

Sequence Stratigraphic Interpretation of Kafe-1 Field, Offshore Western Niger Delta, Nigeria

S. O. Obaje

Nigerian Geological Survey Agency, P.M.B. 1423, Fate, Ilorin, Kwara State, Nigeria

ABSTRACT: *The area of study is located in Kafe-1 Field of the offshore western Niger Delta, Nigeria. The principal aim of the paper is to present a sequence stratigraphic interpretation utilizing data sets from biostratigraphic, well logs and seismic. Standard laboratory procedures were used for data treatment, while computer software such as StrataBugs and GeoGraphix were used for data processing, integration and interpretation. There are five wells studied in the area with the following distributions of sequences: Kafe-1-1 well (5 sequences), Kafe-1-2 (6 sequences), while Kafe-1-4, Kafe-1-5 and Kafe-1-6 wells have 4 sequences, respectively. The candidate maximum flooding surfaces delineated with interpreted gamma ray and resistivity well logs and seismic data were established using biostratigraphic data. Sequence stratigraphic interpretation and correlation of the five wells were performed and the chart produced is useful in further deepening the knowledge of the subsurface geology of the Niger Delta area of Nigeria.*

KEYWORDS: *Sequence stratigraphy, Kafe-1 Field, western Niger Delta, systems tract, well correlation*

I. INTRODUCTION

The area of study is located in Kafe-1 Field of the offshore western Niger Delta, Nigeria (Figs. 1 and 4). The Niger Delta is situated in the Gulf of Guinea on the west coast of Central Africa. Niger Delta lies between latitudes 4° and 6° N and longitudes 3° and 9° E in the south-south geo-political region of Nigeria (Ojo *et al.*, 2009). The Cenozoic Niger Delta is situated at the intersection of the Benue Trough and the South Atlantic Ocean where a triple junction developed during the separation of South America and Africa in the Late Jurassic (Whiteman, 1982).

The scope and objectives of the research study involved the following:

- Identification of foraminifera and calcareous nannofossils and their abundance in the strata penetrated in the wells.
- Utilization of biostratigraphic data to delineate candidate chronostratigraphical surfaces.
- Determination of the ages of the studied wells intervals.
- Drawing of the correlation chart for the wells in study area.
- Interpretation of well log signatures.
- Interpretation, utilization and integration of seismic data.

1.1 Literature Review

Three depositional cycles and lithostratigraphic subdivision of upper sandy continental Benin Formation, intervening unit of alternating sandstones and shales (Agbada Formation) and lower shaly Akata Formation have been identified in the Niger Delta area (Short & Stauble, 1967; Avbovbo, 1978, etc.). The structural geology, sedimentology and petroleum geochemistry of the Niger Delta have been published by several workers (Tuttle, *et al.*, 1999; Weber & Daukoru, 1975, etc.). In addition, the biostratigraphy and sequence stratigraphy of the Niger Delta have been studied (Ozumba, 1999; Adeniran, 1997; Petters, 1982, etc.). However, in the published and unpublished works, integrated approach is lacking.

1.2 Geological Setting

Three main formations have been recognized in the subsurface of the Niger Delta (Short and Stauble, 1967; Weber and Daukoru, 1975; Avbovbo, 1978; Knox and Omatsola, 1989; Tuttle *et al.*, 1999). These are the Benin, Agbada and Akata Formations. These formations were deposited in continental, transitional and marine environments, respectively; together they form a thick, overall progradational passive-margin wedge (Esan, 2002). The Akata Formation is the basal unit composed mainly of marine shales believed to be the main source rock within the basin. The Agbada Formation is made up of alternating sandstone, siltstone and shale sequences

that constitute the petroleum reservoirs of the basin. On the other hand, the Benin Formation largely consists of non-marine sands with a few shaly intercalations (Esan, 2002).

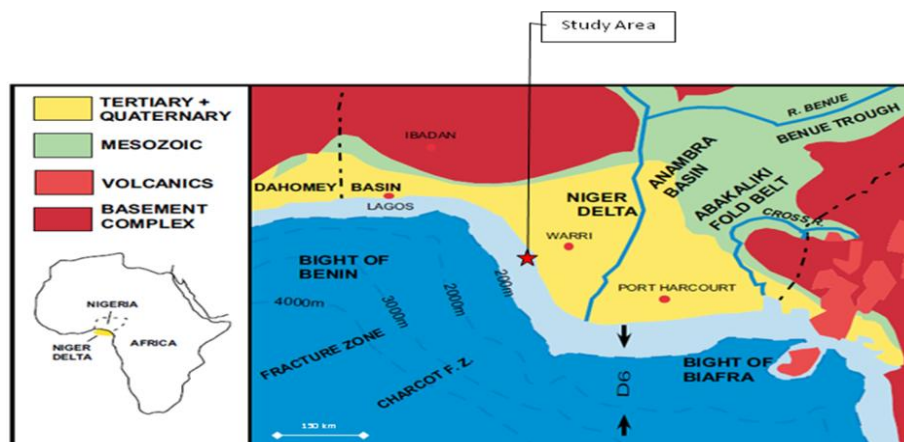


Fig. 1. Index map of Niger Delta and location of study area (after Doust and Omatsola, 1990)

