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SEQUENCE STRATIGRAPHY AND TECTONIC FRAMEWORK OF THE GABO FIELD, NIGER DELTA, NIGERIA

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ABSTRACT

This research examines the sequence stratigraphic and structural framework of the Gabo Field Niger Delta, Nigeria. Materials used in this research include 3D seismic volume in Seg-Y, ditch cuttings and wells logs. The methods applied are standard methods in addition to using the Frazier and Galloway approach for genetic sequences. The tectonic framework was interpreted in terms of deformational, depositional and post-depositional structures. The deformational structures are faults F1 and F2 – which are closely spaced normal faults and F3 is a syn-depositional growth fault. The depositional structures are pinchouts and interbedded sand/shale sequences whereas the post-depositional structures are compaction and smearing or flexure of the shales. The well correlation shows the sequences are cyclic and the facies analysis of T4 – T9 sands are very fine to medium grained, light to dark brown, texturally mature and moderate to well sorted. The facies associations are fluvial distributary channel, tide dominated fluvial channels, abandoned channel or switching and flood plain deposits. While the depositional environments are upper delta plain, lower delta plain and delta front. Sequence stratigraphic analysis explained the observed increase in shale thickness in the intermediate sections and showed sediment deposition occurred in three (3) systems tracts- Lowstand Systems Tract (LST), the Transgressive Systems Tract (TST) and Highstand Systems Tract (HST). The sedimentological model showed the environments of deposition had a tidal influence and ranged from fluvial to estuarine. The findings of this research may be applied to similar deltaic basins around the world in planning of oilfield development. In addition it may correlate cyclic successions and predict facies distributions of similar depositional patterns.

Keywords: sequence, environments, transgressive

INTRODUCTION

The Niger Delta and similar deltaic environments around the world have cyclic sedimentation of successive sand and shale sequences with these cyclic successions reflected in the vertical profile of wells drilled. Facies analysis of these successions reflect the lateral shifts in the environments of deposition. This depositional belt (Niger Delta) reflects an important shift in the paleo-coastline of the delta as sediments continuously moved into the Atlantic Ocean. A review of previous studies in the Gabo Field shows that Agbasi *et al.*, (2021) presented a well-scale geomechanical model of the field to address the pore pressure, borehole stability and fault slip potential attributes whereas Nduaguibe and Ideozu (2019) focused on the controls of depositional environments on reservoir quality in terms of porosity and permeability. In their research, they used results from well logs, core photos and grain size analysis to interpret the environments of deposition. They interpreted the facies associations as predominantly channel and coastal barrier systems while the environments of deposition are distributary channel, upper and lower shoreface environments. The data analysis did not take in to consideration the sequence stratigraphy and tectonic framework (post-depositional framework) of the Gabo Field and this research seeks address the observed increase in shale thickness in the intermediate to deep sections of the field. Didei and Akana (2016) looked at the source rock maturation using vitrinite reflectance and geothermal data from six wells in the Gabo and Wabi fields, onshore Niger Delta, Nigeria while Etimita (2015), carried out the study of reservoir characterization of the G900 sandstones using wireline logs and cores. According to Catuneanu, (2006), a sequence is a fundamental stratal unit of sequence stratigraphy which corresponds to a depositional product of a full cycle of base-level changes or shoreline shifts depending on the sequence model being employed. Miall, (1999), described sequence stratigraphy as a set of predictions that can be made about facies and architecture of sediments formed in a particular range of environments under specific allogenic controls. The allogenic controls are climate (related to clastic supply), tectonics (related to basin uplift/subsidence) and rate of eustatic sea-level change. The sequence stratigraphic succession of the Delta is the result of the different changes in sea levels and clastic supply of sediments by the fluvial transport and discharge. According to Reijers, (2011), delta- wide genetic sequences as defined by Frazier, (1974); Galloway (1989) and which consists of strata bounded by maximum flooding surfaces at the top and transgressive shales at the bottom are readily identifiable in the Niger Delta when compared to other sequence models. The aim of this research is to analyze the tectonic framework and sedimentation pattern and present a knowledge gap perspective of the Gabo Field. The significance of this research is that, the results may be used as a modern analogue to correlate similar deltaic successions and predict facies distributions of similar depositional patterns.

Geologic setting

The geology of the Niger Delta has been discussed by various workers since exploration and finding of commercial hydrocarbon began in the 1950s (Jev *et al.,* 1993). Documentations of the geology including origin, tectonics and stratigraphic framework, have been discussed in details by Evamy *et al.*(1978), Doust and Omatsola, (1990), Kulke (1995), Reijers (2011), Ekweozor and Daukoru (1984) amongst others. The ages of the sedimentary deposits of the Niger Delta range from Eocene to Recent (Short and Stauble, 1967). The Niger Delta is located on the passive margin of western Africa, and has been recognized as a typical example of a continental-margin structural collapse under sediment loading (Magbagbeola and Willis, 2007). According to Kayode (2012), the sedimentary fill is about 12,000metres with sub-sea areas reaching up to 75,000km^2 and extends above 300km from apex to open sea. The delta is a low gradient characterized by a southward tapering profile of a low-angle depositional ramp with high sedimentation rates across a mud-rich slope (Totalenergies, 2021). One characteristic feature of the Niger delta is that it supplies sediments very rapidly more than it can redistribute by basinal processes (wave and tide). In addition, it is characterized by multiple distributary channels that branch from the river Niger Benue system with its sediments influenced by river processes (Fisher *et al.,* 1969; Elliott, 1986; Hudson, 2005). The Niger Delta has been classified as an arcuate shaped wave, tide and fluvial dominated deltaic system (Jev *et al.,* 1993; Magbagbeola and Olayinka, 2019) with processes (fluvial and basinal) at the river mouth resulting to the sorting and deposition of the fluvial bedload. As a result of thermal cooling of the lithosphere, the Niger Delta subsided gradually with increased sediment loading, flexed in a seaward direction (Reijers, 2011). Studies by Evamy *et al.,* (1978); Doust

