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Sequence stratigraphic study of ‘X’ field in eastern offshore of Niger Delta, Nigeria

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An integrated approach to Seismic interpretation that combines techniques of sequence stratigraphic analysis, seismic facies analysis and attribute analysis is one of the most effective approaches for hydrocarbon exploration in growth-faulted deltaic strata of offshore eastern Niger Delta. These strata are generally thick paralic/marine units deposited along an unstable progradational continental margin. Here, shale ridges, toe thrusts and diapirism are common features. Thus, system tracts along this margin differ significantly from those described for classic stable progradational continental margins. Development of good reservoir sands, on the shales of the upper transgressive systems tract form barriers which are good, particularly on the outer shelf where high stand systems tract sediments accumulate. Alternation of the high stand systems tract sands and transgressive systems tract shales provides a bridge linking reservoir facies with the shales or seals of TST which is essential for hydrocarbon accumulation and its stratigraphic trapping in the study field. This work has provided an analytical model for a detailed and cost-effective hydrocarbon prospecting through the use of sequence stratigraphic framework in tandem with seismic data interpretation.

Key words: Sequence stratigraphy, seismic facies, system tracts, offshore Eastern Niger Delta.

INTRODUCTION

Sequence stratigraphy which has its origin in seismic stratigraphy was introduced in 1977 with the publication of “Seismic Stratigraphy: Application to hydrocarbon exploration” and was referred to as AAPG Memoir 26 (Latimer, 2007). Emery and Myers (1996) defined sequence stratigraphy as the subdivision of sedimentary basin fills into genetic packages bounded by unconformities and the correlative conformities. This by implication is the study of genetically related facies within a framework of chronostratigraphically significant surfaces (Van Wagoner et al., 1990). Thus, sequence stratigraphy is not only an effective tool for interpreting time relationships from sedimentary units, but also for mapping and correlating sedimentary facies for stratigraphic prediction. This therefore becomes an acceptable model guiding interpretation in data-poor areas. Cadena and Slatt (2013) claim that pure structural play concepts would not improve exploration opportunities but its integration with

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sequence stratigraphy and sedimentology. Its analysis integrates many different data sources, such as seismic data, wireline logs, cores, biostratigraphic data, production data, outcrop analogues, etc. Such an approach involves recognizing and interpreting a hierarchy of time-significant stratal units and their bounding surfaces. The basic concepts here are accommodation space, such as relative sea level and sediment supply. These often interact and regulate the direction of movement of the depositional system. While the base level controls accommodation, sediment supply directs movement of the depositional system either basin ward (regression) or landward (transgression).

In order to understand the distribution of sedimentary facies in the subsurface, one needs to view it as part of a depositional system (Bacon et al., 2007). Overtime, depositional systems within a basin can change, with abandoned systems being buried and eventually becoming reservoir facies. Using a combination of different datasets, it may be possible to understand the depositional systems well enough to be able to predict sand distribution and quality in data-deficient areas. This may be achieved, in part, by recognizing individual depositional units from, say, seismic data, and, in part, by placing them within an overall basin context. Such step is usually enhanced by the concept of sequence stratigraphy which uses unconformity surfaces to define boundaries of packages of rocks that are of similar age and are deposited within a related group of depositional systems (Bacon et al., 2007). Sequence stratigraphy is therefore the correct geologic interpretation of processes or response events (Dutta et al., 2007) which can predict the likely occurrence of source rocks, reservoir facies and seals.

In deltaic regime, sedimentation consists of stratigraphic cycles characterized primarily by alternation of more energetically supplied and less energetically supplied materials such as sand-shale alternations (Damuth, 1994; Edwards, 1995; Soregham et al., 1999). Deltas are generally of clastic facies, with large deltas inhibiting carbonate deposition (North, 1985). The proportions of the sedimentary types are controlled chiefly by the interaction of the fluvial influence supplying the material and the marine regime receiving it. Deltas are often major hydrocarbon provinces and deltaic processes are excellent means for transporting sands (potential reservoirs) far out into marine basins with organic-rich mud that constitute potential source rocks (Selley, 1980). Since deltas often form in areas of crustal instability, structural deformation generates traps for migrating hydrocarbons. Stratigraphic traps produced by sand pinch-outs and isolated destructional sand bodies are common features in deltaic system especially in areas of maximum intertonguing of delta front sands and marine muds (North, 1985). Structural traps are equally very common in deltas and are of concern to the study of reservoir facies because they influence their deposition by simultaneous growth. Hence growth faults (as they are called) are activated by the progradation of delta front sand over unstable, subsiding prodelta muds at the shelf edge. These interactions cause numerous interruptions in the deltaic sedimentary sequence with thickened repetitions of units on the downthrown side (North, 1985).

Growth fault is a common feature in shelf margin deltas (Doust and Omatsola, 1990) as well as on adjacent slope including offshore region (Damuth, 1994) where it is triggered by differential loading of prodelta muds coupled with high excess pore pressure (Mandl and Crans, 1981). Growth faulting generates different deformational features such as rollover anticlines, and accommodation space histories across the growth fault, thus complicating correlation and interpretation. Deltas have their unique framework orientation and depositional pattern. The present morphology of the Niger Delta (Figure 1) is that of a wave-dominated type with a smooth seaward convex coastline traversed by distributary channels (Tegbe and Akaegbobi, 2000). The Niger Delta is thus subdivided into three diachronous lithostratigraphic units comprising mostly marine undercompacted shales of the Akata Formation, alternating paralic sands and shales of the Agbada Formation, and predominantly continental fresh water bearing sands with back swamp deposits constituting the Benin Formation (Short and Stauble, 1967) (Figure 2).

Stratigraphic studies of the Niger Delta deposits based on three dimensional (3D) seismic records are focussed on relationships between depositional patterns within the compressional toe of this clastic wedge along the base of the continental slope (Morgan, 2004; Corredor et al., 2005). Thus, the Niger Delta is composed of mega units termed depobelt. These are self-made entities with respect to stratigraphy, structures and hydrocarbon distribution. Growth faulting dominates the structural style of the delta with its complexity increasing seaward. In the zone of coastal swamp and offshore depobelts, the structures are large and complex (Doust and Omatsola, 1990).

Location of the study area

The offshore portion of the Niger Delta can be broadly classified into proximal and distal units based on a framework derived from its structural evolution as well as biostratigraphic and sedimentologic history (Beka and Oti, 1995). The proximal offshore unit is a mature belt for hydrocarbon exploration and production and stretches beyond the coast to a bathymetric depth of about 200 m isobaths within the continental shelf.

The petroleum geology and exploration history of this highly prolific proximal belt are well documented in Knox and Omatsola (1989), Bassey and Ojesina (1999), Bassey and Fagbola (2002) and Udoh et al. (2017 a, b). The study area is ‘X’ Field, (Total Nigeria PLC who

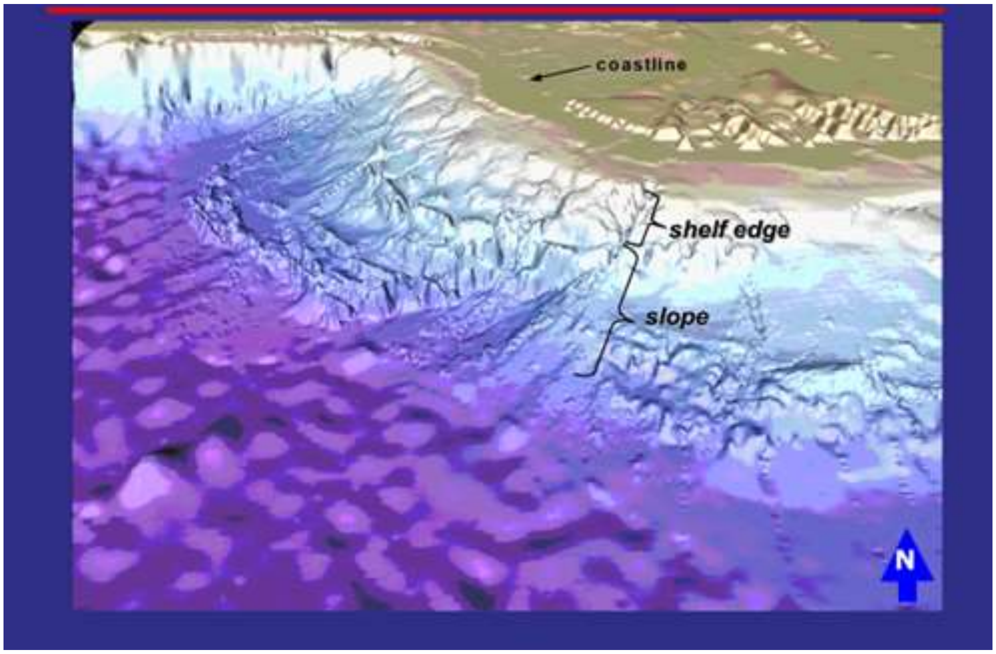

Figure 1. Bathymetric Map of the Niger Delta.

