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Facies Architecture Analysis for Paleo-environment Evaluation in "Tom" Oil Field, Eastern Niger Delta, Nigeria

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ABSTRACT: The cored section of reservoir C, well 4 of the drilled five wells that penetrated three reservoirs A, B and C in "TOM" oil field, Eastern Niger Delta was analysed and described on the basis of lithofacies, sedimentary structures and trace fossil records by using core data and wireline log motifs, with the aim of carrying out thorough geological core analysis to interpret the depositional environment of the oil field. The lithofacies are sandstones with interbedded mudstones and siltstones, the dominant sedimentary structures are parallel to ripple cross laminations, hummocky and swaley cross stratifications, sandy hetherolitics, planar to low angle cross bedding with traces of *Teichichnus* and *Ophiomorpha* burrows. The gamma-ray log motifs were noted and used to further constrain the character of the sedimentary facies and depositional environment of the field. A tidal incised – fluvial dominated shallow marine (lower, middle, upper shoreface) comprises of tidal channel sands and tidal flat of the coastal shelf depositional setting in the marginal marine mega depositional environment had been inferred for the "TOM" field.

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The Niger Delta is situated in the Gulf of Guinea and extends throughout the Niger Delta province. The Basin has been known as one of the world's most prolific petroleum producing Tertiary deltas (Selley 1997) and has been ranked the 12th largest known accumulation of recoverable hydrocarbons, with reserves exceeding 34 billion barrels of oil and 93 trillion cubic feet of gas (Tuttle *et al* 1999). From Eocene to the present, the Delta has prograded south-Westward, forming depobelts that represent the most active portion of the Delta at each stage of the development (Doust and Omatsola 1990). Ever since the commencement of commercial hydrocarbon production in the Niger Delta sedimentary basin by Shell-BP in 1958 (Weber, 1971), there has been an overwhelming concentration of exploration activities as well as scientific researches. The process through which sediment are deposited in river is a reflection of its dominant sedimentary features and structures that determines its depositional environment and characterized its reservoir qualities and hydrocarbon viability. Selley (1997) described the various depositional processes from fluvial, coastal, marine, turbidity current coupled with the rise and fall of sea – level that have determined the stratigraphic fill of the Niger Delta. The stratigraphy is divided into three diachronous unit of Eocene to recent age that forms a major regressive cycle. The Tertiary section of the Niger Delta is divided into three formations, representing prograding depositional facies that are distinguished mostly on the basis of sand-shale ratios. The type sections of these formations are described in Short and Stäuble (1967) and summarized in a variety of papers (e.g. Avbobvo 1978, Doust and Omatola 1990, among others). The Akata Formation at the base of the delta is of marine origin and is composed of thick shale sequences (potential source rock), turbidite sand (potential reservoirs in deep water), and minor amounts of clay and silt. Beginning in the Paleocene and through the Recent, the Akata Formation formed during lowstands when terrestrial organic matter and clays were transported to deep water areas characterized by low energy conditions and oxygen deficiency (Stacher 1995). Deposition of the overlying Agbada Formation, the major petroleum-bearing unit, began in the Eocene and continues into the Recent. The formation consists of paralic siliciclastics over 3700 meters thick and represents the actual deltaic portion of the sequence. The clastics accumulated in delta-front, delta-topset, and fluvio-deltaic environments. In the lower Agbada Formation, shale and sandstone beds were deposited in equal proportions, however, the upper portion is mostly sand with only minor shale interbeds. The Agbada Formation is overlain by the third formation, the Benin Formation, a continental latest Eocene to Recent

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deposit of alluvial and upper coastal plain sands that are up to 2000 m thick (Avbovbo 1978). Nton and Adeshina (2009) who investigated some aspects of structures and depositional environment of sand bodies within the Tomboy field, offshore part of the basin noted that the reservoir sands were deposited in different environments consisting of distributary channels, mouth bars, barrier island and tidal channels, and were deposited across normal growth faults and anticlinal structures.Omoboriowo *et al* (2012) who had integrated well logs and core data of the LEPA reservoirs penetrated by five wells drilled in Amaa field part of the Delta to investigate depositional environment and petrophysical characteristics of the part of the basin, revealed that the environment of deposition of the field lies within the marginal marine depositional environment, and comprise of tidal channels sands, distributary mouth bars, barrier island (lower, middle, and upper shorefaces) and near offshore (the shelf). Other researchers like Fidelis A. Ushie and Thomas A. Harry (2014), Prince Suka Momta *et al* (2015), and others also worked on the depositional environment of the Niger delta.