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and Omatsola, (1990); Reijers, (2011) recognized the stratigraphy of the Tertiary Niger Delta and grouped them into three main units/formations - the Benin, Agbada and Akata Formation with ages ranging from Paleocene to Recent (Reyment 1965; Short and Stauble, 1967). This grouping represent the prograding depositional sequence based on the characteristics of their sand-shale ratios.

Figure 1: Location of the Gabo Field, Western Niger Delta. This represents a satellite image of the field.

The Niger Delta reservoirs and seal facies associations

According to Abrakasa, (2020), the reservoir is a component of the petroleum system that serves as storage facility for the accumulation of hydrocarbon. The reservoirs are a function of the prevailing environment and clastic supply at the time the sediments were deposited. The reservoir rocks of the Niger delta are predominant in the Agbada Formation. It is believed that hydrocarbons expelled from the mature source rocks of the Akata formation migrate (vertically upwards and laterally) into the reservoir sands of the Agbada formation. The facies and reservoir properties of these formations are largely influenced by the paleo-environment of deposition and depth of burial. The reservoir sands of the Niger Delta range from the fluvial channel sands, distributary mouth bar sands, barrier bar sands, beach, point bars to the deep water turbidite sands (Figure 2) (Kulke, 1995). These reservoir sands (facies) may show variable grain sizes, sorting and grain packing. They are believed to have good to excellent reservoir qualities (porosity and permeability). A seal is a rock unit that has the ability to impede the continuous migration of a fluid (hydrocarbon) thereby forming a trap. Similarly, the paleo-environments of deposition have an influence on the accumulation of fine grain source rocks and seal facies in the Niger Delta. The inter-distributary sub-environments (flood plains, swamps, tidal flats), continental shelf and marine settings are the most important environments for the accumulation of source rocks and seal facies associations (Elliot, 1986). These environments are widely believed to be the source of seal facies in the Niger Delta. According to Elliot, (1986) sedimentation in the inter-distributary sub-environments is predominantly by flooding and tidal ranges and this provides an enabling environment for vegetation and the formation of sealing rocks e.g. kaolinite, gypsum and halite precipitation, calcrete development, depending on the prevailing climate.

Tectonic framework of the Niger Delta

According to Reijers, (2011), the evolution of the Niger delta is controlled by pre- and syn-sedimentary tectonics as described by Evamy *et al.* (1978), Ejedawe (1981), Knox and Omatsola (1987) and Stacher (1995). This shows the relationship between the different structural belts of the delta and is discussed in detail by Wu and Bally, 2000; Corredor *et al.*, 2005; Olga *et al.*, 2008 among others. According to Wu and Bally, (2000), the Niger Delta can be described as a classical shale tectonics province. High volume of shale in deltaic sediments influences the deformational patterns. The instability and constant motion of the shales in response to the weight of overlying sediments results in the development of different structural styles found in the different depositional belts of the Niger Delta (Evamy *et al*, 1978; Doust and Omatshola 1990; Stacher 1995; Aminu and Olorunniwo, 2012). The instability of the muds may persist through burial. These structural styles can be seen in the entire Agbada formation and they flatten into detachment planes near the top of the Akata formation (Abija, 2019). According to Ugwueze, (2015) deformational structures readily recognized in the Niger Delta include syn-sedimentary growth faults, simple and complex roll-overs faults with anticlinal crests. These faults can be grouped together to form macro and mega structures. According to Ekweozor and Daukoru, (1984), the Akata shales are typically undercompacted, immature and ductile, as such, frequently move, and smear up and down along growth structures, as a result of the lithostatic pressure of compacting sediments. According to Elliot, (1986), deltaic facies pattern may be significantly influenced by syn-sedimentary deformation (growth faults) nucleating in small to large scales. According to Xiao and Suppe, (1989), growth normal faults are widely observed to be listric (concave upward or, literally, shovel shaped) and are readily found in the Niger Delta and similar environments. This type of deformation may also be related to basement tectonics. Sedimentary factors influencing this type of deformation originate from the rapid deposition of unstable muds in the distal to mid-delta front and continental slope environments. These syn-sedimentary growth faults and other features are readily found in the Niger Delta and similar deltaic basins around the world (Weber, 1971; Evamy *et al*, 1978; Doust and Omatsola, 1990; Kulke, 1995; Reijers, 2011; Ekweozor and Daukoru, 1984).

MATERIALS AND METHODS

Materials

Data used for this research was acquired from one of the multinational oil companies operating in Nigeria through the permission of the Nigeria Upstream Petroleum Regulatory Commission (formerly, the Department of Petroleum Resources - DPR). The data provided include; 3D seismic volume in seg-y, ditch cutting samples and wells data.

Method of research

The method of data analysis range from reservoir modeling, well correlation, ditch cutting examination, facies analysis and inferring the environments of deposition.