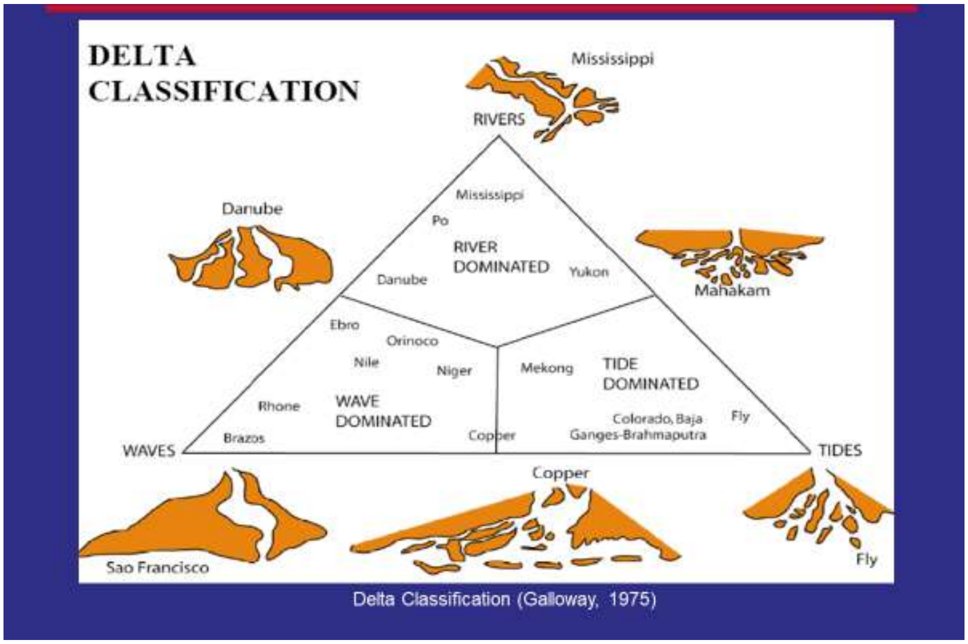

Figure 2. Wave-dominated Niger Delta.
Source: Adapted from Galloway (1975).

provided the data requested that the area be so named) (Figure 3) and falls within the proximal offshore portion of Niger Delta, with an area of 230 km^2. The field is located 30 km off the Southeastern part of the Niger Delta at a shallow depth of about 40 m.

Conventional stratigraphic interpretation from seismic data has been predominantly qualitative and is based on visual inspection of geometric patterns in post-stack reflection data. Sequence stratigraphic analysis has provided a major platform in the understanding of

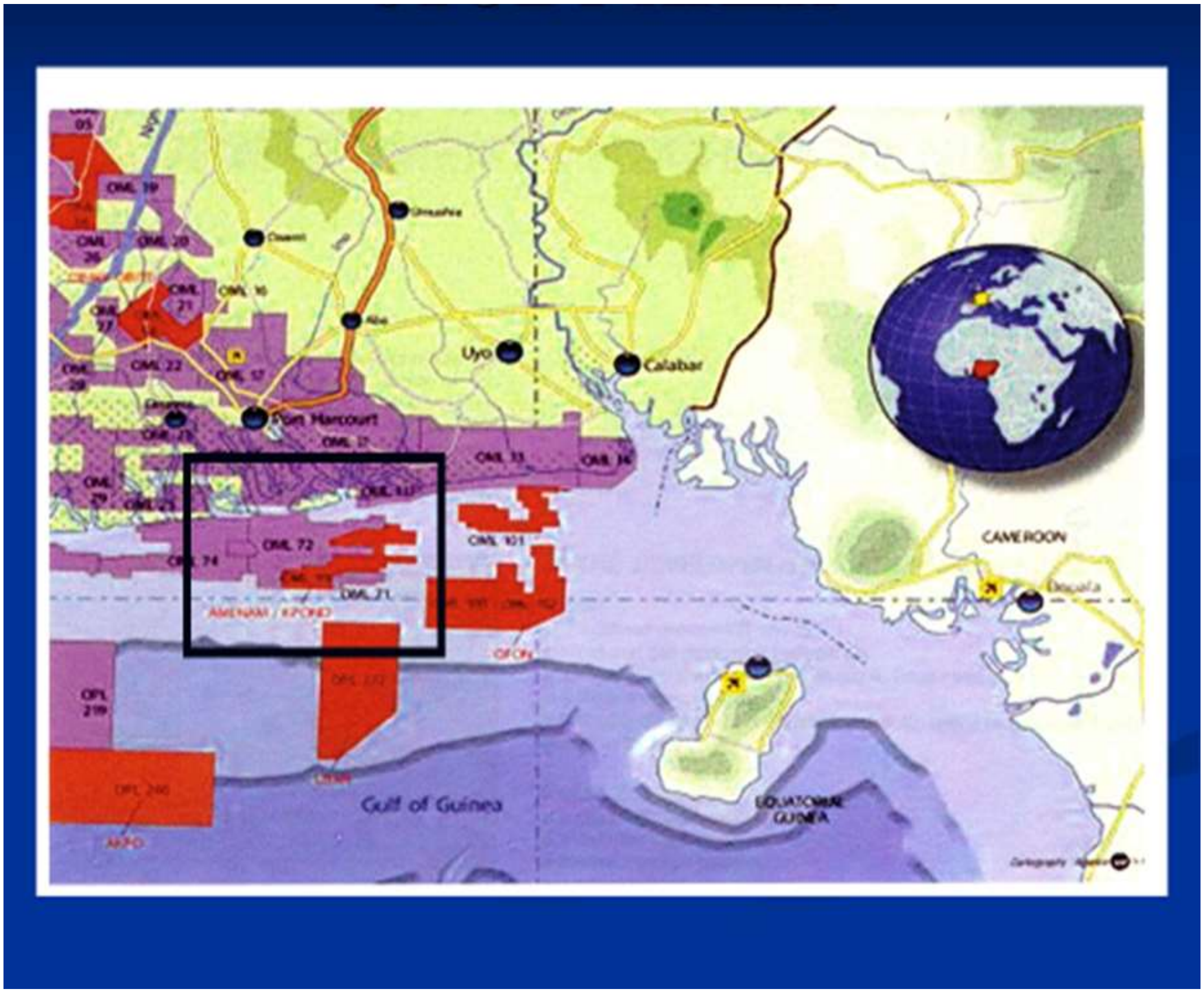

Figure 3. The black rectangle shows the location of the study area.
Source: Offshore-technology.com.

sediment partitioning between non-marine, shallow-marine and deep-marine sedimentary environments in relatively simple tectonic settings, such as passive margins and foreland basins. This study aims at providing a stratigraphic framework consistent with the 3-D seismic interpretation that will not only aid in determining types of systems tract occurring in the field but also identify those systems tracts that are associated with hydrocarbon reservoirs using sequence stratigraphic approach. This will provide a model for stratigraphic interpretation of seismic data that addresses distribution of lithofacies, depositional environments as well as location and continuity of reservoirs.

