments within the shoreface and shallow marine realm. Fluvial, wave, longshore currents and tidal processes are the major forces that may have contributed in the systemic distribution and redistribution of sediments in the area. Typical depositional architectures identified based on the stacking patterns include; beach, barrier, shoreface, mouthbar, and channels (Fig. 6, 12). Depositional architecture is defined by three major controls. They include; sediment influx, subsidence, and sea level changes that provides space for sediment accumulation (accommodation) [18]. Three depositional trends that occur in the study area include; progradation, aggradation and retrogradation (transgression) (Figs. 7 - 12). Each of these events has unique products that aid the reconstruction of their depositional systems.

4.2 Progradation

Progradation is the basinward (seaward) migration of facies belts (shoreline), when sediment supply exceeds the rate of creation of accommodation space. It implies a basinward shift in clinoforms. Progradational patterns form

when the rate of deposition exceeds the rate at which accommodation increases. Stacked progradational parasequences have been identified in the Yowi field (Fig. 8-11). Several repeated progradational patterns (parasequence sets) are observed in the study area indicating a prolong migration of the shoreline, controlled by the larger-scale balance between the rate of sediment supply and accommodation space creation. The architecture generated when the rate of sediment supply is greater than the rate of creation of accommodation space is described in the work of [16]. The stacking pattern is typically of the highstand system tract.

Most siliciclastic parasequences are progradational in nature, resulting in an upward-shoaling (upward-coarsening and -cleaning) association of shallow marine lithofacies [10]. If the rate of sediment supply to a shoreline area exceeds the rate of water deepening as a result of subsidence and/or sea level rise, then sediments will prograde in the basinward [10]. During the Neogene, there was more sediment supply than available space to accommodate them in the Eastern Niger Delta. An evidence for this event is the regional BQISU marking the end of Miocene and beginning of Pliocene time. The delta during this period was at the lowstand [21] when there was serious fluvial incision creating the various channels in the eastern delta – the Qua Iboe Channel inclusive. There was rapid and repeated increase in water depth as sediments were supplied leading to regular marine flooding isolating the sandstone intervals (Fig. 8, 9, 10, 11). This is a typical progradational parasequence set where each parasequence progrades progressively farther basinward than does the preceding parasequence (Fig. 12).

Well log expression of this depositional architecture displays a funnel shape coarsening upward trend. The more homogeneous coarsening-upward architecture indicates higher sand development and stronger wave influence sedimentation within the updrift portions of a prograding delta. Inferred depositional elements could be shoreface deposit, mouth bar or tidal bar. Distributary-mouth deposits are usually reworked by waves and redistributed along the delta front by long-shore currents to form wave-built shoreline features such as beaches, barrier bars and spits.

According to the methods reported in [27,28], the environments of coarsening upward successions can be put into three general categories: (1)

regressive barrier bars, (2) prograding submarine fans, (3) prograding deltas or crevasse splays. The first two environments, regressive barrier bars and prograding submarine fans are commonly deposited with glauconite and shell debris [14,27,4]. Glauconite debris occur in all the samples from about 1800 ft in all the wells, therefore, there is the possibility of the first two environments (regressive barrier bars or prograding submarine fans).The inference made is that, the paleoenvironments of funnel shape facies belongs to regressive barrier bar sand. However, one of the main differences between a prograding delta and a crevasse splay is the deposition scale; the prograding delta is comparatively large. According to the identification system of [14,27], the paleoenvironment of funnel-shaped successions with carbonaceous detritus can be identified as a prograding delta or a crevasse splay.

4.2 Aggradation

An aggradational pattern develops when sediments stack vertically as a result of a balance between sediment supply and rate of creation of accommodation space.

Log facies of this unit has sharp upper and lower contact (blocky) (N5.2 sand in Fig. 6). The thickness of the boxcar motifs in all the studied intervals is less than 25 meters.

Mudlog report shows that the lithologies of these sections are mostly sandstones (off white to creamy white, grey in part, translucent to transparent, very fine to fine, occasionally medium grained, sub-rounded to rounded, sub-spherical, primarily calcareous cement, argillaceous in part poorly to moderately sorted). In the Yowi field, the boxcar shaped gamma-ray log reoccurs in all the wells with average thickness of 58 ft in well A2P2 between the intervals of 3357-3412 ft, 5286-5344 ft, 5750-5813 ft, 6047-6110 ft and 6848-6903 ft.).