II. SEQUENCE STRATIGRAPHY: PRINCIPLES AND CONCEPTS

1.1 Introduction

Sequence Stratigraphy is the study of genetically related facies within a framework of chronostratigraphically significant surfaces (van Wagoner *et al.*, 1990). Sedimentary facies is defined as the sum total of the lithological and paleontological aspects of a stratigraphic unit in a particular place. The parameters of facies are geometry, lithology, paleontology (including ichnofossils), sedimentary structures and paleocurrent patterns (Reijers, 1996). Vertical facies analysis must be done within conformable strata packages to accurately interpret coeval, lateral facies relationships along a single depositional surface. Walther's Law states that a vertical succession of facies, a facies sequence, reflects a similar lateral succession of facies, facies belts, provided that the facies transitions are gradual (Reijers, 1996; Emery and Myers, 1997). There are three main schools of thought on sequences, namely: Exxon school (1977-1988) based on unconformity, Galloway school (1989) based on maximum flooding surfaces and Emery school (1993) based on subaerial unconformity and transgression surfaces (Hart, 2005). Conversely, Hunt and Tucker model and Nummedal *et al.* model are modifications of the above three models. Exxon School (1977-1988): The depositional sequence of the Exxon model is based on highstand and lowstand systems tracts. It is bounded by subaerial unconformity, followed by a regressive surface of marine erosion, and then a correlative conformity (which is often difficult to recognize). The sequence begins with each highstand or progradation onto the shelf. The Exxon model has wide acceptability and application in the hydrocarbon industry (Hart, 2005). Galloway School (1989): The Galloway model of genetic stratigraphic sequences is based on sequences bounded by maximum flooding surfaces often referred to as regressive-transgressive sequences (R-T). According to Hart (2005), the advantage of the genetic stratigraphic model is that only one type of surface is defined, and this maximum flooding surface is easy to identify. However, Hart (2005) warned that in the genetic sequence model, an interpreter should note the possibility of unconformities lying within the sequences. Emery School (1993): The Emery school is also referred to as the Emery and Johannessen model of transgressive-regressive (T-R) sequences. In this model, sequences are bounded by subaerial unconformities and maximum regressive surfaces. There are two systems tracts in the T-R sequence model. The transgressive systems tract lies between the sequence boundary at the base and the maximum flooding surface at the top. The regressive systems tract lies between the maximum flooding surface at the base and the sequence boundary at the top. The T-R is newest concept and it is simple to apply, but not widely used (Hart, 2005).

Depositional sequence is the basic stratigraphic unit of sequence stratigraphy. A sequence is defined as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Vail *et al.*, 1977; van Wagoner *et al.*, 1990, etc.). Sequences can be subdivided into systems tracts, which are linkages of contemporaneous depositional systems (van Wagoner *et al.*, 1990; Hart, 2005, etc.). These include lowstand, transgressive, highstand and shelf margin systems tracts, respectively. Each systems tract is deposited at a predictable position in an interpreted eustatic cycle, and has recognizable signatures in well logs and seismic data (Vail *et al.*, 1977; van Wagoner *et al.*, 1990, etc.).

Sequences and systems tracts can be defined on the basis of strata geometry and physical relationships. Fundamental recognition criteria for sequences include definition of sequence boundaries (unconformities or their correlative conformities) and vertical relationships and facies of systems tracts within the sequences.

III. MATERIALS AND METHODS

The five wells in the study area are Kafe-1-1, Kafe-1-2, Kafe-1-4, Kafe-1-5 and Kafe-1-6. Ditch cuttings sampled at 18.29 meter intervals were given for the five wells in Kafe-1 Field. The standard micropaleontological preparation technique for foraminiferal samples and calcareous nannofossils were used in the Laboratory. The statistical data of the specimens were recorded and StrataBugs software was used for data processing and integration with the well logs data, which were given in LAS format. Other materials for the study are seismic section, well logs, base map and check shot data for five wells in the study area. The 3D seismic volume data supplied in SEG-Y format were loaded on Landmark Workstation. The database was created on the GeoGraphix Discovery R2007.1 platform (Windows) version. The study was performed using SeisVision 3Dimensional (3D) seismic interpretation modules. The following method and workflow plan was adopted: loading of seismic and well data, review of seismic and log data after loading, integration of biostratigraphic data and their calibration with seismic data, identification of candidate sequence boundaries, and the posting of the dominant faults on the transect. The time-depth relationship was determined using the check shot data available for Kafe-1-1 well (Fig. 2). The two-way time (TWT) is given in milliseconds (msec.) on the x-axis, while the true vertical well depth is given on the y-axis in feet (and the conversion value is 1 foot equals 0.304804 meter). The data sets for this study were given by ChevronTexaco Nigeria Limited and the author is deeply grateful.

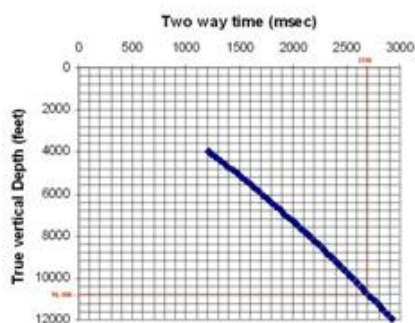


Fig. 2. The Plot of Check Shot Chart for Kafe-1-1 Well (Conversion: 1 foot = 0.304804 metre)

IV. SEQUENCE STRATIGRAPHIC INTERPRETATION OF KAFE-1 FIELD

The absolute ages of the foraminiferal and calcareous nannofossil biozones, sequence boundaries and the third order maximum flooding surfaces were based on correlation zones and cycles of several authors such as Blow (1969, 1979), Martini (1971), Borsetti *et al.* (1979), Iaccarino and Salvatorino (1982), Iaccarino (1985), Berggren *et al.* (1985), Bolli *et al.* (1987), Adeniran (1997), Ozumba (1999). The sequence stratigraphic approach of Vail and Wornardt (1990) was employed in this study. The following procedures were used;