General geological setting

The evolution of the delta is controlled by pre- and synsedimentary tectonics as described by Evamy et al. (1978), Ejedawe (1981), Knox and Omatsola (1987) and Stacher (1995). The delta growth is summarized below. The shape of the Cretaceous coast line (Figure 4; Reijers et al., 1997) gradually changed with the growth of the Niger Delta (Figures 5 and 6). A bulge developed due to delta growth. This changing coastline interacted with the palaeo-circulation pattern and controlled the extent of incursions of the sea (Reijers et al., 1997). Other factors that controlled the growth of the delta are climatic variations and the proximity and nature of sediment source areas.

During the Middle-Late Eocene, sediment was deposited (Figure 6A) west of the inverted Cretaceous Abakaliki High and south of the Anambra Basin in what became the ’northern depobelt of the Niger Delta’ (Figure 6).The first coarse clastic deposits have been dated on the basis of micro floral units (Evamy et al., 1978) (Figure 5) as Early Eocene. Trade winds generated long shore currents with two cells converging along the western estuarine coast sector (Burke, 1972; Berggren and Hollister, 1974; Reijers et al., 1997) (Figure 6A). Studies

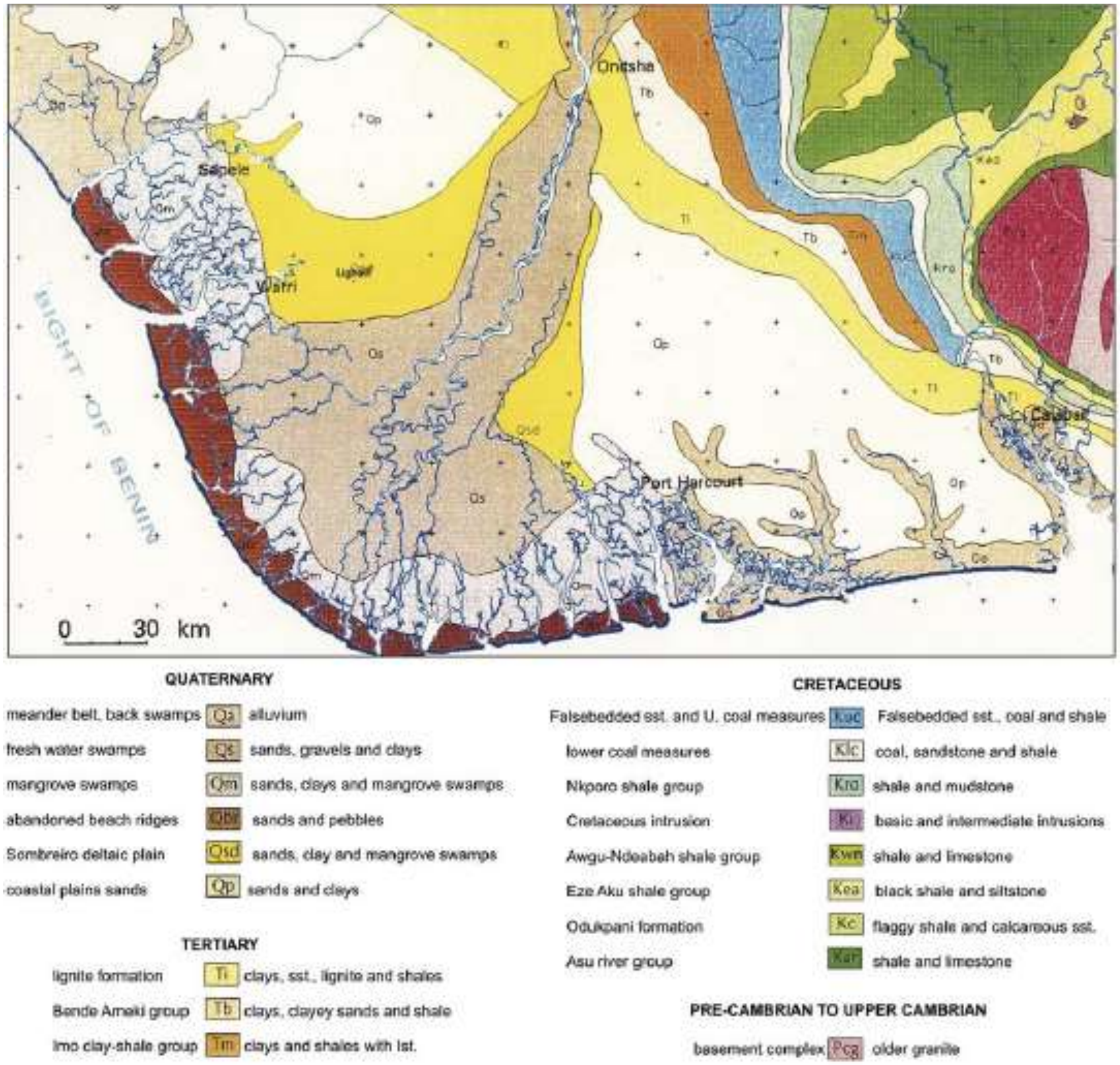

Figure 4. Geological map of the Niger Delta and surroundings. Source: Reijers (2011).

by Weber and Daukuro (1975), Ejedawe (1981) and Ejedawe et al. (1984) clarified that the embryonic delta subsided during the Late Eocene to Middle Oligocene <700 m/Ma and prograded approximately 2 km/Ma along three depositional axes that fed irregular, early delta lobes (Figure 6) that eventually coalesced. Thick sandy sediment accumulations thus formed in the active 'Greater Ughelli depobelt'.

During the Late Oligocene to Middle Miocene, the delta subsidence remained steady at some 700 m/Ma but delta progradation increased to 8-15 km/Ma. Incision of the Opuama Channel (Figures 5, 6B and 7A) in the western sector of the delta occurred at this time (Petters, 1984; Knox and Omatsola, 1987). From the Middle Miocene onward, the delta prograded over a landward dipping oceanic lithosphere. The 'Escalator Regression Model' of Knox and Omatsola (1987) shows the average delta subsidence rates and progradation figures used here. During the Miocene, the average progradation was some 1000 m/Ma. Depocentres in the eastern sector of the delta merged laterally and the enlarged delta front prograded pulse-wise, occasionally advancing at rates of 16-22 km/Ma (Figures 5, 6B and 7). The coastline, now convex, broke up the longshore current into two divergent drift cells. During the Middle-Late Miocene, a rising hinterland supplied substantial amounts of sediment that