With the increasing demand of hydrocarbon products to meet global needs in the 21st century despite the fall in the global oil price there is however need for more research on the depositional environments of other fields with a view to increasingly support reservoir appraisal, development and thus optimize hydrocarbon production from the basin since depositional environment can ultimately affect reservoir qualities; hence the main objective of this research work is to qualitatively analysis the provided core photos and wireline log motif for the depositional environment interpretation of the field.

Geological Setting: The TOM oil Field (Figs.1 and 2) is located in the eastern Niger Delta province which comprises the eastern (or Atlantic) session of the coastal south-south Nigeria and stretches from the Akassa River eastwards to the Cross River area. The Niger Delta is a marginal sag basin located in the continental margin of the Gulf of Guinea in equatorial West Africa, covering an area of about 75,000km^2, with an average thickness of about 12km and lies between latitudes 3° and 6°N and longitudes 5° and 8°E (Knox and Omatsola 1989). It is bounded in the west - northwest by the Okitipupa Hinge line; in the north by the Benin Flank; in the northeastern part by the Abakaliki High; and in the east – southeastern part by the Calabar Flank while the offshore boundary of the province is defined by the Cameroon volcanic line to the east; and the two kilometre sediment thickness contour or the 4000 – metre bathymetric contour in areas where sediments is greater than two kilometre to the south and southwest (Corredor *et al* 2005). The formation of the basin has also been related to the separation of Africa from South America and the consequent opening of the South Atlantic in Mid Cretaceous times (Evamy *et al* 1978; Doust and Omatsola 1990).

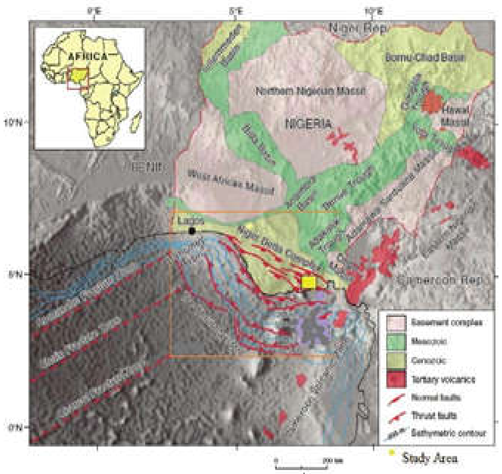

Fig 1: Location map of the Study Area (After Corridor *et al*, 2005)

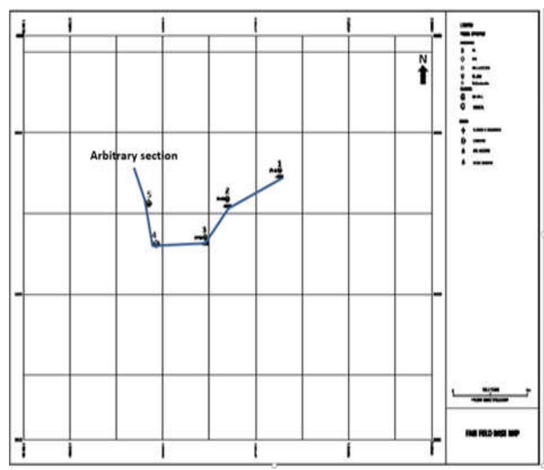

Fig 2: Base Map of the study Area

MATERIALS AND METHODS

The core photographs (1 – 9) of the reservoir of the well 4 provided were studied and described from bottom to top. The visible facies characteristics observed on the photos particularly, the lithology, sedimentary structures (cross bedding, lamination and bioturbation) and geological succession were studied.

Based on these, lithofacies types and associations were determined and interpreted. From the composite log suite provided, the shapes of gamma ray log were noted and further used to constrain the character of the sedimentary facies and depositional environment based on the views of Scholle and Spearing (1998) and Coleman and Prior (1980).

The gamma ray log motif for the cored section was used to calibrate and constrain the interpretation for the uncored section.