- (a) High-resolution biostratigraphy and paleoecologic zonations using foraminifera and calcareous nannofossils. The foraminiferal and calcareous nannofossil biozonations were correlated to the magnetobiostratigraphic schemes of Berggren *et al.* (1985) and Martini (1971).
- (b) Interpretation of well log responses (gamma-ray and resistivity logs) was confirmed with ditch cutting characteristics of sediments assessed using stereo-binocular microscopy. The well log patterns were used to delineate the sequences to different kinds of systems tracts (Fig. 4). The identified sequence boundaries were found at inflection of progradation to retrogradation of parasequences in a shallowing upward sand unit, and also at the inflection of the lowstand prograding complexes (lowstand systems tract). The higher gamma ray and lowest resistivity readings were used to identify maximum flooding surfaces (Vail and Wornardt, 1990).
- (c) From the faunal and floral abundance/diversity peaks (using the first and last down-hole occurrences), four maximum flooding surfaces dated 12.8 Ma, 11.5 Ma, 10.4 Ma and 9.5 Ma, and five sequence boundaries dated 13.1 Ma, 12.1 Ma, 10.6 Ma, 10.35 Ma and 8.5 Ma, respectively, were recognized. The fluctuation in specimens abundances have been established to reflect specimens' migration that has been linked to eustatic changes in sea level (Adegoke, 2002; Vail and Wornardt, 1990).

4.1 KAFE-1-1 WELL

Five sequences have been recognized in this well (Fig. 4).

4.1.1 Sequence I (3,313.48 – 3,791.71 m)

In this sequence, the lowstand systems tract was not penetrated. The transgressive systems tract (TST: 3,446.37 - 3,791.71 m) is made up of retrogradational stacking pattern of interbedded clay, shale, mudstone, silty mudstone, argillaceous siltstone and single unit of 7.62 m thick sandstone (fine - medium grained texture) at 3,589.02 m. The transgressive systems tract thinned into a major condensed section (MFS, 12.8 Ma) indicated by the abundance peaks of FDO: *Cassidulina neocarinata* (THALMANN) at depth of 3,446.37 m. The highstand systems tract (HST: 3,313.48 – 3,446.37 m) is made up of shale/mudstone prograding to argillaceous siltstone that changed to aggradational unit of sandy mudstone interbedded by thinly bedded fine - medium grained sandstone of about 3.81 m thickness. The highstand systems tract is terminated at the top by sequence boundary (SB: 12.1 Ma) at 3,313.48 m depth, which is defined at the point of inflection in the stacking pattern from net coarsening upwards to net fining upwards. The noticed abrupt change in the gamma ray log signature indicated an erosional truncation that defined the aforementioned sequence boundary.

4.1.2 Sequence II (3,046.17 - 3,313.48 m)

This sequence is mainly made up of transgressive systems tract and highstand systems tract. The transgressive systems tract (TST: 3,150.41 - 3,313.48 m) is made up of two lithological units of lower argillaceous sandstone underlying sandy mudstone. The stacking pattern is retrogradational with upward fining units with low blocky to serrated well log patterns. The abrupt change of the well log signature coupled with major faunal/floral abundance peaks are indicative of maximum flooding surface (MFS: 11.5 Ma) at 3,150.41 m. The MFS is dated by the FDO: *Globorotalia obesa* (BOLLI) marker fossil. The highstand systems tract (HST: 3,046.17 – 3,150.41 m) is made up of aggradational stacking pattern of two sandy units. At the sequence boundary (SB: 10.6 Ma) at 3,046.17 m, the sandy mudstone unit changed from aggradational to retrogradational stacking pattern.

4.1.3 Sequence III (2,639.57 - 3,046.17 m)

This sequence is made up of transgressive systems tract and highstand systems tract. At the sequence boundary (SB: 10.6 Ma at 3,046.17 m) indicated by the abrupt change of the well signature and faunal/floral abundance/diversity minor peaks, the sandy unit of the highstand systems tract of the previous sequence abruptly changed from aggradational to retrogradational stacking pattern. The transgressive systems tract (TST: 2,731.31 - 3,046.17 m) is made up of units of sandstones interbedded by thinly bedded shales. The sandstone units are individually aggradational with fining upward stacking pattern towards the maximum flooding surface (MFS: 10.4 Ma) at 2,731.31 m depth. The highstand systems tract (HST: 2,639.57 - 2,731.31 m) is made up of two sandy units interbedded by thinly bedded shale intercalations. The HST is dominantly made up of aggradational stacking pattern of two sandy units. The net fining upward pattern is noticed and the wireline log signature and seismic section signify an erosional truncation that defined the sequence boundary (SB: 10.35 Ma) at 2,639.57 m depth.

4.1.4 Sequence IV (2,268.93 - 2,639.57 m)

This sequence is made up of three systems tracts, namely: transgressive systems tract, highstand systems tract, and lowstand systems tract (lowstand prograding complex). The transgressive systems tract (TST: 2,431.39 - 2,639.57 m) is made up of fining upward retrogradational stacking pattern of sandy units interbedded by thinly bedded shales. The maximum flooding surface (MFS: 9.5 Ma) is defined at the top of the transgressive systems tract at depth of 2,431.39 m with shaly condensed section defined by FDO: *Uvigerina sparsicostata* (CUSHMAN & LAI-MING) and *Discoaster hamatus* (MARTINI & BRAMLETTE). The highstand systems tract (HST: 2,268.93 - 2,431.39 m) is made up of two units of sand interbedded by shale and argillaceous siltstone. The HST is dominantly made up of aggradational stacking pattern of two sandy units which fines to the top into an erosional truncation that defined the sequence boundary (SB: 8.5 Ma) at depth of 2,268.93 m. The highstand systems tract argillaceous siltstone with fining upward stacking pattern changed to coarsening upward pattern of the sandstone unit of the overlying lowstand prograding complex.