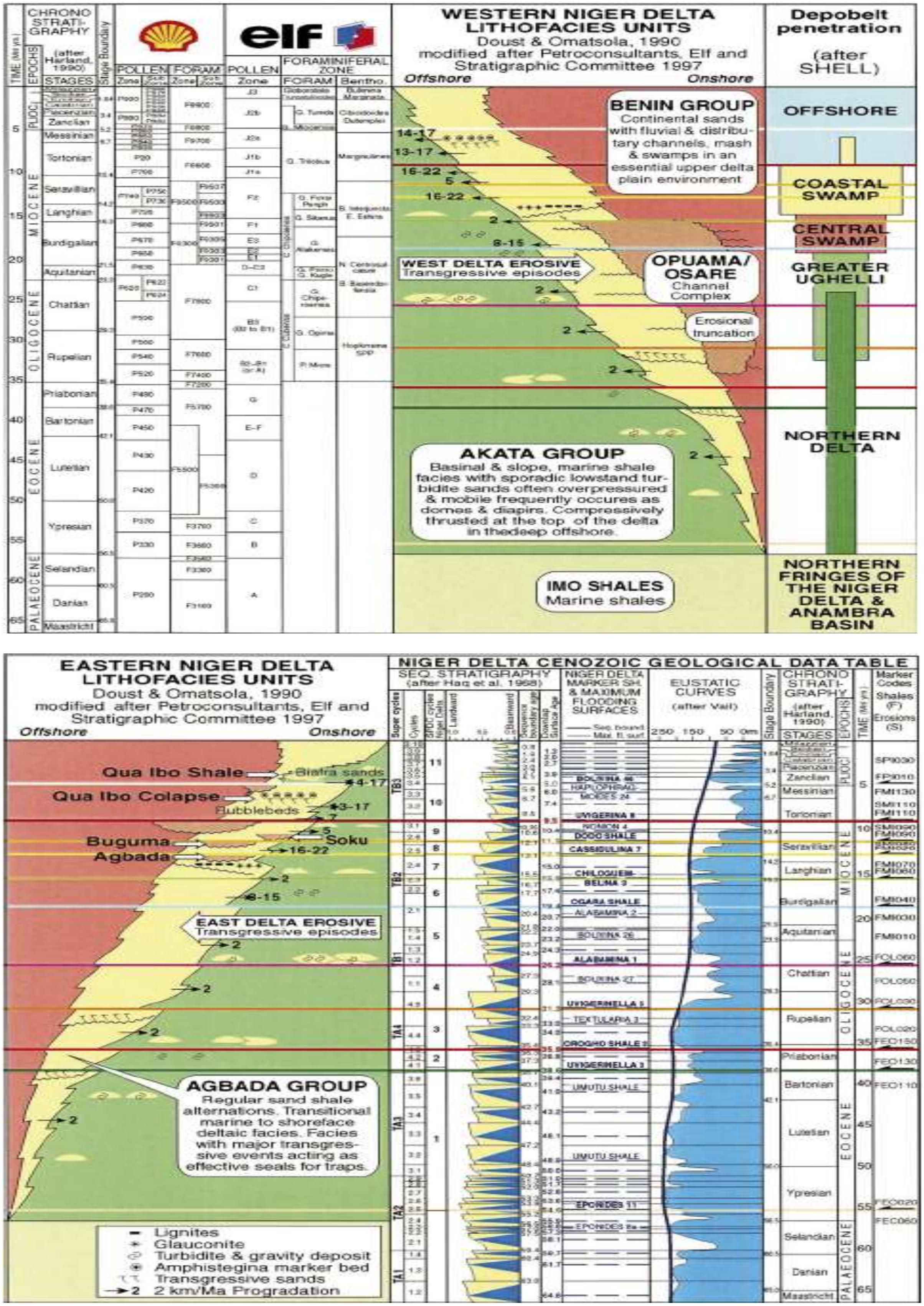

Figure 5. Stratigraphic data sheet of the Niger Delta.
Source: Adapted from Reijers (2011).

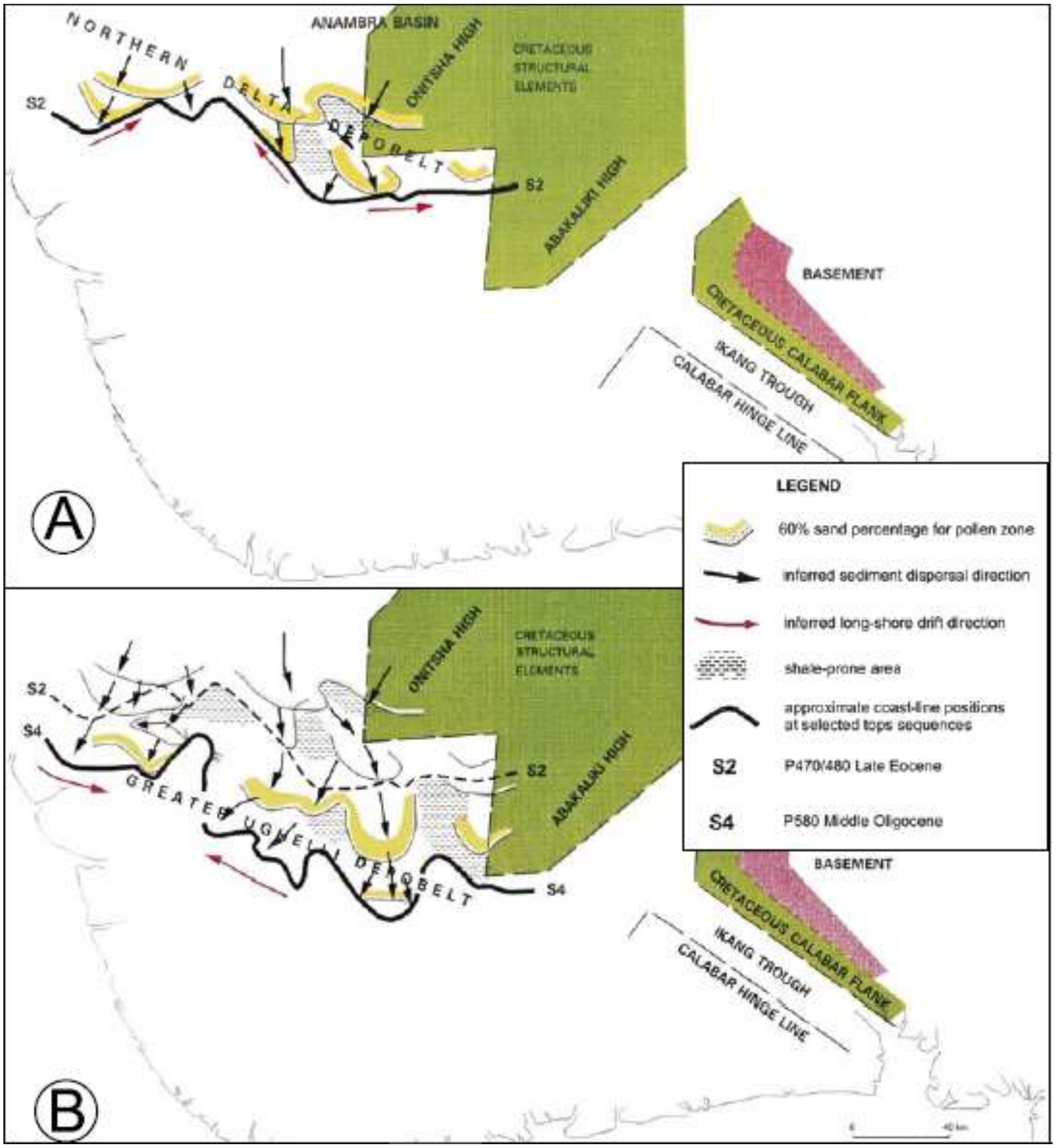

Figure 6. Palaeo-drainage trend and advancing coastline of the Niger Delta (modified after Edjedawe, 1981; Ejedawe et al., 1984). (A) Position at start of sequence 3 (Orogho-shale transgression); (**B**) Position at start of sequence 5 (*Alabamina*–1 shale transgression.

accumulated in the active Central Swamp and in the northern sector of the Coastal Swamp. Progradation maintained at a steady rate of 13-17 km/Ma (Figure 5) and stabilized in the Late Miocene-Pliocene when the Coastal Swamp and offshore depobelts became active. In the eastern delta, sedimentation was interrupted by cutting-and-filling events (Burke, 1972; Petters, 1984), resulting in the Agbada, Elekelewu, Soku and Afam 'channels' (Figures 5 and 7B). 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.

MATERIALS AND METHODS

One seismic (one inline) section, ten composite wireline logs comprising gamma ray, resistivity, neutron-density and acoustic logs as well as analysed biostratigraphic data from Wells C and F were the materials used for the study.