4.3 Retrogradation

Retrogradation is landward migration of facies belts when the rate of sediment supply is less than the rate at which accommodation space is generated. The log characteristic of this unit shows a sharp lower contact with a gradational top (Fig. 9). It is a transgressive unit. The bell shaped succession usually occurs in three types of environments: tidal channels, turbidite fills and fluvial or deltaic channels. Tidal channels and turbidite fills also commonly include glauconite and shell debris [4,27,28]. The only bell shaped successions with carbonaceous detritus are deposited in environments of fluvial or deltaic channels [27,28].
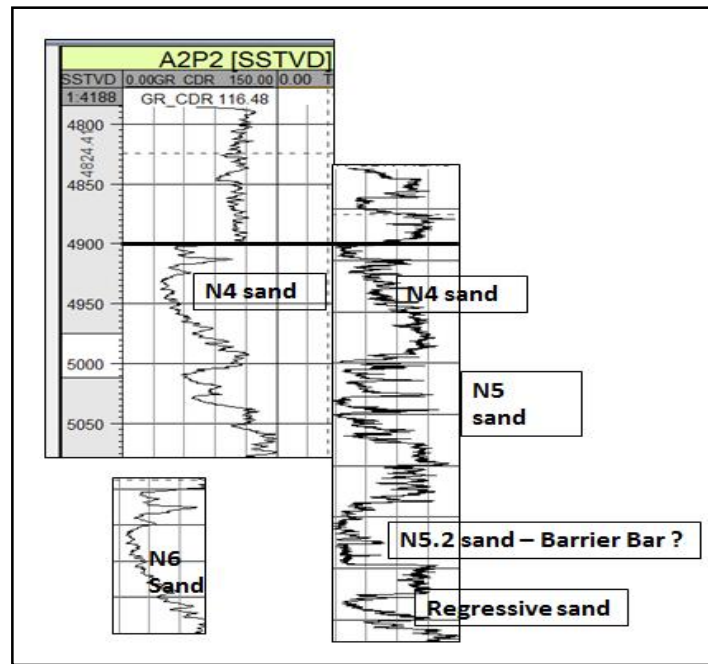

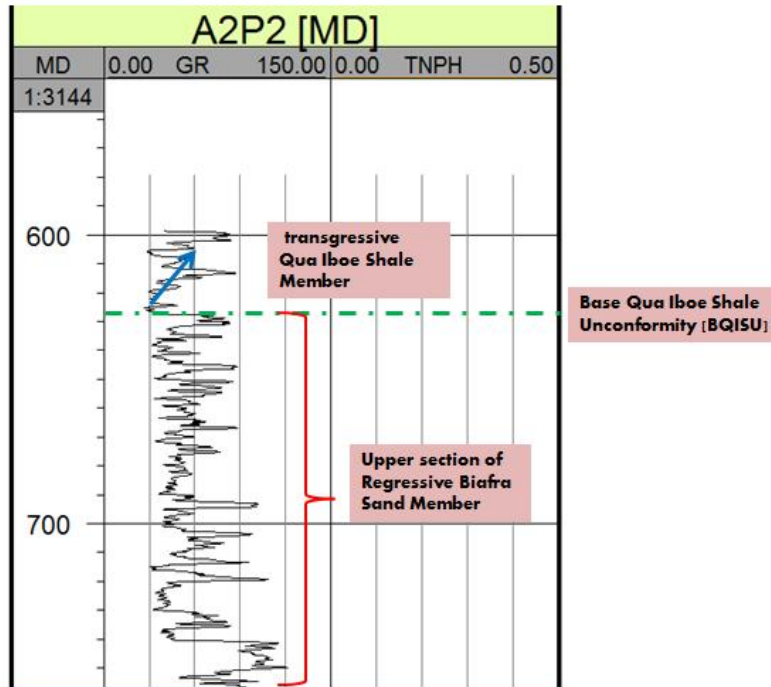**Fig. 6. Stacked progradational parasequence (N6 reservoir) and parasequence set (N4, N5)**