4.1.5 Sequence V (1,527.05 - 2,268.93 m)

This sequence is made up only of the lowstand prograding complex. It is dominantly made up of continental sandstone interbedded by sequences of mixed sandstones (70% coarse grained), siltstones, mudstones, shales and clays. The lithofacies is referred to as the Benin Formation. The interval (1,527.05 -

2,268.93 m) is barren of fossils. The well log signature pattern is serrated shaped with coarsening upward stacking pattern.

4.2 Kafe-1-2 Well

This well has six sequences (Fig. 4).

4.2.1 Sequence I (3,441.80 – 3,781.71 m)

In this sequence only the highstand systems tract was penetrated via drilling. The wireline log readings are suppressed, thus the stacking pattern is not obvious. The point of change in the stacking pattern delineates the sequence boundary (SB: 13.1 Ma) at 3,441.80 m depth. The 13.1 Ma SB is dated with *R. pseudoumbilicus* (> 7µm) (GARTNER) and *Cyclicargolithus floridanus* (ROTH & HAY).

4.2.2 Sequence II (3,386.94 - 3,441.80 m)

The sequence is made up of transgressive systems tract and highstand systems tract. The transgressive systems tract (TST: 3,404.92 - 3,441.80 m) has retrogradational stacking pattern and it is capped by MFS, 12.8 Ma at depth of 3,404.92 m. The MFS is defined by marker fossil, *Globigerinoides subquadratus* (BRÖNNIMANN). The highstand systems tract (HST: 3,386.94 - 3,404.92 m) is made up of a single unit of sandy mudstone with aggradational stacking pattern. The point of transition of aggradational to progradational was used to define the sequence boundary (SB: 12.1 Ma) dated with FDO: *Calcidiscus premacintyreii* (THEODORIDIS) and *H. stalis* (THEODORIDIS) at depth of 3,386.94 m.

4.2.3 Sequence III (3,157.12 - 3,386.94 m)

The sequence is made up of transgressive systems tract and highstand systems tract. The transgressive systems tract (TST: 3,218.08 - 3,386.94 m) is made up of four sandy units, which are retrogradational. The transgressive systems tract is capped by MFS, 11.5 Ma dated with FDO: *Discoaster bellus* (BUKRY & PERCIVAL), *S. moriformis* (BRÖNNIMANN & STRADNER), LDO of *Catinaster coalitus* (MARTINI & BRAMLETTE), FDO: *Spirosigmoilina oligoceanica* (CUSHMAN), *Globorotalia obesa* (BOLLI), LDO: *Globorotalia continuosa* (BLOW) and *Globorotalia mayeri* (CUSHMAN & ELLISOR). The highstand systems tract (HST: 3,157.12 - 3,218.08 m) is made up of a single sandy unit that has aggradational stacking pattern. At the top of the HST, the sandy unit fines into shaly unit and there is an abrupt change of the gamma ray log signature indicating erosional truncation, which defines the sequence boundary (SB: 10.6 Ma) at depth of 3,157.12 m.

4.2.4 Sequence IV (2,855.06 - 3,157.12 m)

This sequence is made up of 3 systems tracts, namely: lowstand systems tract (lowstand prograding complex), transgressive systems tract and highstand systems tract. The lowstand prograding complex (PGC: 2,907.79 - 3,157.12 m) lies immediately above the 10.6 Ma SB. It is made up of five sandy units interbedded by thin shale intercalations. The PGC has coarsening upward stacking pattern. The transgressive systems tract (TST: 2,882.80 - 2,907.79 m) has retrogradational stacking pattern. The thin sandy unit (7.62 m thickness) in the TST fines upward and changed into shaly condensed section defining the maximum flooding surface (MFS: 10.4 Ma) at depth of 2,882.80 m. The highstand systems tract (HST: 2,855.06 - 2,882.80 m) is made up of aggradational stacking pattern that fines upward to the sequence boundary (SB: 10.35 Ma) at depth of 2,855.06 m. The 10.35 Ma sequence boundary was characterised by the LDO of *D. hamatus* (MARTINI & BRAMLETTE) and the associated markers are *Catinaster calyculus* (MARTINI & BRAMLETTE), *R. haqii* (BACKMAN), *R. pseudoumbilicus* (medium, 3-5 µm) (GARTNER).

4.2.5 Sequence V (2,420.11 - 2,855.06 m)

The sequence is made up of 3 systems tracts, viz: lowstand systems tract (PGC), transgressive systems tract and highstand systems tract. The lowstand prograding complex (PGC: 2,471.32 - 2,420.11 m) has nine sandy units separated by thinly bedded shales. The PGC has coarsening upward stacking pattern. The upper sandy units fine upward into a shaly unit that forms a condensed section defining the transgressive surface. The transgressive systems tract (TST: 2,431.39 - 2,471.32 m) has a single unit of fining upward retrogradational stacking pattern that is capped by maximum flooding surfaces (MFS: 9.5 Ma) at depth of 2,431.39 m. The 9.5 Ma MFS is dated with the FDO of *D. hamatus* (MARTINI & BRAMLETTE) and ACME: *Sphenolithus abies* (DEFLANDRE) and LDO *Globigerinoides extremus* (BOLLI & BERMUDEZ). The associated markers are *Catinaster mexicanus* (BUKRY), *D. pentaradiatus* (TAN), *H. carteri* (WALLICH), *Uvigerina sparsicostata* (CUSHMAN & LAI-MING) and *Globorotalia obesa* (BOLLI). The highstand systems tract (HST: 2,420.11 - 2,431.39 m) is made up of a single unit of sandy mudstone with an overall aggradational stacking pattern. It

finer upward to a sequence boundary (SB: 8.5 Ma) at 2,420.11 m depth. The 8.5 Ma sequence boundary is dated with the LDO: *D. quinquerramus* (GARTNER) and the associated marker species are *R. haqii* (BACKMAN), *D. braarudii* (BUKRY), *Coccolithus pelagicus* (WALLICH), *D. pentaradiatus* (TAN), *S. abies* (DEFLANDRE), *H. carteri* (WALLICH), *U. jafari* (MÜLLER) and *U. rotula* (KAMPTNER).