RESULTS AND DISCUSSION

Geological Core Analysis: Three reservoirs A, B, and C were delineated in the TOM oil Field from the data set provided. These were correlated across five wells (Fig.3) of which only well 4 which lies within 12863.4 – 13441.0ft. (3920.8 – 4096.8m), of reservoir C with average thickness of 295.42ft (90.04m) was cored and described from bottom to top on the basis of lithofacies and sedimentary structures.

Core 1, Reservoir C, Well 4 (13435.0 – 13441.0ft. or 4095.0 – 4096.8m): This core (Fig.4) is characterized by moderate to intensely bioturbated hummocky and swaley cross stratification sandstone with interbedded siltstone. The fine grained sandstone and the interbedded siltstone have been heavily bioturbated with some intervals completely reworked. It has brownish to dark well sorted ripple cross laminated sands. Though the ripple cross laminations have been nearly complete obliterated by bioturbation, the relicts can be seen at a closer look.

This section on the gamma-ray log (fig.3) shows a serrated funnel shape and exhibits a coarsening - upward grain size profile. The presence of lamination units is indicative of cyclic changes in supply of sediment during deposition.

The changes were probably to have occurred in clay percentage, microfossil content, organic material content, or mineral content that often resulted in pronounced differences in colour between the laminae. Lamination develops in fine grained sediment when fine grained particles settles, which can only happen in quite water environment (Blatt *et al 2006,* and Boggs S. JR. 1987).

The intensely bioturbated units is indicative of reduced sedimentation rates on a low energy or more slowly prograding shoreface. The hummocky cross stratification is a reflection of sedimentation under storm waves in the outer shoreface and transitional zone between fair weather wave base and storm wave base (Yagishita *et al* 1992, Monaco 1994, Tucker 2003). It is interpreted that this facies is deposited in the lower shoreface environment.

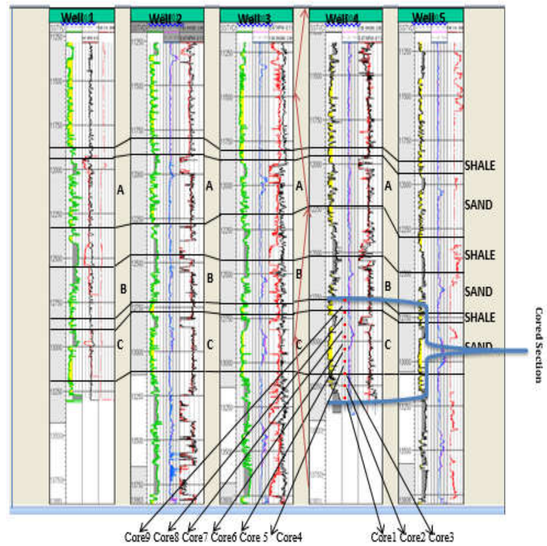

Fig 3: Correlation of Reservoir Sands in TOM Oil Field

Core 2, Reservoir C, Well 4 (13313.0 – 13319.0ft. or 4057.8 – 4059.6m): This core (fig.4) is characterized by moderate to intensely bioturbated hummocky and swaley cross stratification sandstone. The hummocky and swaley cross bedding, though has been strongly obliterated by bioturbation, however the relicts can be observed at a closer look, particularly at the upper section of the core. There are observable large traces of *Ophiomorpa* burrows with the intensity of the burrows increases up section and are somewhat mottled with dark organic material. On the gamma-ray log (fig.3) this section shows a serrated funnel shape and exhibits a coarsening – upward grain size profile. The intensely bioturbated units is indicatives of reduced sedimentation rates on a low energy, or more slowly prograding shoreface. The presence of hummocky and swaley cross bedding is indicative of fine grained, well sorted sands deposited by storm waves in the outer shoreface and transitional zone between fair weather wave base and storm wave base. The presence of *Ophiomopha* reflects a well oxygenated and nutrient rich setting which are commonly found within the shoreface environment, particularly at the Lower – Midde Shoreface environment (Frey *et al* 1978, Boggs 2001, Mude 2011). It is therefore interpreted that this facies is deposited in the lower – middle shoreface environment.