Building the structural model was the first step in the evaluation of the deformation, depositional and post-depositional framework. Seismic data is measured in two-way travel time, which is the time it takes for an acoustic wave to travel to a reflector and return to the receiver (Cannon, 2018) thus, faults were picked from the seismic volume in time (ms) and converted to depth (m). The deformational, depositional and post-depositional features were captured by integrating the depth-converted seismic horizons and depth converted fault sticks. The juxtaposed strata relationships were analyzed by taking cross sections $A\text{-}A^1$ and $B\text{-}B^1$.

The sequence models of Galloway (1989) and Frazier (1974) for genetic sequences was adopted to explain stratigraphic observations on the well logs. The well correlation defined the genetically related surfaces. This showcased the erosive events, pinchouts or abandonment or switching, stratigraphic dip directions and well offsets. The facies analysis captured the reservoir architecture and variability based on well log data and sedimentological analysis of the ditch cuttings.

A facies model should always honour the Walther's law of superposition, which states

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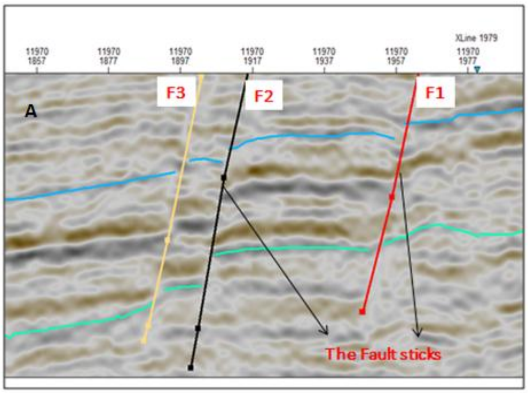
that within a relatively conformable succession of genetically related strata, vertical shifts in facies reflect corresponding lateral shifts of facies (Catuneanu, 2006). Attempt was therefore made to predict the sedimentary processes, facies associations and reconstruction of their environments of deposition. The sequence stratigraphic predictions became necessary to explain observed trends on the vertical profiles of the well logs. This was achieved by recognizing intervals bounded by maximum flooding surfaces at the top and transgressive shales at the base.

RESULTS AND DISCUSSION

Tectonic framework of Gabo Field

The results of this research is presented in Figures 2 – 8 and Table 1. An overview of the entire structure shows a southward sloping profile of a low-angle depositional ramp (Figure 2 and 3) (TotalEnergies, 2021). Most deltas usually require a basin, and some form of subsidence for sediment maturity. Basin subsidence is as a result of crustal stretching of plate boundaries and this leads to increase in heat flow which supports the maturation of petroleum source rocks (Miall, 1999; Allen and Allen, 2005). The structural framework of the Gabo Field shows the relationship between the deformational, depositional and post-depositional frameworks (see also Figure 3). Three faults were recognized labeled F1, F2 and F3 (Figure 2a, 3 and 4). Cerveny *et al.*, (2004), defined a fault as “a planar discontinuity, or damaged plane, in a rock mass along which there is observable displacement, or slip”. The deformational structures identified are faults F1 and F2 which are closely spaced normal faults and shows anticlinal (asymmetrical) crest (Figure 5) (Corredor *et al.*, 2005; Olga *et al.*, 2008; Ugwueze, 2015). This may have resulted from brittle failure of the sandstones and is an indication of an extensional environment. According to Haywick, (2008), brittle failure is predominant in shallow settings of the earth crust where confining pressures are relatively low. The faults F3 is interpreted as a syn-depositional growth fault with thick sedimentation on the down thrown block, as a result there may be an uneven distribution of the sediment load (Figure 2). These faults may have segmented the field into separate compartments. The depositional structures identified are pinchouts (abandonment or switching) and interbedded sand/shale sequences (Figure 3). The pinchouts may be as a result of an abandoned fluvial channel while the sand/shale sequences are best explained bearing in mind the sequence stratigraphic frame work of the Niger Delta. The post-depositional structures identified are compaction, bending, flexure or smearing of shales (Figure 4). These post-depositional structures may have resulted from ductile failure and is predominant in soft rocks that have a high tendency to flow (Haywick, 2009). These structures may also be explained from a diagenetic view point (Syed *et al.*, 2010). They are surface expressions of the overpressured or undercompacted shales and may be responsible for the mild asymmetrical folds (Figure 6 and 7) (Elliot, 1986; Haywick, 2009). Compaction is a prominent process response of diagenesis and the results of this process are the inefficient dewatering of sediments, reduction in stratigraphic thickness, formation of sedimentary rocks, increase in bulk density of the shales, pore pressure enhancements (confining pressures), loss of porosity and permeability (reservoir quality and heterogeneity). Rapid sedimentation in the delta may have resulted to overpressuring, smearing and undercompaction of the ductile clays (Figure 5). These conditions when met usually generate series of diapiric traps and roll-over anticlines (symmetrical and asymmetrical) (Evamy *et al.*, 1978, Ejedawe, 1981; Knox and Omatsola 1987; Stacher, 1995; Ugwueze, 2015).