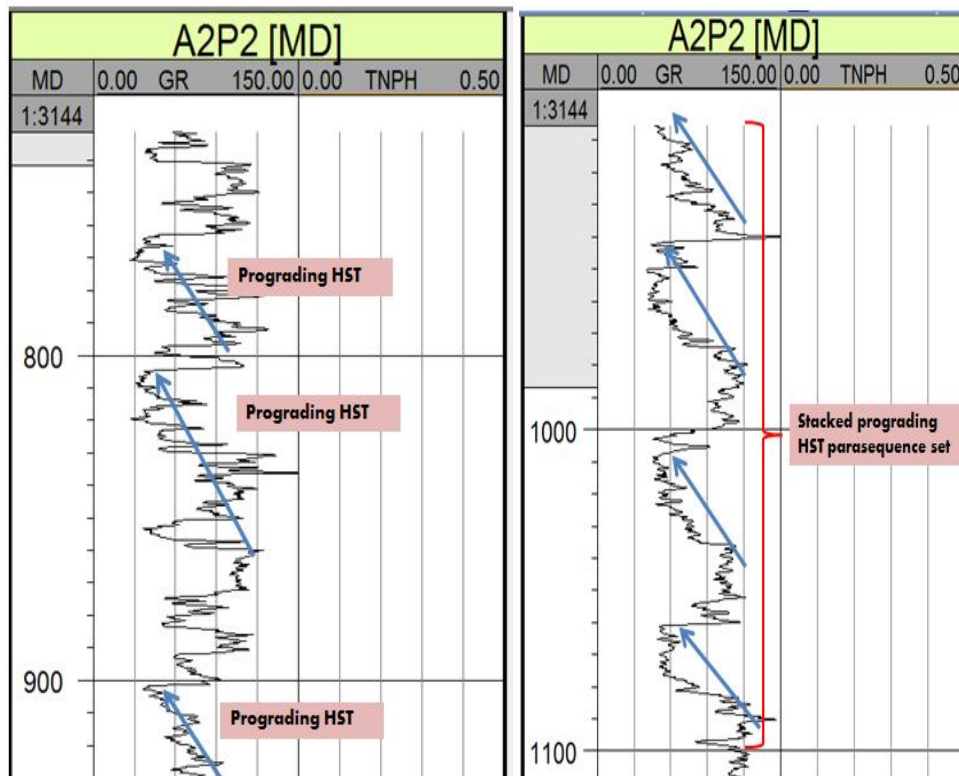**Fig. 7. Regional unconformity (QISU) separating the Biafra sequence and the Qua Iboe Shale**

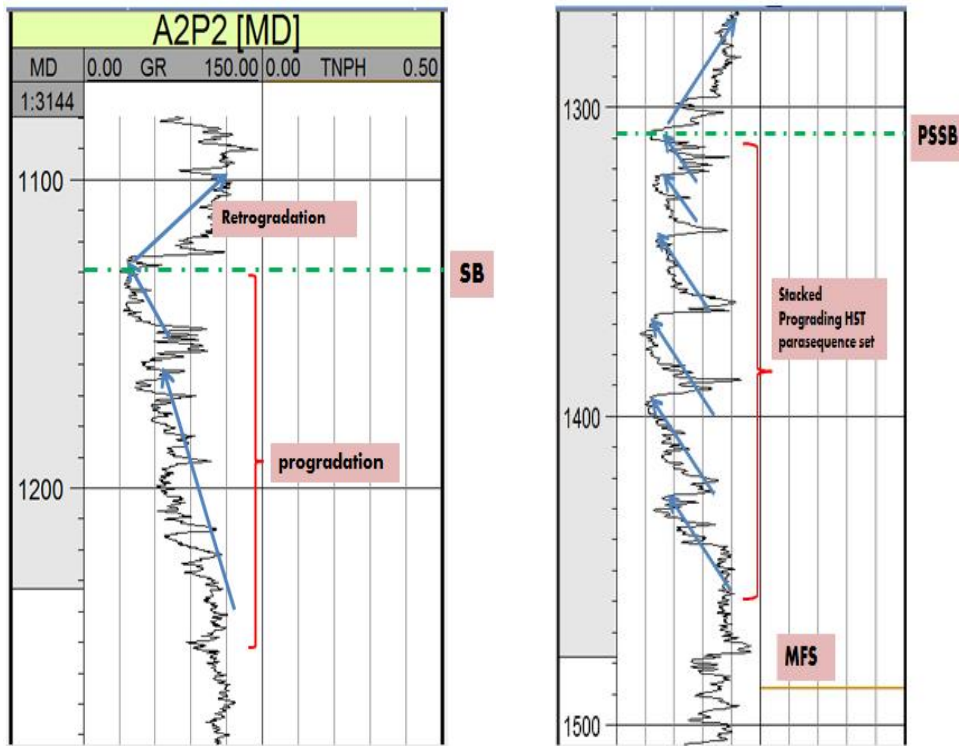**Fig. 8. Stacked progradational parasequence set**