As shown on the base map provided (Figure 8), the ten wells drilled traverse the field of study and their trajectories displaced on seismic section depict that wells F, G and H are located toward north; Wells A, A_1 and B are sited on the southern (deepest) part while Wells C, D, E and E_1 are in the middle of the field. Wireline logs are used to generate more information regarding the sequence of rocks penetrated by the wells (Kearey et al., 2002).Of particular value is the ability to decipher depths to geological interfaces which have a characteristic geophysical signature that provide means of

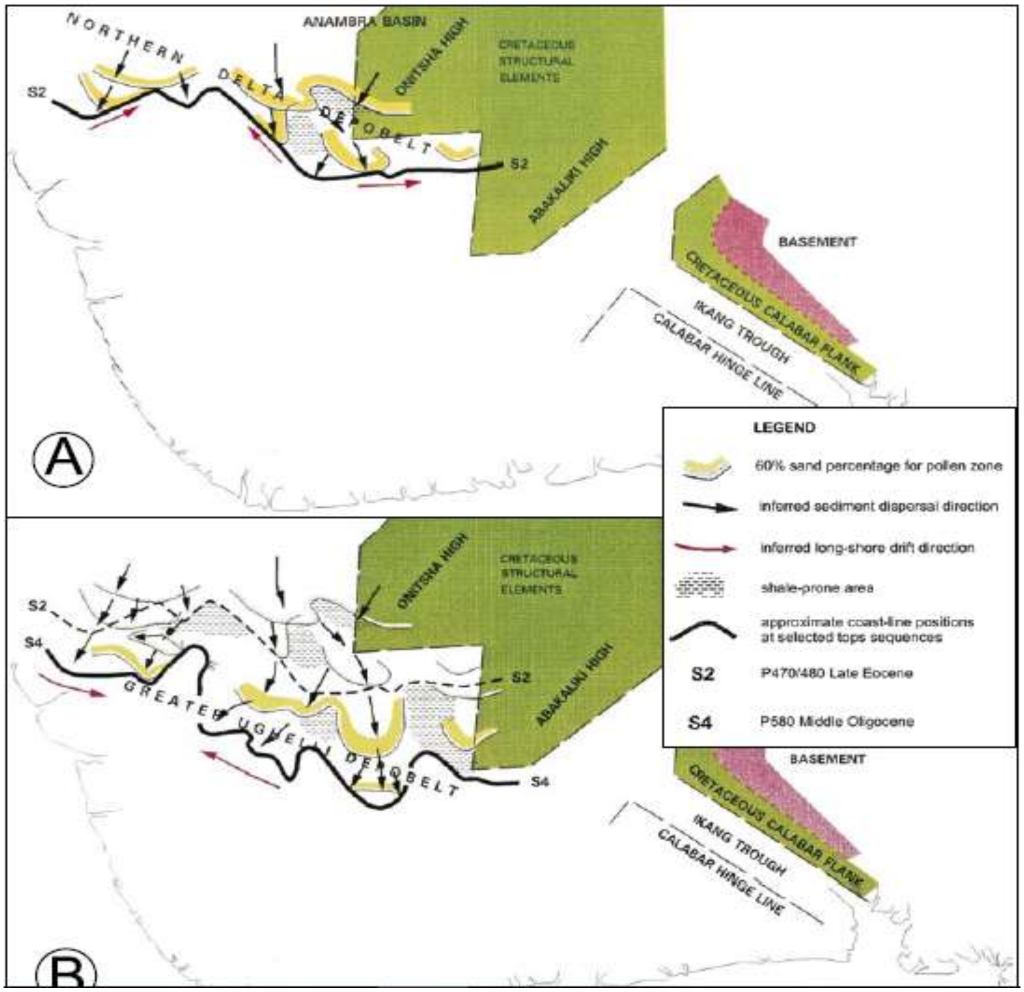

Figure 7. Palaeo-drainage trend and advancing coastline of the Niger Delta (modified after Edjedawe,1981; Ejedawe et al., 1984). (A) Position at start of sequence 9 (Dodo- shale transgression); (B) Position at start of sequence 11 (*Bolivina*–46 shale transgression).

correlating geological features within wells as well as obtain information on *in situ* properties of wall rocks. Well log data therefore allow lithology and depositional environment to be worked out and placed on seismic section thus linking seismic facies, rock properties and sedimentologic facies together (Emery and Myers, 1996). Well logs also resolve bedding details which seismic data cannot, thereby creating room for more detailed and dependable stratigraphic interpretation to be made.

The concept of biostratigraphy is based on the principle that organisms have undergone successive changes over geologic time. Any stratal unit can therefore be characterized and dated by its fossil content. This implies that on the basis of its contained fossils, any stratigraphic unit can be differentiated from stratigraphically younger and/or older unit (Boggs, 2006) and its depositional environment assessed (Peter, 1982).

RESULTS AND DISCUSSION

Interpretation of all the datasets was carried out step by step, starting with seismic section. To accomplish the objective of interpreting structure, stratigraphy and depositional facies from seismic data, one must identify characteristic features of seismic reflection records and relate them to the geologic factors responsible for the reflections (Boggs, 2006). An understanding of these factors that generate seismic reflections is therefore critical to the entire concept of seismic stratigraphy. Fundamentally, primary seismic reflections occur in response to the presence of significant density-velocity changes at structural defects such as unconformity and bedding surfaces. Reflections are generated at unconformities because they separate rocks having different structural attitudes or physical properties. The density-velocity contrast along unconformities may be further enhanced if the rocks below the unconformities have been altered by, say, weathering. Reflections are also generated at bedding surfaces because, owing to lithologic or textural differences, a velocity-density contrast exist between some sedimentary beds.

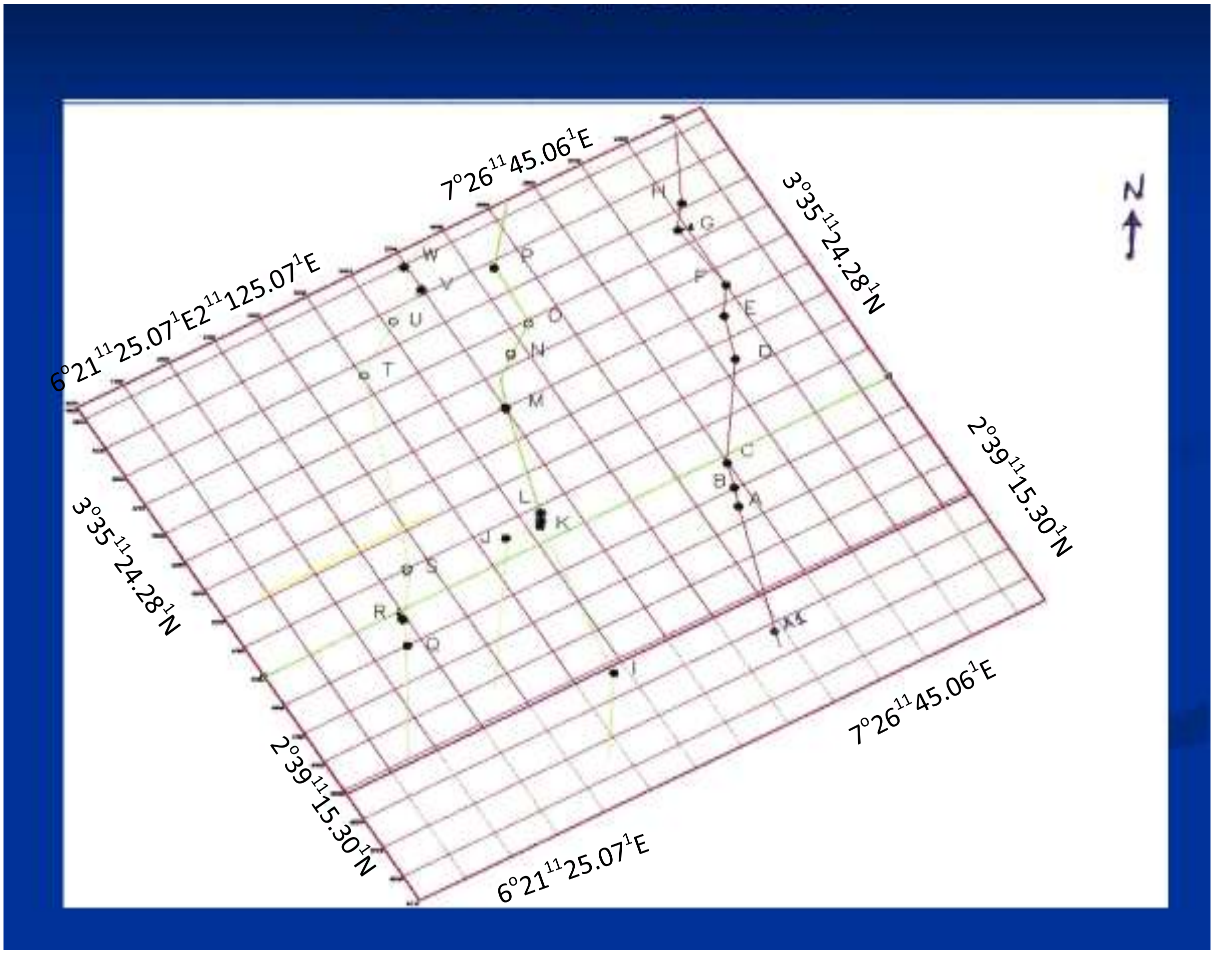

Figure 8. Showing Wells A1 – H used in this study.