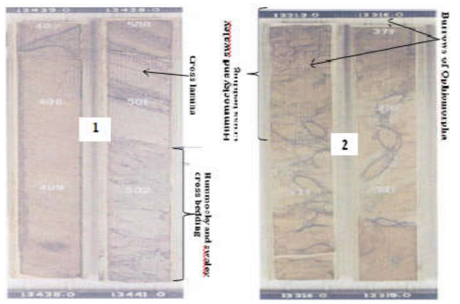

Fig 4: Cores 1 & 2, reservoir c, well 4

Core 3, Reservoir C, Well 4 (13235.0 – 13241.0ft. or 4034.0 – 4035.9m): This core (fig.5) is characterized of mudstone with siltstone and very fine sandstone intervals. It is predominantly dark coloured mudstone at the top and grades into fine grained silty sandstone at the lower section. There are preservation of thin laminations like parallel laminations, wave laminations, current ripples laminations, streaks of very fine silty sandstone laminae within mudstone, and the ripple lamination of the silty sandstone below the mudstone facies. It is so depleted in bioturbation which may indicate prevalence of anoxic condition during sedimentation. On the gamma-ray log (fig.3) this section shows a serrated finning – upward grain size profile thus suggested a tidal influenced stacked channel fill. The fine grained nature is an indicative of low energy depositional condition where suspension fallout dominated the depositional process. It should however be noted that mudstone, siltstone and sandstone are the most commonly characterized sedimentary rocks of the tidal flat in the transitional environment, and lamination as one of the dominant sedimentary structures, It is therefore interpreted that this facies is deposited in the tidal flat of the coastal shelf environment. According to Stutz and Pilkey (2002), Schmalzer (1995) and Dyer *et al* (2000) who had written that tidal flats comprising only about seven per cent (7%) of the total coastal shelf areas and can be found between mean high-water and mean low-water spring tide datums, and are generally located in estuaries and other low energy marine environments.

Core 4, Reservoir C, Well 4 (13054.0 – 13060.0ft. or 3978.9 – 3980.7m): This core (fig.5) is characterized by laminated, bioturbated, hummocky and swaley cross stratification, heterolithic sandstone with interbedded mudstone. It consists of fine to very fine grained and well sorted laminated sandstone with interbedded mudstone. The degree of bioturbation increased from bottom to top with visible traces of Teichichnus and Ophiomorpha burrow. On the gamma-ray log (fig.3) this section shows a serrated funnel shape and exhibits a coarsening – upward grain size profile. The presence of ripple cross laminations indicate bedforms of the lower flow regime that reflects agitation by water current or waves. Lamination in sandstone is often formed in a coastal environment where wave energy causes a separation between grains of different sizes (Monroe *et al* 1997, Potter, Pettijohn 1977, Blatt *et al* 2006, Boggs 1987, Boggs 2006). The interbedded mudstone reflects fair weather deposition which may depict the later stage of sediment fallout after high energy sedimentation. The heterolithic nature suggests sedimentation in alternating suspension fallout and bed-loads within a low energy setting below wave-base (Monta and Essien 2016). It is interpreted that this facies is deposited in the lower shoreface environment.

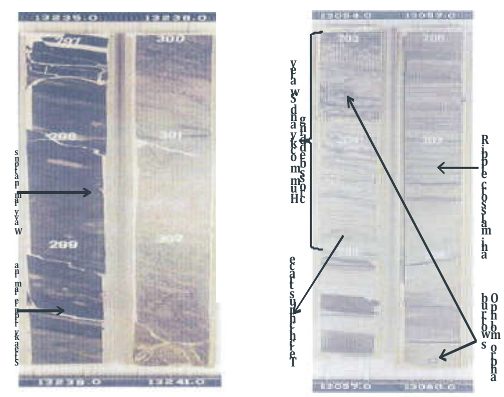

Fig 5: Cores 3 & 4, reservoir c, well 4

Core 5, Reservoir C, Well 4 (13022.0 – 13028.0ft. or 3969.1 – 3970.9m): This core (fig.6) is characterized by bioturbated hummocky and swaley cross stratification interbedded sandstone and mudstone, with traces of Teichichnus and Ophiomorpha burrows. It is predominantly of well sorted fine grained sandstone to dark grey mudstone. The very fine grained sandstone and the mudstone interbeds reflects deposits of fair weather which may depict the later stage of sediment fallout after the high energy sedimentation. The intense bioturbation of the core caused partial to complete obliteration of the sedimentary structures. The presence of *Teichichnus* traces depict inchnofacies found within Lower Shoreface, Lagoons, Bays and brackish water coastal/shallow marine environment, and the presence of interbedded mudstone is an indicative of low energy sub-aqueous deposit within delta. It is interpreted that this facies is deposited in the lower shoreface environment.