4.2.6 Sequence VI (1,527.05 - 2,420.11 m)

This sequence is made up of only lowstand systems tract (PGC). The lowstand prograding complex is characterised by serrated “saw-shaped” gamma ray log signature, which is indicative of sandstones interbedded by thinly bedded shale intercalations. The sequence is barren in fossils and it is called the Benin Formation. There is a fault between Kafe-1-1 and Kafe-1-2 wells. The down-thrown side of the recognized growth fault is located at Kafe-1-2 well area, while the up-thrown side is at the Kafe-1-1 area.

4.3 Kafe-1-4 Well

This well has four sequences (Fig. 4).

4.3.1 Sequence I (3,404.62 – 3,493.01 m)

This sequence is relatively short and it is dominantly made up of shales with sandy intercalation. The net composition of the ratio of sandstones to shales is about 10%:90%. The sequence is incomplete because the drilling in the well penetrated only the transgressive systems tract at the given depth. It has retrogradational stacking pattern, which is capped by sequence boundary (SB: 12.1 Ma) at depth of 3,404.62 m. The 12.1 Ma sequence boundary is dated with the FDO: *Calcidiscus premacintyeri* (THEODORIDIS) and the associated fossil marker is *H. stalis* (THEODORIDIS). On the other hand, it may be inferred that the highstand systems tract in this sequence may have been completely eroded leaving behind an erosional truncation that defined the aforementioned sequence boundary at 2,535 to 2,752 microseconds in the seismic sections.

4.3.2 Sequence II (3,157.42 - 3,404.62 m)

This sequence is made up of two systems tracts, namely: the transgressive systems tract and the highstand systems tract. The transgressive systems tract (TST: 3,219.00 - 3,404.62 m) is made up of two sandy units interbedded by argillaceous siltstone and shales. The transgressive systems tract has an overall retrogradational stacking pattern. The lower sandy unit coarsens upward, while the upper sandy unit though initially coarsened, it later fines upward into a condensed section of shale unit forming the maximum flooding surface (MFS: 11.5 Ma) at depth of 3,219.00 m. The 11.5 Ma MFS is dated with the FDO: *Spirosigmolina oligoceanica* (CUSHMAN). The highstand systems tract (HST: 3,157.42 - 3,219.00 m) is made up of a single unit of argillaceous sandstone bounded at top and base by shales. The well log signature shows a fining upward stacking pattern. There is an abrupt change at the point of inflection that defines the sequence boundary (SB: 10.6 Ma) at depth of 3,157.42 m.

4.3.3 Sequence III (2,433.22 - 3,157.42 m)

This sequence has three systems tracts, namely: lowstand systems tract, transgressive systems tract and highstand systems tract. The lowstand systems tract is present as lowstand prograding complex (PGC). The PGC is found at the depth interval of 2,727.96 – 3,157.42 m. It has an inverted Christmas tree-shaped well log signature. It is made up of four sandy units in which the lower sandy body fines upward while the middle sandy body coarsens upward. On the other hand, the upper sandy bodies fine into shaly condensed unit, which defines the transgressive surface. The transgressive systems tract (TST: 2,433.22 - 2,727.96 m) is composed of seven sandy units that are separated by thinly bedded shale intercalations. The transgressive systems tract has retrogradational stacking pattern, however, three sandy units within it have individually coarsening upward aggradational units. The upper sandy body fines upward into a major condensed shale unit, which defines the maximum flooding surface (MFS: 10.4 Ma) at depth of 2,433.22 m. The 10.4 Ma MFS is dated with the ACME of *D. hamatus* (MARTINI & BRAMLETTE) and the associated marker fossils are *R. haqii* (BACKMAN), *R. pseudoumbilicus* (medium 3-5 μm) (GARTNER) and the LDO of *Catinaster calyculus* (MARTINI & BRAMLETTE).

The highstand systems tract (HST: 2,273.81 - 2,433.22 m) is made up of two sandy units of about 45.72 – 76.20 m thickness and they are interbedded by thinly bedded shales. The earlier sandy unit has aggradational stacking pattern, while the latter unit has progradational stacking pattern. The top of the HST fines upward into a shaly unit, which defines the sequence boundary (SB: 10.35 Ma) at depth of 2,273.81 m. The 10.35 Ma sequence boundary is dated with the LDO of *Discoaster hamatus* (MARTINI & BRAMLETTE).

4.3.4 Sequence IV (731.52 - 2,273.81 m)

This sequence is made up mainly of lowstand systems tract (PGC). The lowstand prograding complex (PGC: 731.52 - 2,273.81 m) is composed of thirteen units of medium to coarse grained sandstones that are interbedded by argillaceous siltstones, siltstones, clays, mudstones, shales, etc. This PGC is non-marine and it is barren of fossils. It constitutes the set of lithofacies that form the Benin Formation. It is of continental fluvial environment of deposition. There is fault between Kafe-1-2 and Kafe-1-4 wells. The down-thrown side of the recognized growth fault is located at the Kafe-1-4 well area, while the up-thrown side is at the Kafe-1-2 well area (Fig.3).

4.4 Kafe-1-5 Well

Four sequences were recognized in this well (Fig. 4).