However, not every bedding surface generates seismic reflection. Also, a given reflection event identified on a seismic record may not necessarily be caused by reflection from a single surface but may represent the sum or average of reflections from several bedding surfaces, particularly if the beds are thin.

The seismic records produced as a result of primary reflections have distinctive characteristics which can be related to depositional features such as lithology, bed thickness and spacing, and continuity. The principal parameters which are useful in seismic stratigraphy for interpreting geologic features are reflection configuration, continuity, amplitude and frequency, interval velocity and external form and association of seismic facies units (Boggs, 2006).

According to Brown (2012), stratigraphic features, after being deposited on a flat-lying surface, will bend and break by later tectonic movements. Stratigraphy and structure then become interwoven and will require sound interpretative skills to separate them. The structures must be delineated first before stratigraphy can be appreciated. Faults are recognized on seismic sections using the following indicative features: (i) Termination of seismic events and offset of reflections; (ii) Abrupt change in the geologically significant dip configuration; (iii) Abrupt lateral velocity change; (iv) Mistie around loop, etc. (Enikanselu and Omosuyi, 2003).

Gross fault interpretation

Based on this, a total of eleven faults (F_1 to F_{11}) were identified on the seismic section (Figure 9). Eight of the identified faults (F_2, F_3, F_5, F_7, F_8, F_9, F_{10}, F_{11}) are normal growth faults dipping basin ward (southward) while three (F_1, F_4, and F_6) are antithetic faults dipping landward (northward) (Figure 9). Antithetic and synthetic faults commonly disrupt the continuity of bedding in the deformed hanging wall and contribute to the overall extension of the structure (Song and Cawood, 2001). A collapsed crest is formed where the antithetic faults impinge against the growth fault. This typifies the structural style of offshore depobelt in the Niger Delta (Doust and Omatsola, 1990; Stacher, 1995).

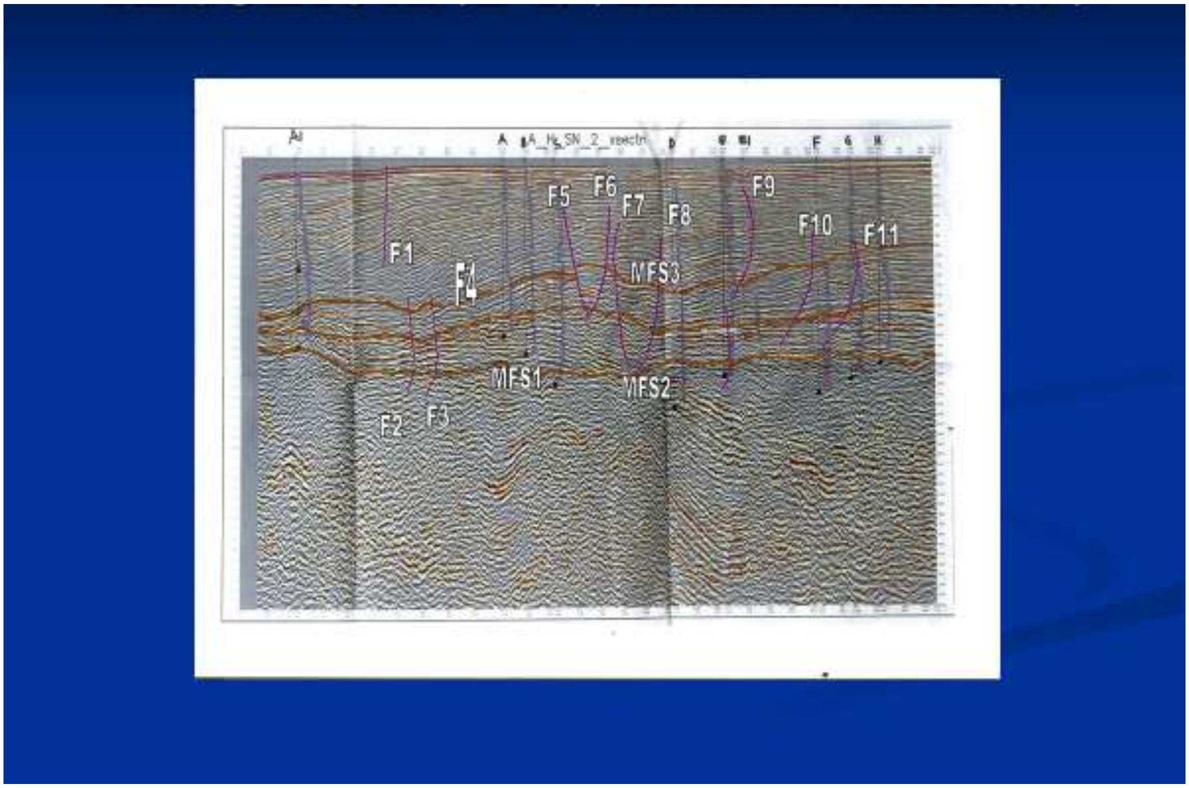

Figure 9. Fault delineation.

Seismic facies analysis

Seismostratigraphic description focuses on the reflection configuration within an interval between two picked horizon tops. Two seismic sequences (SS1 and SS2) were identified on the S-N seismic section (Figure 10). The seismic facies showed a change in reflection pattern from prograding reflections in the south to parallel reflections in the north (Figure 10). The objective of seismic sequence analysis is to interpret depositional sequences and systems tracts on seismic sections by identifying discontinuities based on reflection terminations (Sangree and Mitchum, 1992; Mitchum et al., 1977). There are two types of reflection termination patterns which lapout above this discontinuity. These are onlap and downlap patterns. Three types of reflection termination patterns that terminate below the discontinuity are truncation, toplap, and apparent truncation (Figure 10).

Sequence stratigraphic interpretation

Integration of the seismic, well log, and biostratigraphic datasets results in the evolution of the sequence stratigraphy of the field. The biodata sets utilized in this study were derived from Wells A, C and F (Tables 1 to 3) which served as the reference wells. They were used in the delineation of ages, zones, paleo- bathymetries and systems tracts. Additional information obtained from log signatures, sedimentologic and depositional attributes from wells drilled also assisted in refining the sequence stratigraphy of the field. Based on the biodata sets (Tables 1 to 3), two sequence boundaries (SBs) and three maximum flooding surfaces (MFSs) were identified and the systems tracts delineated were then named as transgressive systems tract (TST) and high stand systems tract (TST).

The TST developed during an increase in the rate of relative sea level rise. During this period, deltaic progradation ceased and much of the sand was trapped updip in estuaries (Posamentier and Vail, 1988). Such included back stepping (fining upward) facies of thin hemipelagic shales (Mitchum et al, 1990). These sediments were deposited in outer neritic to bathyal paleowater depths. Thus, the transgressive systems tract is associated with retrogradational stacking pattern corresponding to fining upward of the gamma ray log. At the end of each transgressive phase, a maximum flooding surface, characterized by high faunal abundance and diversity peak occurs, which marks the period of maximum sea level rise.