Core 6, Reservoir C, Well 4 (12965.0 - 12971.0ft. or 3951.7 – 3953.6m): This core (Fig.6) is characterized by parallel, ripple cross laminated sandy heteroliths, planar to low angle cross bedded sandstone. On the gamma-ray log (fig.3) this section shows a serrated funnel shape and exhibits a coarsening-upward grain-size profile thus indicative of interbedded sand and shale deposition with sand to shale ratio increasing upwards. The presence of parallel to ripple laminated sandy heteroliths suggests deposition in tidally influenced subaqueous environments under fluctuating flow conditions (Nwachukwu *et al* 2011). Such environments are often characterized by high flow velocity (caused by high tidal action) alternating with slack water stage during period of low tidal influence. Deposition of sand is favoured during period of high tidal current with high flow conditions whereas, at low tide, energy is weak and therefore favours shale or clay deposition (Archer and Kvale 1989, Hettinger 1995, Shanley *et al* 1992). Although such settings may range from coastal to deep marine (Boggs 2001, sheikh *et al* 2006, Roberts 2007), however, the presence of low angle cross bedding, couple with other characteristics suggests its deposition in middle to upper shoreface environment.

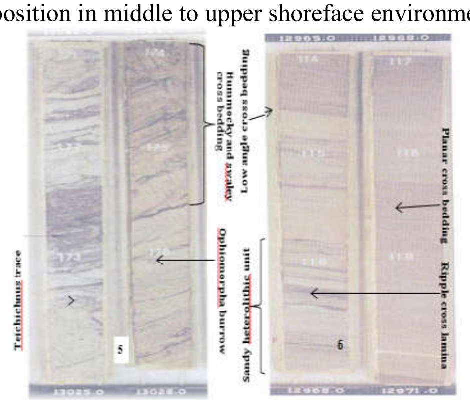

Fig 6: Cores 5 & 6, reservoir c, well 4

Core 7, Reservoir C, Well 4 (12936.0 - 12951.0ft. or 3942.9 – 3947.5m): This core (fig.7) is characterized by ripple cross laminated, planar cross bedding, sandy heterolithic fine grained sandstone with interbeded mudstone and siltstone. The degree of bioturbation is low with visible traces of <u>*Teichichnus*</u> in the lower section of the core. The upper section (12936.0 – 12939) exhibits grain size uniformity with no evidence of bioturbation. The grain size increases upward from dark grey mudstone into fine brown sandstone. The ripple laminations depict bedforms of the lower flow regime that indicates agitation by water current or waves (Monroe *et al* 1997, Potter, Pettijohn 1977, Boggs 2006). The presence of gradational contact between the upper shoreface sequence and the underlying lower shoreface couple with other characteristics suggests its deposition in lower to upper shoreface environment.

Core 8, Reservoir C, Well 4 (12906.0 - 12909.0ft. or 3933.7 – 3934.7m): This core (fig.7) is characterized by bioturbated parallel to ripple cross laminated fine grained heterolithic sandstone. The parallel to ripple cross laminated sandstone is overlain by intensively bioturbated sands in which the degree of bioturbation tends to completely obliterate the sedimentary structures. On the gamma-ray log (fig.3) this section shows a serrated bell shape and exhibits a finning – upward grain size profile, thus suggested a tidally influenced channel filled with sand to shale ratio decreasing upward. It is interpreted that this facies is deposited in the lower shoreface environment comprises tidal channel sands. It should however be noted that (Dean R.G 1987, Cowell *et al* 1999, Masselink G and Huges M.G 2003, Aagaard T and Masselink G 1999) had written that though sediment transport on the beach and shoreface are dominated by waves and wave induced current, however tidal currents may be locally important near tidal inlets and estuaries, where the tidal current in a tidal inlet on a coastline is responsible for the exchange of sands between the littoral zone and the lagoon.