4.4.1 Sequence I (3,387.24 - 3,535.68 m)

Two systems tracts were penetrated in this well; they are the transgressive systems tract and the highstand systems tract. The transgressive systems tract (TST: 3,466.80 - 3,535.68 m) is composed mainly of shales, which fines upward in a retrogradational stacking pattern. The transgressive systems tract is capped by maximum flooding surface (MFS: 12.8 Ma) at depth of 3,466.80 m. The 12.8 Ma MFS is dated with the FDO of *Globigerinoides subquadratus* (BRÖNNIMANN). The highstand systems tract (HST: 3,387.24 - 3,466.80 m) is composed mainly of sandy mudstone interbedded by thin argillaceous siltstone of about 7.62 m thickness. The highstand systems tract has fining upward stacking pattern. It is truncated at the top by an erosional surface, which defines the sequence boundary (SB: 12.1 Ma) at depth of 3,387.24 m. At the point of inflection, there is an abrupt change in the stacking pattern from net fining upward to a net coarsening upward stacking pattern.

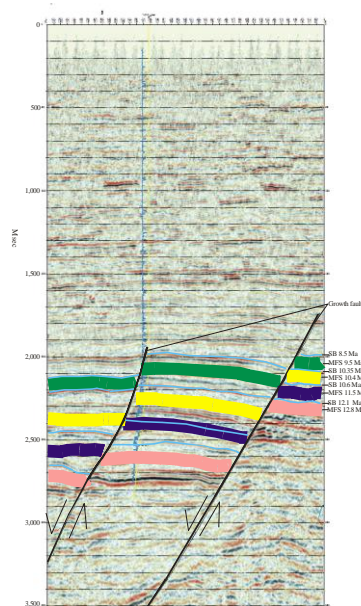


Fig. 3. Structures with growth faults along cross-line (strike) 1,600 [Scale: vertical: 100 msec.; horizontal: 10 strike lines]

4.4.2 Sequence II (2,909.93 – 3,387.24 m)

This sequence has three systems tracts, namely: lowstand prograding complex, transgressive and highstand systems tracts, respectively. The lowstand prograding complex (PGC: 2,956.56 - 3,387.24 m) is made up of six fine to medium grained sandy units that range in thickness from about 15.24 - 106.68 m. Thin beds of shales and argillaceous siltstones of about 15.24 - 48.77 m thickness separate the sandstone units, respectively. The lower sandstone units are downlap, progradational, while the upper units are toplap with aggradational stacking pattern. These sandy units coarsen upward but at the top, they fine upward into shaly unit, which defines the transgressive surface at depth of 2,956.56 m. The transgressive systems tract (TST: 2,933.10 - 2,956.56 m) is composed of a set of backstepping parasequences of shales. It begins with the transgressive surface, which is the first and minor marine flooding surface above the lowstand prograding complex. The transgressive systems tract backsteps until the point of maximum marine transgression was reached. It is capped by a major marine flooding surface (MFS: 11.5 Ma) at depth of 2,933.10 m. The 11.5 Ma MFS is dated with the FDO: *Globorotalia obesa* (BOLLI) and *Globorotalia foshi lobata* (BERMUDEZ). The highstand systems tract

(HST: 2,909.93 - 2,933.10 m) is composed of shales with fining upward stacking pattern. There is an abrupt change in the gamma ray log signature indicating an erosional truncation that defines the sequence boundary (SB: 10.6 Ma) at depth of 2,909.93 m.

4.4.3 Sequence III (2,417.98 - 2,909.93 m)

This sequence has three systems tracts, namely: lowstand prograding complex, transgressive and highstand systems tracts, respectively. The lowstand prograding complex (PGC: 2,575.56 - 2,909.93 m) is made up of four sandy units separated by shaly intercalations. The lower unit is composed of coarse grained sandstones with 83.82 m thickness and overlain by shales with 114.30 m thickness serving as very good reservoir seal. Shales of 7.62 m to 30.48 m thickness interbed the other sandy units, which have thicknesses in range of 30.48 - 91.44 m, respectively. The PGC has net coarsening upward stacking pattern that looks like "inverted Christmas tree" shape in the gamma ray log. There is an abrupt change in the gamma ray log signature signifying transgressive surface at depth of 2,575.56 m.

The transgressive systems tract (TST: 2,443.89 - 2,575.56 m) is composed of four units of sands (7.62 - 30.48 m thickness) overlain by shales, which may form good stratigraphic seal over the reservoir sands. Though the overall stacking pattern is retrogradational, the gamma ray log signature indicates that the lower sandy units have individual coarsening upward stacking pattern, while the upper sandy units fine upward into a shaly unit, which defines the major marine flooding surface (MFS: 10.4 Ma) at depth of 2,443.89 m. The 10.4 Ma MFS is dated by the ACME of *D. hamatus* (MARTINI & BRAMLETTE) and the associated marker fossils are *R. pseudoumbilicus* (medium 3-5 μm) (GARTNER) and the LDO of *Catinaster calyculus* (MARTINI & BRAMLETTE). The highstand systems tract (HST: 2,417.98 - 2,443.89 m) is composed of marine shales with fining upward retrogradational stacking pattern. It fines into sandy siltstone at an inflection point marking the sequence boundary (SB: 10.35 Ma) at depth of 2,417.98 m. The 10.35 Ma SB is dated by the LDO of *D. hamatus* (MARTINI & BRAMLETTE) and the associated marker fossils are *Catinaster calyculus* (MARTINI & BRAMLETTE), *Reticulofenestra haqii* (BACKMAN), *R. pseudoumbilicus* (medium 3-5 μm) (GARTNER).

4.4.4 Sequence IV (1,219.20 - 2,417.98 m)

This sequence is principally composed of the lowstand prograding complex (PGC). The PGC is made up of ten sandy units, which are separated to two distinct lithological units on the basis of their environments of deposition. The lower part is made up of two sandy units of 30.48 m thick sandstones interbedded by sandy siltstone at the base and shales at the top. This lower part forms the upper part of the fossiliferous Agbada Formation at depths of 2,273.81 - 2,417.98 m. On the other hand, the upper part is made up of eight sandy units that are medium to coarse grained in texture. These sandy units have 30.48 - 228.60 m thickness and separated by thinly bedded argillaceous siltstones, mudstones, clays and shales. It is non-marine, barren in fossils, and forms the upper part that constitutes the Benin Formation at depths of 1,219.20 - 2,273.81 m.