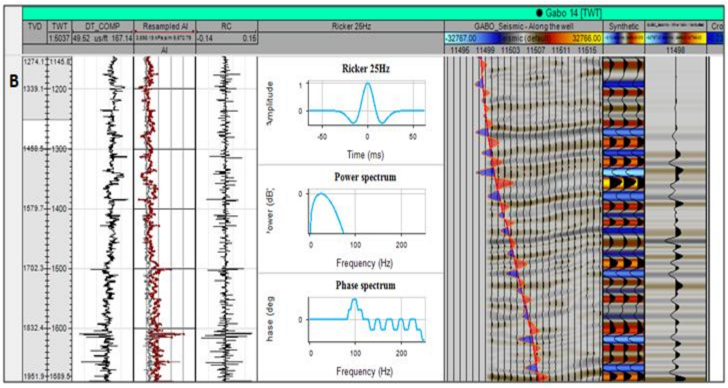


Figure 2a: The seismic section showing the fault relationships
Figure 2b: Result of the synthetic seismogram showing mis-tie points at well location

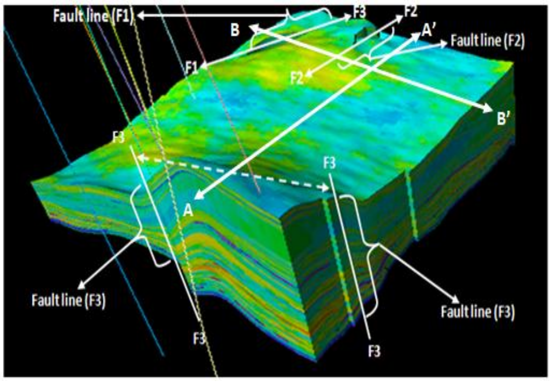


Figure 3: The Gabo Field in 3D with intersection slices A-A' and B-B'.

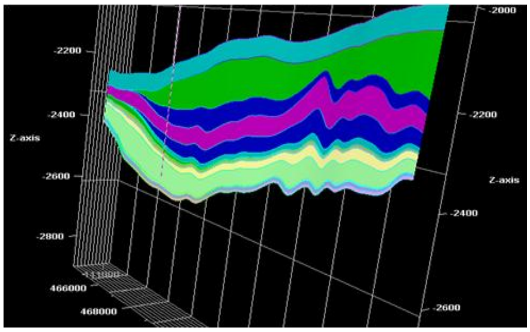


Figure 4: Cross section A-A' across the field, showing evidence of pinchout, differential compaction and smearing of the shales.

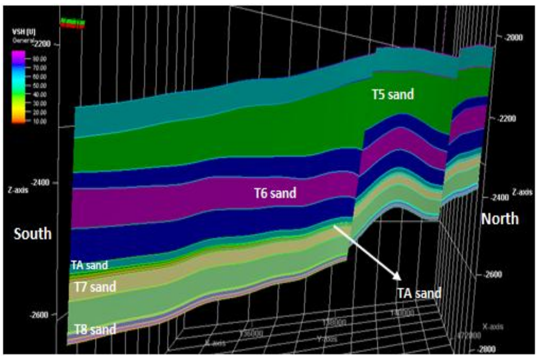


Figure 5: Cross section B-B' showing reservoirs stacked in a conventional delta play trapping system – closely spaced normal faults, juxtaposed strata and asymmetrical crest.

Sedimentation in Gabo Field

Sedimentation in the Niger Delta is influenced by the Niger-Benue river discharge (since most of its sediments are transported by the Niger-Benue river system) and basinal processes (wave and tide) at its mouth (Elliot, 1986; Miall, 1999). The stratigraphy of the Gabo Field from well logs suggest a cyclic succession of sands and shales at the top while the shale thickness appeared to have increased in intermediate to deeper sections (Figure 6 - 8). This observation has wide implications for hydrocarbon prospects of the field. The facies analysis of the T4 – T9 sands are very fine to medium grained, light to dark brown, texturally mature and moderate to well sorted (Table 1.0). The facies descriptions/analysis was used to gain understanding of the sediment response attributes (texture, grain size) and facies associations that may have environmental significance. The character of the sediments is a reflection of the processes that prevailed during its transport, deposition and the duration through which such conditions prevailed. The facies associations were interpreted as fluvial distributary channel, tide dominated fluvial channels, abandoned channel or switching and flood plain deposits. This indicates that the fluvial

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bed load (sand, silt and clay) was deposited in an alternating high and low energy regimes and transport mechanism was predominantly traction (bouncing and rolling) and suspension respectively (Table 1.0). The depositional environments are interpreted as upper delta plain, lower delta plain and delta front.