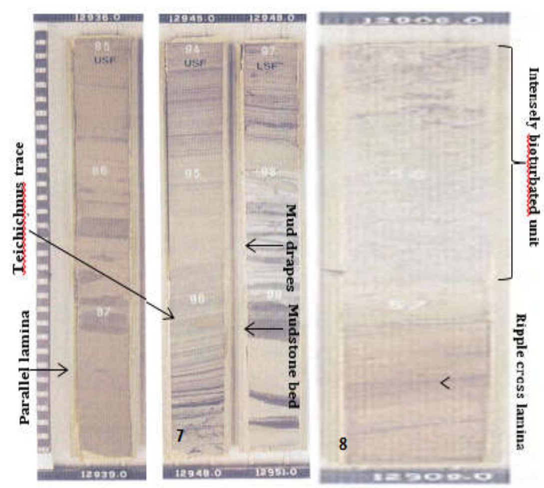

Fig 7: Cores 7 & 8, reservoir c, well 4

Core 9, Reservoir C, Well 4 (12863.4 - 12866.4ft. or 3920.8 – 3921.7m): This core (fig.8) is characterized by fine grained, intensely bioturbated grey to dark grey sandstone.

The high degree of bioturbation had strongly obliterated the lamination of this facies but the relicts can be observed at a closer look. On the gamma-ray log (fig.3) this section shows a finning – upward grain size profile that indicates interbedded deposits of sand

and shale with sand to shale ratio decreasing upward, thus suggested a tidal influenced stacked channel fill. The characteristics of this core couple with it association with core 8 suggests a tidal channel sands associated with lower shoreface environment

Table 1: Summary of geological core analysis of the TOM field [The missing depth intervals are due to depth shift between the core and the wireline log (GR)]

Core	Depth in feet (ft.)	Depth in metre (m)	Lithology	Characteristics	Sedimentary structures	Depositional environment
9	12863.4-12866.4	3920.8-3921.7	Sandstone	Grey to dark grey coloured, intensely bioturbated, fining upward	Laminations	Tidal channel sands associated with lower shoreface
8	12906.0-12909.0	3933.7-3934.7	Sandstone	Fine grained, intensely bioturbated in the upper section, fining upward, tidally influenced channel	Ripple cross laminations, sandy heterolithic	Lower shoreface comprises tidal channel sands
7	12936.0-12951.0	3942.9-3947.5	Sandstone with interbedded mudstone and siltstone	Low degree of bioturbation, trace of *Teichichnus* , coarsening upward	Sandy heterolithic, ripple cross laminations, planar cross bedding, gradational contact between upper and lower shoreface	Lower-upper shoreface
6	12965.0-12971.0	3951.7-3953.6	Sandstone	Coarsening upward grain size profile	Parallel to ripple cross laminated heterolithic, planar to low angle cross bedding	Middle-upper shoreface
5	13022.0-13028.0	3969.1-3970.9	Interbeddedsandstone and mudstone	Well sorted, very fine grained, intensely bioturbated with visible traces of *Ophiomorpha* burrows and *Teichichnus*	Hummocky and swaley cross stratification	Lower shoreface
4	13054.0-13060.0	3978.9-3980.7	Sandstone with interbedded mudstone	Fine to very fine grained, well sorted, bioturbated with traces of *Teichichnus*, coarsening upward	Hummocky and swaley cross stratification, laminated heterolithic	Lower shoreface
3	13235.0-13241.0	4034.0-4035.9	Mudstone with intervals of siltstone and very fine sandstone	Predominantly dark coloured, depleted in bioturbation, fining upward	Laminations	Tidal flat of the coastal shelf environment
2	13313.0-13319.0	4057.8-4059.6	Sandstone	Moderate to intensely bioturbated, fine grained and well sorted, large traces of *Ophiomorpha* burrows, coarsening upward	Hummocky and swaley cross stratification	Lower-middle shoreface
1	13435.0-13441.0	4095.0-4096.8	Sandstone with interbedded siltstone	Moderate to intensely bioturbated, fine grained, well sorted brown to dark grey coloured, coarsening upward	Ripple cross lamination, hummocky and swaley cross stratification	Lower shoreface