4.5 Kafe-1-6 Well

Four sequences were recognized in Kafe-1-6 well (Fig. 4).

4.5.1 Sequence I (3,845.05 - 3,962.40 m)

In this sequence, two systems tracts were penetrated in this well. The systems tracts are the transgressive and highstand systems tracts. The transgressive systems tract (TST: 3,907.23 - 3,962.40 m) is composed of two sandy units of 7.72 - 30.48 m thickness separated by 3.05 - 21.34 m thick shale intercalations. The units have an overall retrogradational stacking pattern. The upper argillaceous sandstone unit fines into a condensed section of shaly unit, which defines the maximum flooding surface (MFS: 12.8 Ma) at depth of 3,907.23 m. The 12.8 Ma MFS is dated with *Rectoglandulina comatula* (LOEBLICH & TAPPAN) fossil marker.

The highstand systems tract (HST: 3,845.05 - 3,907.23 m) is mainly composed of hemi-pelagic shales/mudstones. The overall stacking pattern is aggradational and fines upward with an abrupt change of the gamma ray log signature signifying an erosional truncation that defines the sequence boundary (SB: 12.1 Ma) at depth of 3,845.05 m. The 12.1 Ma sequence boundary is dated with FDO of *Calcidiscus premacintyreii* (THEODORIDIS) and the associated fossil marker is *H. stalis* (THEODORIDIS).

4.5.2 Sequence II (3,592.37 - 3,845.05 m)

This sequence has two systems tracts, namely: transgressive and highstand systems tracts. The transgressive systems tract (TST: 3,622.55 - 3,845.05 m) is composed of two units of an underlying argillaceous sandstone that is overlain by shales. The gamma ray log signature shows a retrogradational stacking pattern. The

argillaceous sandy unit fines upwardly into shaly condensed section that defines a maximum flooding surface (MFS: 11.5 Ma) at depth of 3,622.55 m. The 11.5 Ma MFS is dated with the FDO of *Globorotalia mayeri* (CUSHMAN & ELLISOR) and the associated fossil marker is LDO: *Globorotalia continua* (BLOW). The highstand systems tract (HST: 3,592.37 - 3,622.55 m) is composed mainly of shales that fines upwardly and progrades into an erosional truncation that defines a sequence boundary (SB: 10.6 Ma) at depth of 3,592.37 m. The 10.6 Ma sequence boundary is dated with the LDO of *D. hamatus* (MARTINI & BRAMLETTE) and the FDO of *Catinaster coalitus* (MARTINI & BRAMLETTE) and the associated fossil markers are *D. bellus* (BUKRY & PERCIVAL), *U. jafari* (KAMPTNER) and *D. bollii* (MARTINI & BRAMLETTE).

4.5.3 Sequence III (2,948.33 – 3,592.37 m)

Three systems tracts were recognized in this sequence. These are the lowstand prograding complex, transgressive and highstand systems tracts. The lowstand prograding complex (PGC: 3,314.70 - 3,592.37 m) is composed of six sandy units, which are individually interbedded by shales. The overall stacking pattern is aggradational, and coarsens upward. A shaly condensed section that defines the transgressive surface caps the upper sandy unit. The gamma ray log signature also indicates abrupt change from very low value of 20 API to very high value of 125 API, signifying the presence of transgressive surface at depth of 3,314.70 m. The transgressive systems tract (TST: 3,258.01 - 3,314.70 m) is made up of marine shales with retrogradational stacking pattern and fines upwardly to a maximum flooding surface (MFS: 10.4 Ma) at depth of 3,258.01 m. The 10.4 Ma MFS is dated with the ACME of *D. hamatus* (MARTINI & BRAMLETTE) and the associated marker fossils are *R. haqii* (BACKMAN), *R. pseudoumbilicus* (medium 3 - 5 μ m) (GARTNER) and the FDO of *Catinaster calyculus* (MARTINI & BRAMLETTE). The shales of the transgressive systems tract may form good seal for the reservoir sands of the underlying PGC. The highstand systems tract (HST: 2,948.33 - 3,258.01 m) is composed of six sandy units. The lower earlier units, at depths of 3,133.34 - 3,238.50 m, have aggradational stacking pattern and coarsen upward. On the other hand, the upper later units have progradational stacking pattern and capped by shaly unit that fines into the erosional truncation, which defines the sequence boundary (SB: 10.35 Ma) at depth of 2,948.33 m. The 10.35 Ma sequence boundary was dated with the LDO of *D. hamatus* (MARTINI & BRAMLETTE) and the associated marker fossils are *Catinaster calyculus* (MARTINI & BRAMLETTE), *Reticulofenestra haqii* (GARTNER) and *R. pseudoumbilicus* (medium 3-5 μ m) (GARTNER).

4.5.4 Sequence IV (1,222.25 - 2,948.33 m)

This sequence is made up of lowstand prograding complex. The PGC has two units, namely: marine and non-marine units, respectively. The marine unit, found at depths of 2,301.24 - 2,948.33 m, is made up of sandy units separated by argillaceous siltstones, mudstones, clays and shales that contain fossils. This constitutes the upper part of the Agbada Formation. On the other hand, the non-marine unit is made up of medium to very coarse-grained, thickly bedded sandstones with 15.24 - 152.40 m thickness that are interbedded by thinly bedded argillaceous siltstones, mudstones, clays and shales. This unit (at depth of 1,222.25 - 2,301.24 m) barren of fossils, is of the continental, fluvial depositional environment and it constitutes the Benin Formation.