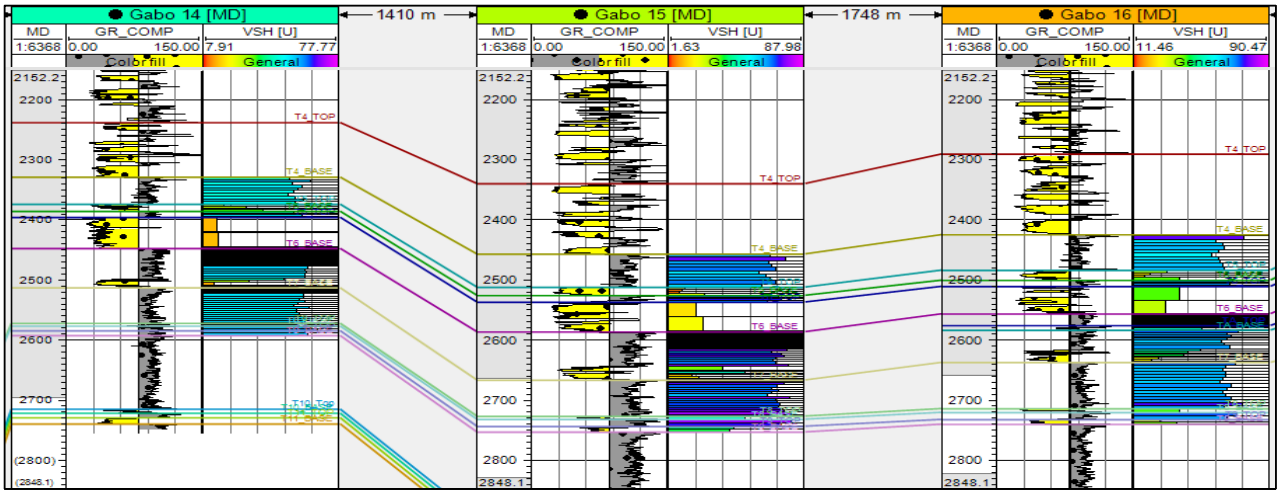

Figure 6: Result of well correlation showing a cyclic succession of sand and shale sequence with the shale increasing in the intermediate to deeper sections. Well offset distances are 1,410m and 1,748m respectively.

Environments of deposition

The sedimentological model (highstand) shows the environments of deposition have a tidal influence and ranged from fluvial to estuarine (Figure 8). The environments extend from the continental shelf through a limit of tidal influence suggesting an estuarine environment (Dalrymple *et al.*, 1992) to the basin floor. This also reflects the lateral shifts in the environments of deposition inferred from the vertical profile of the well logs. See Table 1.0.

Upper Delta plain

The results of the environment of deposition shows that facies of the T4 – T6 reservoirs are deposited in the upper delta plain environment (Table 1). The upper delta plain environments of the Niger Delta is influenced by fluvial processes. It is characterized by a single distributary channel (braided and meandering channels). The braided environments are made up of the fluvial channel, lacustrine and flood plain environments while the meandering environments are characterized by the point bars. The fluvial drainage flows from the alluvial valleys of the Niger-Benue River and discharge its sediments through multiple distributary channel mouths into the Atlantic Ocean. The less dense bedload may have been discharged at the shelf areas and the sediments may be reworked by waves and tidal energies. The scarcity of burrows (e.g. the skolithos, psilonichus) in this environment distinguishes it from the tide dominated channel fill deposits. Sedimentation is river dominated and constituted by an aggregate stacking of braided, amalgamated channels with interbedded shales (flood plain deposits).

Table 1.0 Gabo Field Environment of deposition and sequence stratigraphic framework

Depth interval (m)	Lithology	Sedimentary process	Facies association	Environment of deposition	Sequence stratigraphic framework
2175 – 2208	Shale	Low energy	Flood plain deposits	Upper delta plain	Sub aerial unconformity (Sequence boundary)
2209-2238	T4 Sand	Medium - high energy regime	Fluvial distributary channel - braided	Upper delta plain	Stack of prograding and laterally extensive sand (HST)
2239 - 2251	Shale	Low energy	Flood plain deposits	Upper delta plain	laterally extensive with sealing potential
2252 -2285	T5 Sand	Medium energy	Fluvial channel - meandering (Point bar) or abandonment or switching	Lower delta plain	Prograding and pinched out sand (HST)
2286 - 2383	Shale	High - low energy flow regime	Flood plain deposits	Upper delta plain	Laterally extensive
2384 - 2425	T6 Sand	Medium to low energy - prograding	Fluvial distributary channel - braided	Upper delta plain	Prograding and laterally extensive sand (HST)
2426 - 2499	Shale	Low energy flow regime	Flood plain deposits	Lower delta plain	Laterally extensive
2426 - 2499	Shale	Low energy flow regime	Flood plain deposits	Lower delta plain	Laterally extensive
2500 - 2525	TA Sand	High energy flow regime	Fluvial inter distributary channel - meander	Lower delta plain	Prograding, thin and laterally extensive (HST)
2526 - 2570	Shale	Low energy flow regime	Flood plain deposits	Lower delta plain	Laterally extensive
2571 - 2590	TC Sand	High storm event	Fluvial inter distributary mouth -	Delta front	Prograding, thin sand (HST)
2591 - 2650	Shale	Low energy flow regime	Flood plain deposits	Lower delta plain	Laterally extensive
2651-2675	T7 Sand	High energy flow regime	Fluvial distributary	Lower delta plain	Prograding, thin and laterally extensive (HST)
2676 - 2715	Shale	Low energy flow regime	Swamp - Flood plain deposits	Lower delta plain	Laterally extensive (MFS)
2716 - 2726	T8 Sand	Medium - low energy	Distributary channel	Lower delta plain	Thin and extensive (TST)

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2727 - 2755	Shale	Low energy flow regime	Swamp - flood plain deposits	Lower delta plain	Laterally extensive, retrogradational (TST)
2756-2770	T9 Sand	Medium energy	Distributary channel	Delta front	Thin and pinched out (TST)
2771 - 2962	Shale	Low energy	Flood plain deposits	Delta front	Laterally extensive, retrogradational (TST)

Channel abandonment

It is believed that one of the major causes of channel abandonment (T5 sand) is distributary channel switching (Figure 6; Table1). It is a characteristic feature of fluvial-dominated deltas (Figure 7 -8). Deltas are believed to be formed in two historical cycles and they include a constructive phase (sedimentation) and the destructive phase (abandonment) (Elliot, 1986; Hudson, 2005). Sediments are believed to be deposited in the constructive phase while the destructive phase is characterized by a reduction in sediment supply resulting to an abandonment of delta lobe. According to Hudson (2005), the progradation and extension of the distributary network has major consequences which include, a reduction in stream gradient and a reduction in hydraulic efficiency (diversion of flow). In addition, it may also result from a rise in sea-level, fluctuations in sediment input due to climatic changes in the source area, or from tectonically induced river capture (Elliot, 1986).