Depositional Environment Architecture: The environment of deposition of the TOM oil field had been proposed by this research to be a tidal incised - fluvial dominated shoreface (lower, middle, upper) comprising of tidally influenced channel sands and tidal flat of the coastal shelf depositional setting of the marginal marine mega depositional environment (fig.9) based on core description and well logs interpretation. Omoboriowo *et al* (2012) and Boggs (2006) had written extensively on Shoreface depositional settings in their separate books. While Omoboriowo described the depositional environment of Amaa field part of Niger Delta to have lied within marginal marine environment and comprises of tidal channels sands, distributary mouth bars, barrier island (lower, middle, upper shoreface) and near offshore (the shelf), Boggs (2006), summarized shoreface depositional environment as one that extends from mean low-tide level on the beach to the lower limit of fair-weather wave base, with its division into upper, middle, and lower shoreface corresponds roughly to the surf zone, breaker, and outer shoaling zones, with each zone characterized by distinguished faciese, that served as guides in naming the depositional environments of the various facies in this research. Hence; the Gross Depositional Environment (GDE) of the "TOM" field was interpreted as ranging from coastal setting to shallow marine by using similar gamma-ray log motif in the cored section as constraint and calibration for the uncored section. It should however be noted that the gamma-ray log motif of the five wells used in this study shows succession of stacked channels interbedded by marine shales and are therefore indicative of deposition by transgressive and regressive phases of the delta build up.

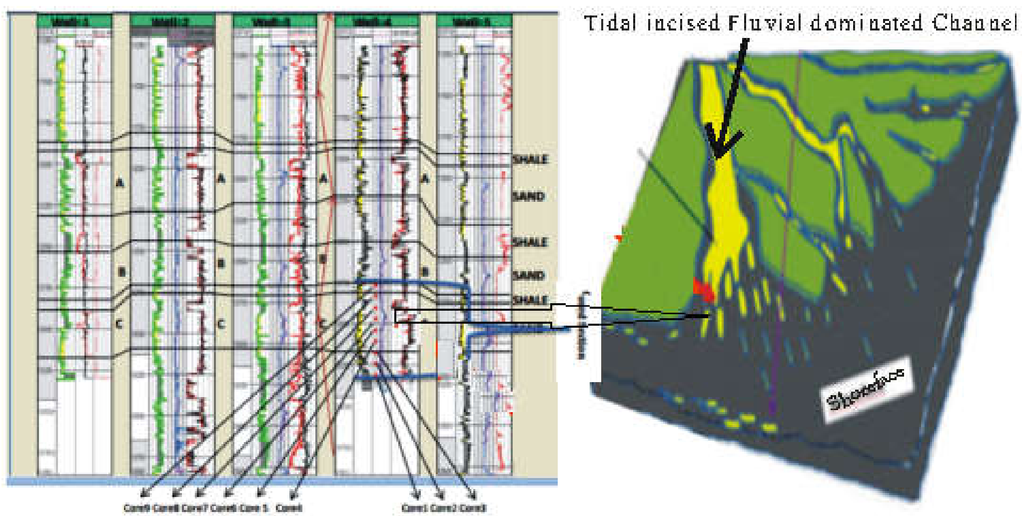

Fig. 9. Conceptual depositional model of Tom oil Field

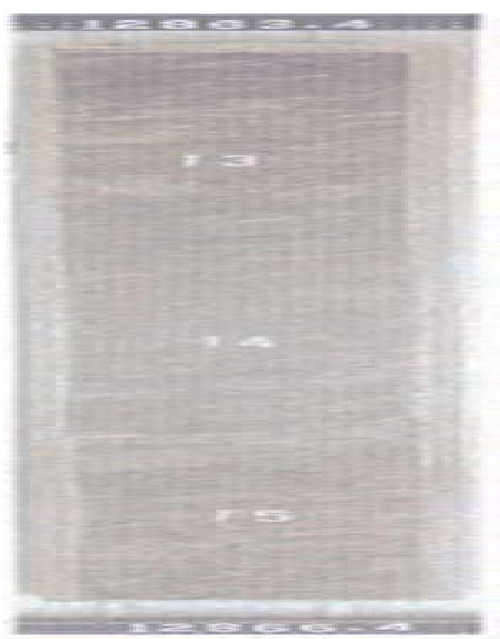

Fig 8: Core 9, reservoir c, well 4

Conclusion: The study area "Tom" oil field is interpreted to have deposited under fluvial dominated condition associated with tidal influence in the shallow marine (lower, middle, upper shoreface) of the coastal shelf depositional setting in the marginal marine mega depositional environment. The study recommends that further study be carried out on the petrophysical evaluation, thin-section petrographic characterization, and clay mineralogy studies of the delineated reservoir sandstone to determine the reservoir quality and as well accessing the seal potentials.

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