V. CONCLUSION

The aim and objectives of the study were achieved. Several workers have carried out researches into many aspects of the geology, sedimentology, geochemistry, biostratigraphy, seismic stratigraphy and sequence stratigraphy of the Niger Delta area of Nigeria; however, most of the published and unpublished works lack integrated approach to the sequence stratigraphic interpretation.

Moreover, the principles and concepts of sequence stratigraphy and the prevailing schools of thought on the subject were discussed. Nevertheless, the discussion on the merit or demerit of the various approaches to sequence stratigraphy was avoided because it is outside the scope of this paper. The interpretation of well log responses (gamma-ray and resistivity logs) was confirmed with ditch cutting characteristics of sediments assessed using stereo-binocular microscopy. The well log patterns were used to delineate the sequences to different kinds of systems tracts. The identified sequence boundaries were found at the inflection of progradation to retrogradation of parasequences in a shallowing upward sand unit, and also at the inflection of the lowstand prograding complexes (lowstand systems tract). The higher gamma ray and lowest resistivity readings were used to identify maximum flooding surfaces, which were further established with biostratigraphic data. There are five wells studied in the area. From the faunal and floral abundance/diversity peaks (using the first and last down-hole occurrences), four maximum flooding surfaces dated 12.8 Ma, 11.5 Ma, 10.4 Ma and 9.5 Ma, and five sequence boundaries dated 13.1 Ma, 12.1 Ma, 10.6 Ma, 10.35 Ma and 8.5 Ma, respectively, were recognized. The fluctuation in specimens abundances have been established to reflect specimens' migration that has been linked to eustatic changes in sea level. There is a fault between Kafe-1-1 and Kafe-1-2

wells. The down-thrown side of the recognized growth fault is located at Kafe-1-2 well area, while the up-thrown side is at the Kafe-1-1 well area. In addition, there is another growth fault between Kafe-1-2 and Kafe-1-4 wells. The down-thrown side of this growth fault is located at the Kafe-1-4 well area, while the up-thrown side is at the Kafe-1-2 well area. Erosional truncation and downlap surfaces were prominent structures mapped in the seismic sections for sequence stratigraphic interpretation of the studied wells. The wells were drilled to the depths of 3,782.57 m (Kafe-1-1), 3,791.71 m (Kafe-1-2), 3,489.96 m (Kafe-1-4), 3,535.68 m (Kafe-1-5) and 3,962.40 m (Kafe-1-6).

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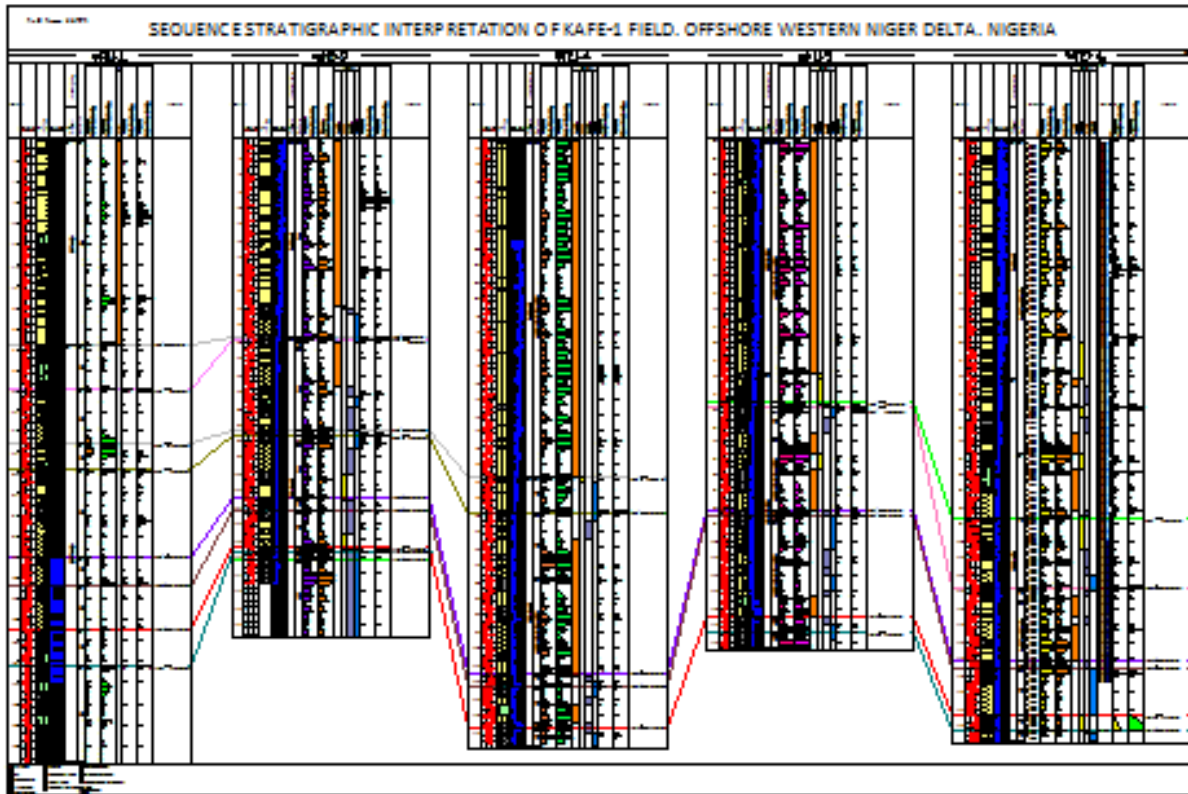


Fig. 4. Sequence stratigraphic and correlation chart of Kafel Field wells