The lower delta plain

The T7 – T8 reservoirs are deposited in the lower delta plain environments (Table 1). The lower delta plain environments of the Niger Delta is influenced by tidal ranges (Figure 8). They are characterized by several tidal distributary channels, mangrove swamps (vegetated intertidal flats), and the complex meandering tidal creeks (Allen, 1965d). According to Elliot, (1986), tidal currents may enter the distributary channels during tidal flood stage overflow the channel banks and inundate adjacent inter distributary areas. In addition, tidal distributary channels are less prone to switching and abandonment, but can migrate laterally. The tidal channel deposits may be distinguished by the presence of clay drapes and marine burrows in addition to cross bedding, ripple bedding and scoured bases. Ophiomorpha burrows may also be recognized. Sedimentation is constituted by multiple distributary channels, mangrove swamps and tidal complexes.

Delta front environments

The T9 and T10 reservoirs are deposited in the delta front environments (Table1). According to Elliot, (1986), the delta front is the environment were sediment-laden fluvial currents enter a standing body of water (basin) and are dispersed while interacting with basinal processes (wave and tide) (Figure 7 - 8). The delta front environments are characterized by thin laminated sand, silt and shale facies with a coarsening upward sequence. Sediment-laden flow from the river channels decelerates and is dispersed by wave and tide. According to Hudson, (2005), sediment sorting and deltaic sedimentation (deposition) occurs at this stage. This initiates a regressive sequence of deltaic deposits that prograde over the pro-delta marine shales. The sands and interbedded silt and shales are deposited in a series of cyclic successions.

Sequence stratigraphy

These predictions became necessary to explain the observed trend on the well logs. The well logs were observed to have cyclic succession of sands and shales at the updip intervals while the shale thickness appeared to increase in the intermediate to deeper sections. The sequence stratigraphic framework was predicted from the well logs only. Delta wide genetic sequences as defined by Frazier, (1974) and Galloway (1989) that consists of strata bounded by maximum flooding surfaces at the top and transgressive shales below was adopted. The sequence stratigraphic framework across expanded sections of the Gabo Field (Figure 10) shows that the sediments were deposited in three systems tracts and they are; the lowstand systems tract (LST), the transgressive systems tract (TST) and the highstand systems tract (HST). This prediction agrees with the Frazier, (1974) and Galloway (1989) sequence models.

The Lowstand Systems tract: The deeper well sections (T10 sand below) reflect the lowstand systems tract (LST) (Figure 7). In this setting, coarse grained bedload may have been carried beyond the continental shelf to the continental slope and marine setting. Deposition in the lowstand systems tract is known to be aggradational to progradational with interbedded fissile shales, silt and sand which may be influenced by wave and tidal ranges. The sands, interbedded silt and shales are deposited in a series of cyclic successions and the facies are characterized by coarsening upward sequence.

The Transgressive systems Tract:

Above the lowstand systems tract (intermediate sections) lie the transgressive systems tract (TST) (Figure 8). The top of the TST corresponds to the maximum flooding surface (MFS – a downlap surface), commonly a very wide spread shale while the base lies the maximum regressive surface or transgressive surface (Miall, 1999; Catuneanu, 2006). The maximum flooding surface separates retrograding strata below from prograding (highstand) strata above (Frazier, 1974; Van Wagoner *et al.*, 1988; Galloway, 1989). These surfaces are readily preserved and easier to recognize on well logs (Figure 10). The base of the T7 sand is interpreted as a maximum flooding surface. Below the T7 sand is made up of a long column of sand dominated retrograding strata. The transgressive reservoir sands between the T7 and the top of T10 sands are interpreted as late stage events being deposited under high storm events, they may be described as high energy traction deposits (sand lenses) that may have been deposited when the rate of sea level rise slowed down (Posamentier, 2002). It reflects a short period of high clastic supply during the late stage transgressive cycle. The interbedded T8 and T9 sands are thin, fine to very fine grained with some silt and dark brown in colour. The T8 sand lie within a depth interval of 2716 - 2726m, with an average thickness of 10m while the T9 sand lie within an approximate depth interval of 2756 - 2770m, with an average thickness of 14m. These reservoir sands (T8 and T9) are sandwiched between the floodplain fines and according to Catuneanu, (2006) the potential for petroleum exploration towards the landward end of the shoreline, of the transgressive systems tract is generally moderate to poor. The results of the facies analysis shows that the early to mid transgressive shales may be bimodal suggesting a tidal influence, typical of estuarine environments. In tide influenced environments, tidal currents may flow into and out of fluvial channels, modifying the fluvial sediments (Elliot, 1986). In addition, tide-dominated environments may show evidence of sediment redistribution by bi-directional basinal processes that may results to sand-filled and funnel-shaped distributaries. This environment is well described by Dalrymple *et al.*, (1992). According to Dalrymple *et al.*,

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(1992) an estuary is the seaward portion of a drowned valley system which receives sediments from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth. This may be responsible for the gradual increase in the shale thickness observed on the well logs in the intermediate to deep sections. Catuneanu, (2006) recognized the contribution of the transgressive systems tract in the development of petroleum systems to be the widespread accumulation of source rocks and seal facies.