The HST deposits formed during the late relative sea level rise and early sea level fall overlie the TSTs and are associated with aggradational-progradational stacking pattern corresponding to coarsening up of the gamma ray

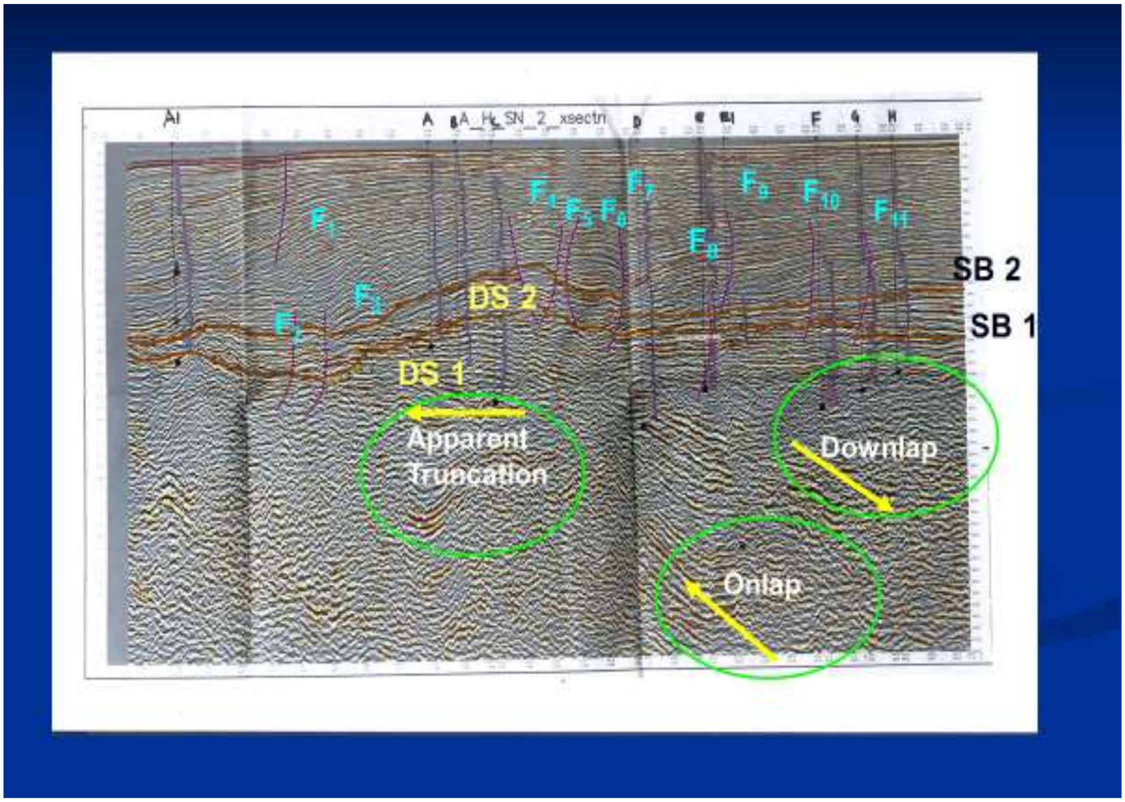

Figure 10. Reflection terminations and seismic sequences.

Table 1. Biomarkers recovery for well F.

Depth (m)	Biomarker	Occurrence	Species type	Age (Ma)	Sequence surface indicated
700	Benthic Foram	FDO	*Miliamina costata*	2.45	MFS 240
1060	Nano- chlorophyte	FDO	*Sphenolithus abies*	3.2	Near SB 300
1125	Nano-chlorophyte	FDO	*Reticulofenestra pseudoumbilica*	3.3	Near MFS 340
1760	Benthic Foram	FDO	*Uvigerina rustica*	4.2	SB 420
1775	Benthic Foram	FDO	*Valvulineria flexilis*	5.0	MFS 500
1775	Benthic Foram	FDO	*Textularia paruvula*	5.0	MFS 500
2230	Benthic Foram	FDO	*Dentalina quinqueranus*	5.6	Near 550

First Downhole Occurrence (FDO) = Local Stratigraphic Last Appearance Datum.
WELL F: A representative well in the northern axis of the field.

log (Mitchum et al., 1990) deposited in inner to middle neritic environments. Early highstand sediments are usually shaly (Neal et al., 1993) while late highstand complex which is deposited as the rise in sea level slows, contains silts and sands. Gamma ray responses show a gradual decrease in gamma ray readings indicating coarsening upward trend associated with decreasing water depth. Seismic reflections within this interval are characterized by sigmoidal S-shaped stratal pattern similar to prograding wedge reflections. There may be deltaic and shoreface sands at the top of this section but this systems tract generally has poor reservoir sands and updip seals are uncommon. The top of this highstand systems tract corresponds to a sequence boundary that marks the end of the sequence.

Relative ages of the sequence boundaries and maximum flooding surfaces inferred from bioevents encountered in Wells C, F and A (Tables 1 to 3) in

Table 2. Biomarkers recovery for WELL C.

Depth (m)	Biomarker	Occurrence	Species Type	Age (Ma)	Sequence surface indicated
875	Benthic Foram	FDO	*Trifarina mexicana*	2.4	Sb 240
1060	Benthic Foram	FDO	*Miliamina costata*	2.45	MFS 245
1720	Nano-chlorophyte	FDO	*Sphenolithus abies*	3.2	Near 240
1725	Nano-Chlorophyte	FDO	*Reticulofenestra pseudoumbilica*	3.3	Near MFS
1860	Benthic Foram	FDO	*Uvigerina rustica*	4.2	SB 420
1875	Benthic Foram	FDO	*Valvulineria flexilis*	5.0	MFS 500
	Benthic Foram	FDO	*Textularia paruvula*	5.0	MFS 500
2175	Nano-Chlorophyte	FDO	*Dentalina quinqueranus*	5.6	Near SB 550

WELL C: A representative well in the middle axis of the field.

Table 3. Biomarkers recovery EOR well A.

Depth (m)	Biomarker	Occurrence	Species type	Age (Ma)	Sequence surface indicated
875	Benthic Foram	FDO	*Textularina mexicana*	2.4	Sb 240
1060	Benthic Foram	FDO	*Miliamina costata*	2.45	MFS 245
1720	Nano-Chlorophyte	FDO	*Sphenolithus abies*	3.2	Near 240
1725	Nano-Chlorophyte	FDO	*Spiroloculina pseudoumbilica*	3.3	Near MFS
1860	Benthic Foram	FDO	*Uvigerina rustica*	4.2	SB 420
1875	Benthic Foram	FDO	*Valvulina flexilis*	5.0	MFS 500
	Benthic Foram	FDO	*Textularia parvula*	5.0	MFS 500
2175	Nano-Chlorophyte	FDO	*Discocyclina quinqueramus*	5.6	Near SB 550

First Downhole Occurrence (FDO) = Local Stratigraphic Last Appearance Datum.
Well A representing wells in the southern axis of the field.

conjunction with the Niger Delta Chronostratigraphic charts, form the basis for the well- to- well correlations in the field (Figure 11). These correlations show that Well C is on the downthrown side relative to Well B, with an approximate average displacement of about 525 m, while Well F is on the downthrown portion relative to Well D, with an approximate displacement of about 600 m.

The character of sequence development and depositional facies preserved depends on relative rates and patterns of regional structural collapse as well as shifts in sediment accumulation produced by sea level changes. The interplay of eustatic sea level change and local subsidence determines the type of unconformity and lowstand basin physiography that controls the morphology of the resulting transgressive systems tract (Posamentier and Allen, 1993). Picking all the unconformities within the area of shooting breaks the whole volume of data into various sequences while tracing how the reflections slope (whether they form an S-curve or are just parallel or concave upward, etc.) tells story about the deposition.

The patterns of deposition within the Agbada Formation changed with clastic wedge progradation into the basin, the shoaling of depositional environments, and changes in rates of structural deformation. The increase in sandstone relative to shale up- section clearly records long term regional production. Deposits directly above sequence boundaries are fine-grained in most places and generally coarsen upward.