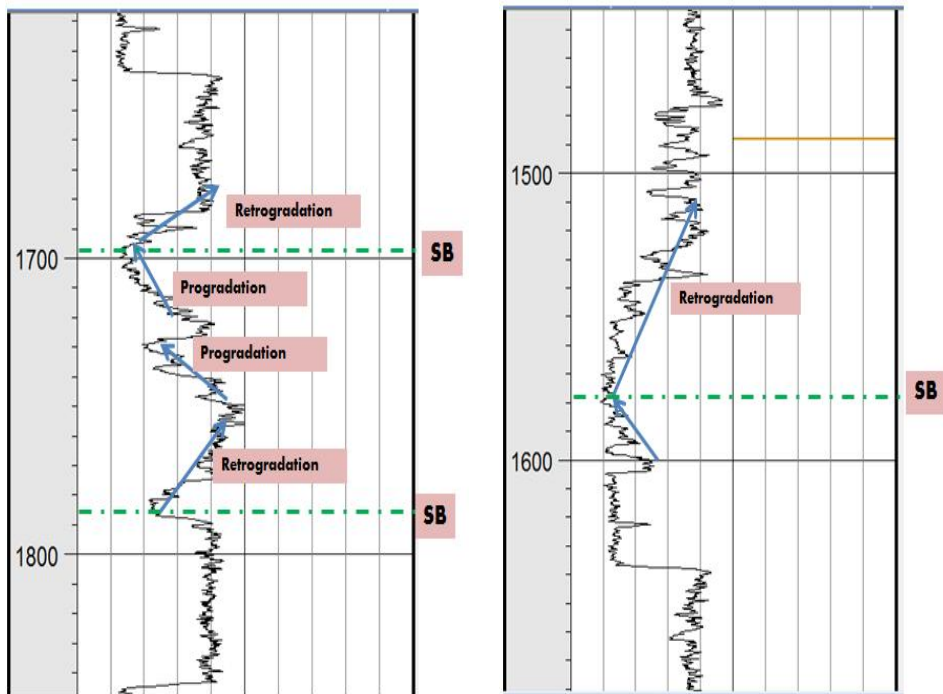**Fig. 9. Progradation-retrogradation relationship**

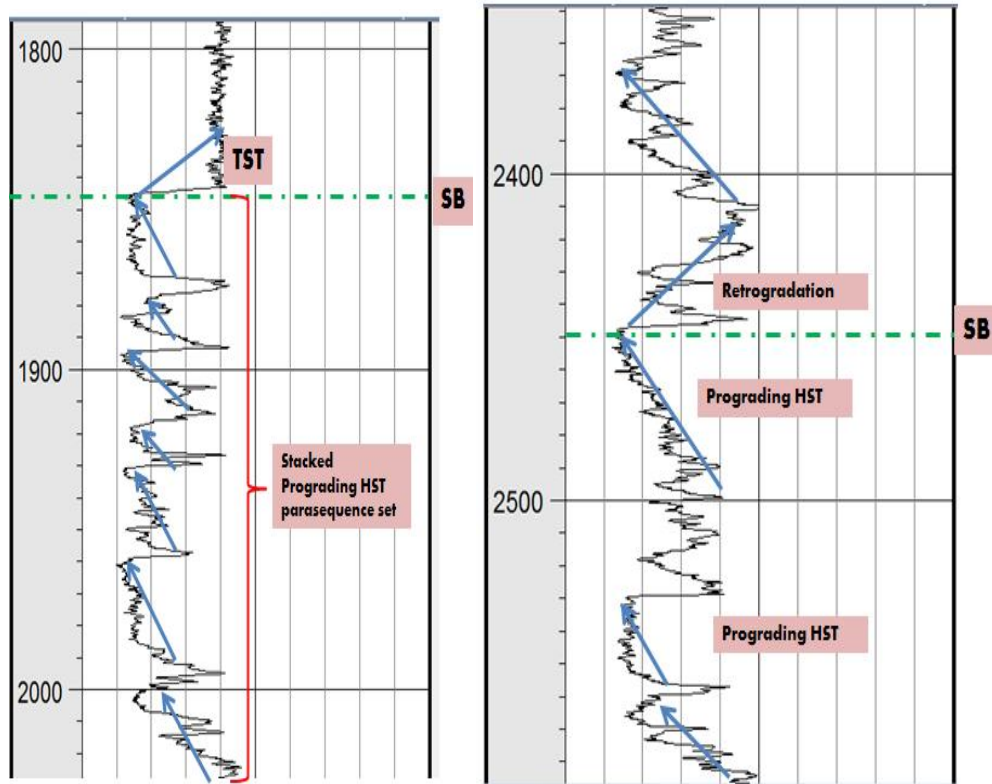**Fig. 10. Relationship between stacking patterns and sequence boundary**