The Highstand Systems Tract (HST):

River-dominated deltas are widely formed in the highstand systems tracts and rapid burial may preserve the fluvially formed facies and sedimentary structures. It is bounded at the top by sub aerial unconformity and at the bottom by the maximum flooding surface (Figure 8). This is predicted to have formed top (updip sands) of the stratigraphic sequence, it is typically aggradational to progradational consisting of shelf to non-marine deposits arranged in successive facies patterns or parasequences (Miall, 1999). Aggradational environments allow the mixing of fluvial and sea waters as a result of low density differential (Elliot, 1986). The highstand and the lowstand system tracts may show some clinoform architectures on seismic. The prograding sands are correlated between the T4 sand and bottom of the T7 sands. The result of the facies analysis showed that the T4 – T7 tops are predominantly sand, medium to very fine grain sized, light-dark brown in colour with thin interbedded shales. The well correlation shows that the T4 sand lie within a depth interval of 2209-2238m, with an average thickness of about 29m. The T5 sand pinches out towards the south west and lie within a depth interval of 2252 -2285m, with an average thickness of 33m. The T6 sand top lie within a depth interval of 2384 – 2425m, with an average thickness of about 41m. The TA and TC sand tops lie within depth intervals of 2500 – 2525m and 2571 – 2590m, with an average thickness of about 25m and 19m respectively. While the T7 sand lie within a depth interval of 2651-2675m, with an average thickness of 24m. According to Catuneanu, (2006) the petroleum play significance of the highstand systems tract shows that the accumulation of reservoir facies occurs at proximal settings (fluvial to coastal and shoreface environments) while the source rocks and seal facies are found at distal areas of the basin (shallow to deep water environments).

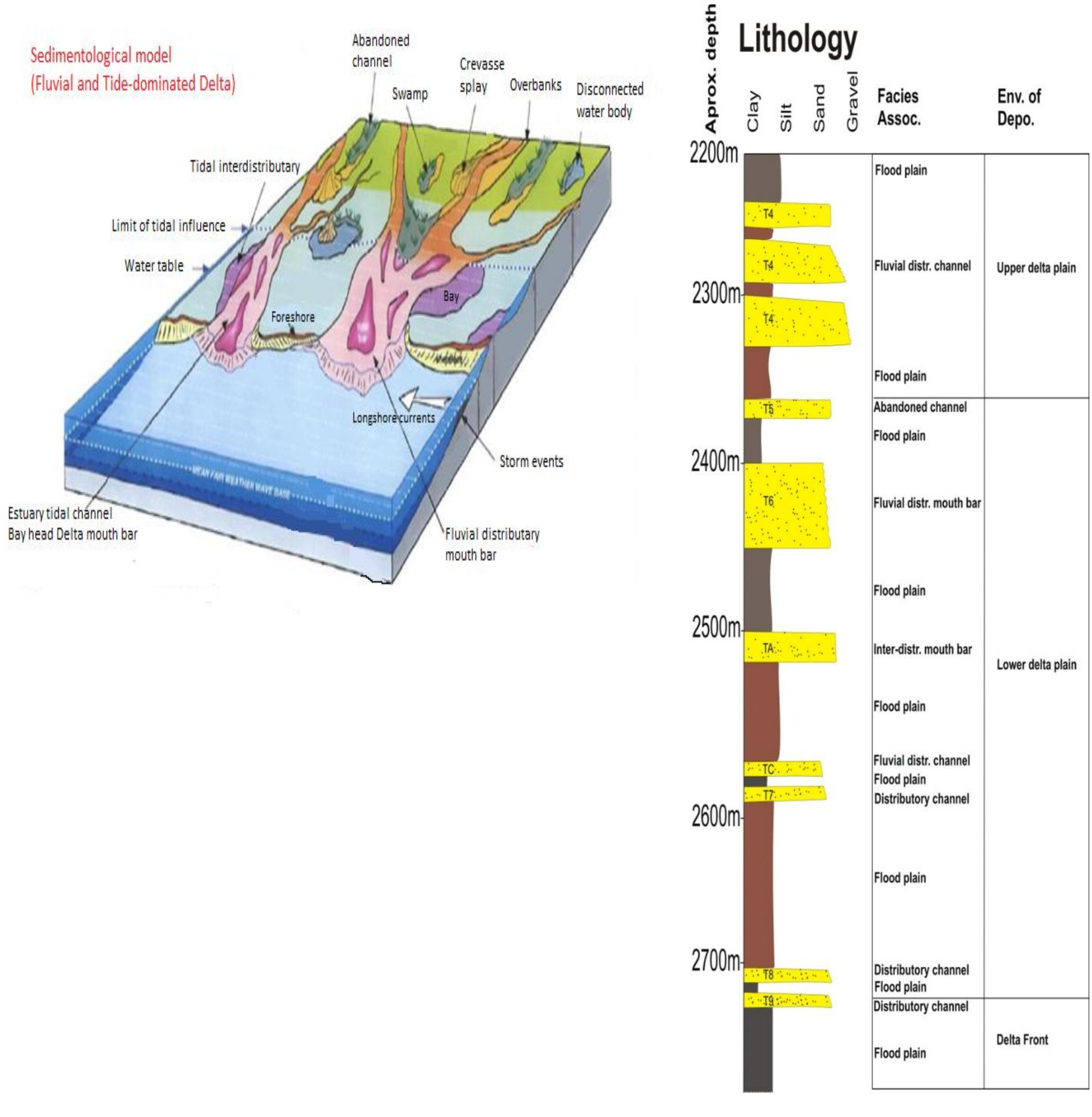

Figure 7: Gabo Field - depositional model (highstand) from well data and seismic (After TotalEnergies, 2021)