Standard sequence stratigraphic models for prograding deltaic deposits suggest that a sequence-bounding-erosion surface should cap a coarsening and shoaling upward succession (forward-stepping parasequences). The erosion surface should mark an abrupt coarsening particularly where the surface is incised deep into the underlying deposits. Thus, deposits directly above the sequence boundary are expected to record falling stage and lowstand incision of fluvial channels, and the filling of these valleys with sandy fluvial sediments during subsequent sea-level rise (Van Wagoner et al., 1990). These incised fluvial deposits are overlain by an upward fining succession recording transgression of shorelines and a shift in sandstone deposition to more proximal areas of the basin. For much of their length, incised valleys commonly are encased in middle to outer neritic stretch because they incise during a relative fall in sea level.

Maximum flooding surfaces are characterized by

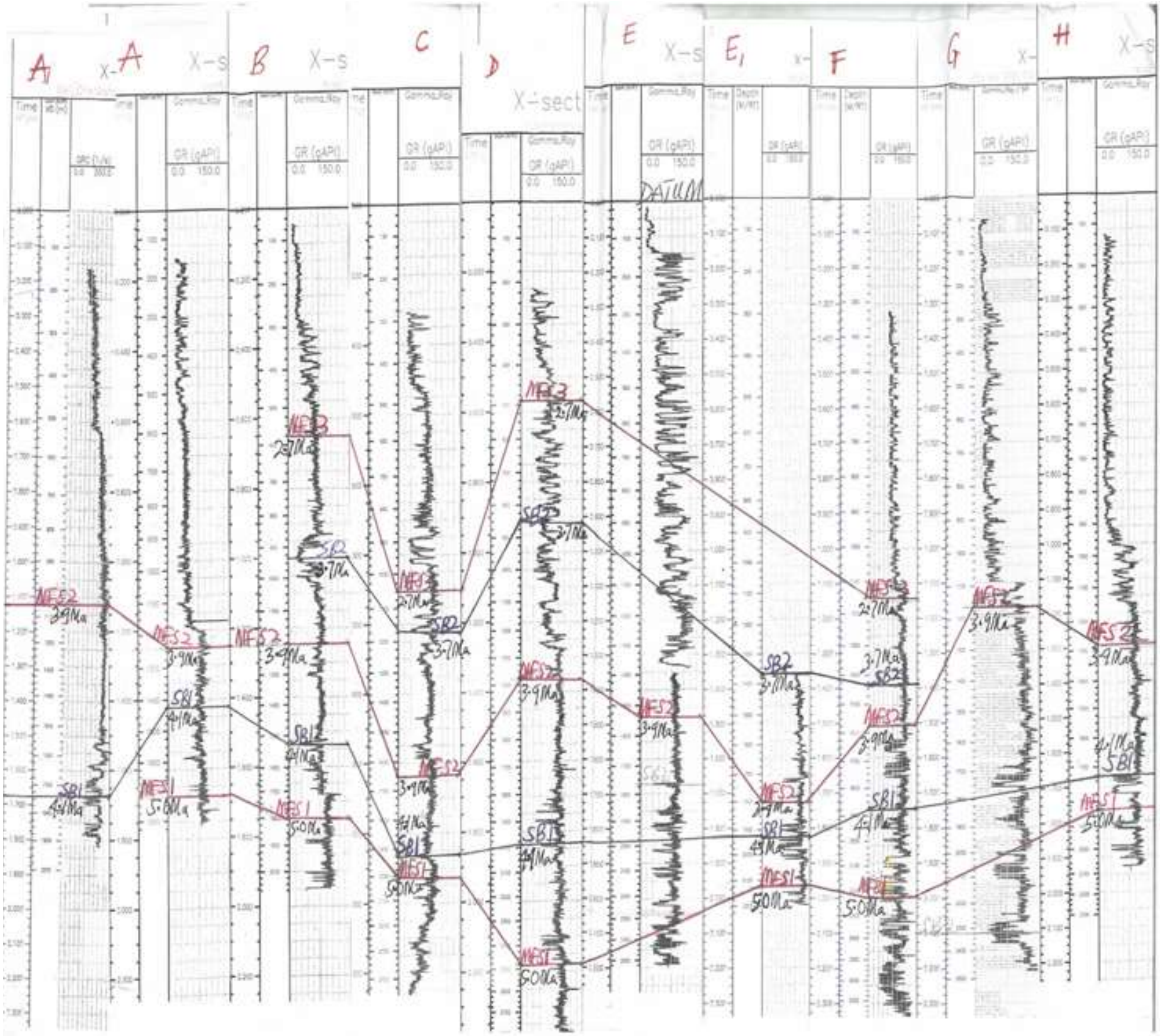

Figure 11. Sequence stratigraphic correlation of 'X' field.

downlap of clinoforms. In field setting, faunal abundance makes the maximum flooding surface commonly a much better time-stratigraphic interval for tying shelf to slope sediments than the unconformity, thus the maximum flooding surface represents a continuum of deposition for fine basinal sediments (Posamentier and James, 1993). The conformable part of the sequence boundary is a more synchronous surface than the maximum flooding surface, because it is less subject to local variations in subsidence and sediment flux (Wehr, 1993).

Reservoir intervals in Agbada Formation have been interpreted to be deposits of high stand and transgressive systems tracts in proximal shallow ramp setting (Evamy et al., 1978). The reservoir units were delineated using biofacies data (Tables 1 to 3) from the reference wells (that is, Wells C, F and A). In Well C, the reservoir intervals stretch between 890 and 975 m and from 2250 to 2375 m while in Well F the units range from 1625 to 1750 m and between 2050 and 2200 m (Figure 10). The fluvial sandstones of the reservoir units vary in grain size and tend to be coarser than the delta front sandstones.

Changes in thickness of strata between sequence boundary and intra-sequence reflector as well as thickness between intra-sequence reflectors provide an indication of the amount and location of growth strata superimposed on overall aggradation associated with clastic wedge progradation, channel incision and regional subsidence. Deposits in hanging wall blocks tend to be thicker directly basin ward of areas showing greater stratigraphy offset across faults and are relatively thinner down basin from areas with lesser fault displacement. On a broad scale, the seismic record is characterized by a series of nearly parallel reflections offset by listric normal faults, dipping to the south. Normal faults are more closely spaced while antithetic faults occur, hindering correlation of stratigraphic surfaces. Where the antithetic fault impinges against the growth fault, the crest of the rollover anticline collapses on the down dropped block lying across the fault, thus typifying the structural style of the offshore depobelt of Niger Delta. Seismic reflections also become more chaotic deep down within the seismic record where diapiric movement of underlying mobile shale has complicated reflector geometry.

Conclusion

A sequence stratigraphic framework for a growth-faulted deltaic deposit through the Agbada Formation encountered within the field of study was constructed using 3-D Seismic, well logs and biostratigraphic data. Two sequence boundaries and three maximum flooding surfaces were mapped. The sequences developed above a succession of basin ward dipping normal faults where hanging walls were displaced basin ward during their deposition. The petroleum geology of this offshore portion of Niger Delta appeared different from other parts of the basin since it is located in a complex structural terrain occasioned by deep-seated shale deformation plus associated faulting. Shale ridges, toe thrusts and diapirism are of common occurrence in this part of the basin. There is therefore high probability of formation of stratigraphic traps in this field.

The development of good reservoir sands together with the shales of the upper transgressive systems tract form seals that are good at least on the outer shelf which is characterized by the high stand systems tract. Thus, the alternation of high stand systems tract sands and transgressive systems tract shales provides a union of reservoir and seal deposits which is essential for hydrocarbon accumulation and stratigraphic trapping.

Without the application of sequence stratigraphy to clastic (and/or carbonate) reservoirs, the interpretation of seismic data and well motifs could be flawed. This is because the thickness of reservoir interval is often below the vertical resolution of seismic wavelet and lateral continuity of the reservoir lithologic layers tied between wells is often below the horizontal resolution of the well logs. By understanding global changes in sea level, local arrangement of sand and shale in the field can be decoded. This enhances understanding of depositional mechanics and steers explorationists toward prospects missed by conventional interpretation. In the light of the foregoing the use of sequence stratigraphic framework in conjunction with seismic data interpretation promises to be a more beneficial and cost-effective technique in petroleum exploration than the use of any one of the techniques in isolation.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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