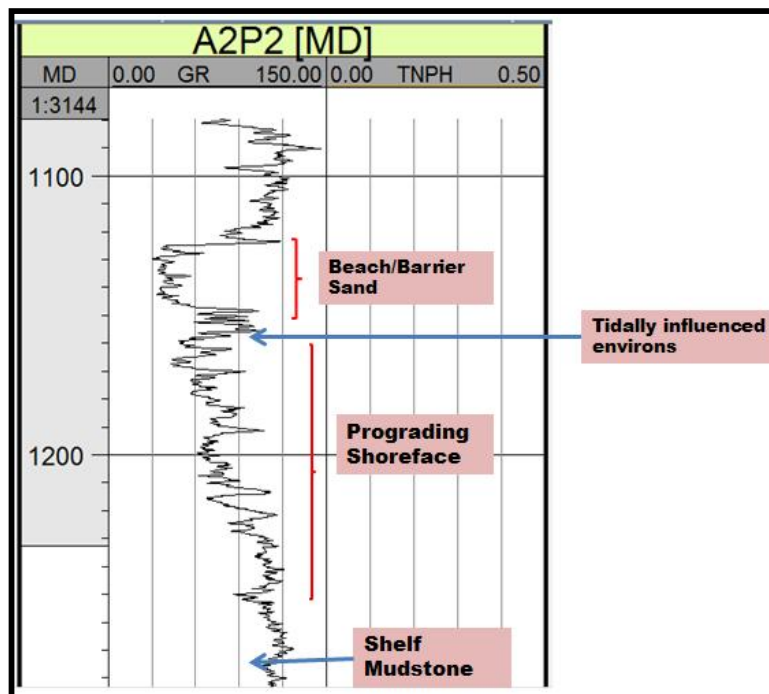**Fig. 11. Stacking patterns showing progradation parasequences and retrogradation**

Fig.12. Environments associated with progradation (beach, barrier bar & shoreface)

4.4 Sequences & Depositional Architecture

The inference drawn from the preponderance of stacked HST signifies mostly regressive sediments of fluvial origin deposited within the shallow marine realm. The uppermost sequence displays the highest stacked regressive parasequence sets of eight highstand systems tracts (HST) (Table 1; Fig. 3a, 8, 9, 10), with an overall shallowing upward trend towards the top of the Agbada and base of the Qua Iboe Shale Member. This repetitive parasequences and the highest occurrence of calcareous benthonic foraminifera (*Ammonia beccarii*) at 2250 ft in well A9P2 is an indication of progradation of sediments in coastal to shallow-water systems. The processes and their responses show sediments supplied by river action and reworked into barrier bars, beaches and shoreface deposits through the action of marine energy flux, longshore currents and tidal action. The various sequence boundaries cut across the field and have potential for stratigraphic traps. Several incised valleys may be associated with the lowstand systems tracts (LST) and channels. Depositional trends portray a highly regressive sediments basinward. There is high potential of successful exploration and exploitation for hydrocarbon in the highstand sands within the field and adjacent areas. These marginal to shallow marine reservoirs are typically laterally continuous, and in good stratigraphic relationship with the transgressive shales to enhance accumulation and entrapment of hydrocarbon in the field.

5. CONCLUSIONS

Sequence stratigraphy has helped in the demarcation of the various stratigraphic intervals in the field into six complete depositional sequences with their component systems tracts. Pliocene to Recent sediments are still prograding fastly into the offshore areas and will provide opportunities in the adjacent fields offshore. A predominantly marine and deltaic sequences strongly influenced by clastic output from the continent is inferred from both well log and paleontological data analysis. Paleowater depth is interpreted to fluctuate considerably and deposition occurred within a variety of littoral and neritic environments ranging from nearshore barrier sand complexes to fully marine outer shelf mudstones. The lower part of the Agbada Formation penetrated by A2P2 deep test well (8950ft TD) is interpreted to have been deposited in the outer shelf or upper slope setting. Six complete depositional cycles occur in the Yowi Field, representing sediments deposited probably during the Late Middle Miocene to Upper Miocene (Serravallian - Tortonian).

The dominant depositional trend observed in the study area shows progradation. The sediments are rapidly deposited within the shallow marine realm and reworked into longitudinal bars by wave action, strong longshore drift and tidal effects. The rapid deposition may not be unconnected with the late Miocene catastrophic event associated with the Qua Iboe collapse; proximity of the adjacent Cameroun Mountain and the Oban massive as provenance sources, and the Kwa/Calabar Rivers providing conduits for constant sediment supply. This also, may have accounted for the proper development of parasequences and parasequence sets resulting from the rapid sediment deposition.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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