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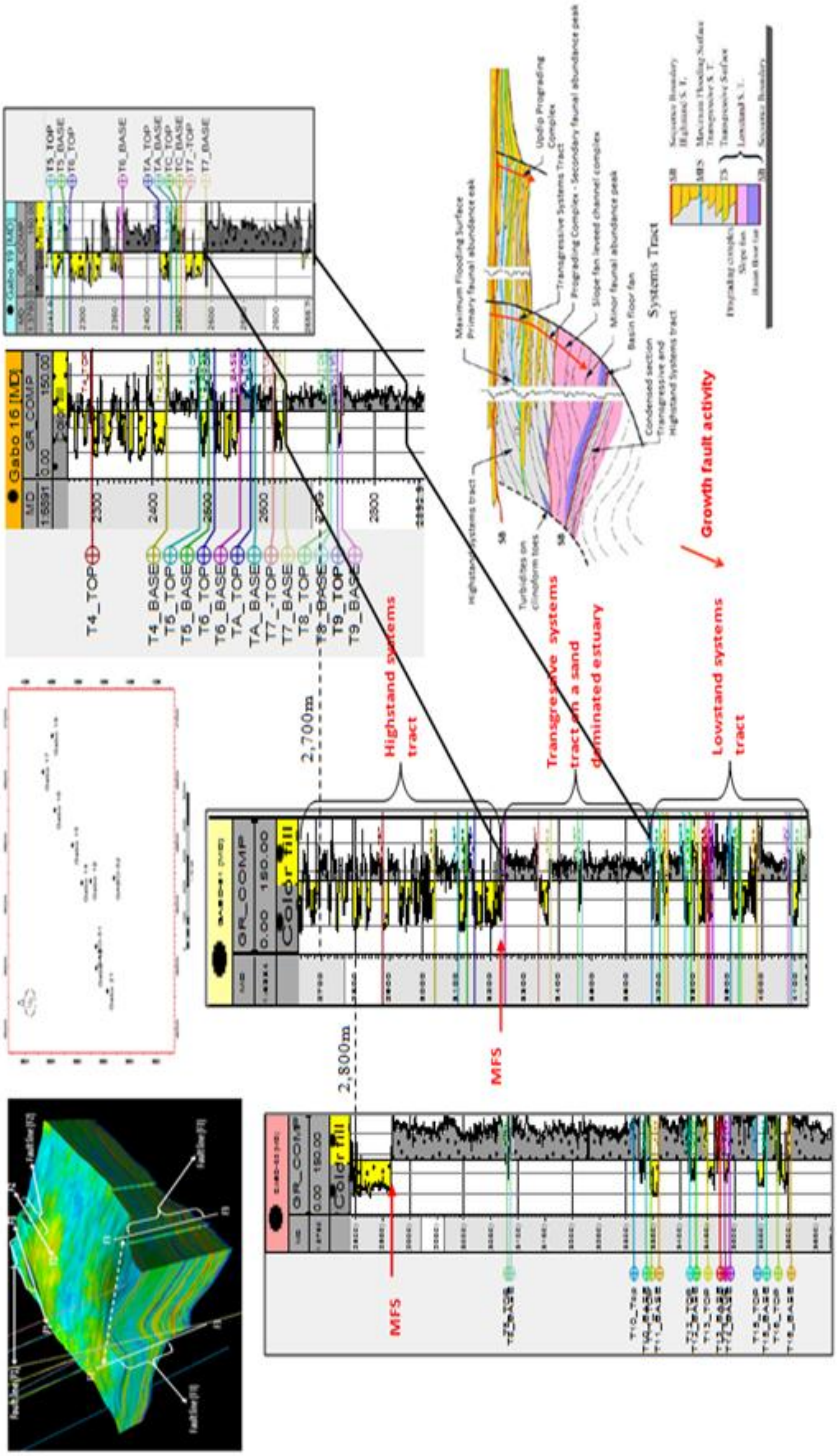

Figure 8: Gabo Field - sequence stratigraphic framework (After Frazier, 1974; Van Wagoner *et al.*, 1988; Galloway, 1989)

SUMMARY AND CONCLUSION

The Gabo Field deformational, depositional and post-depositional structures are similar to those identifiable in the Niger Delta setting (Evamy *et al*, 1978; Doust and Omatsola, 1990; Kulke, 1995; Reijers, 2011; Ekweozor and Daukoru, 1984). The deformational structures are faults F1 and F2 and they are closely spaced normal faults while fault F3 is a syn-depositional growth fault. Faults F1 and F2 agree with the relationship between the structural belts of the Niger Delta (Corredor *et al.*, 2005; Olga *et al.*, 2008; Ugwueze, 2015). Fault F3 agree with syn-sedimentary structures found in the Niger Delta and is discussed in detail by Weber, 1971; Evamy, *et al.*, 1978; Elliot, 1986 among others. In addition, these results agree with that of Agbasi *et al.*, (2021). The depositional structures are abandonment channel or pinchouts and interbedded sand/shale sequences whereas the post-depositional structures are compaction and smearing or flexure of the shales. These structures agree with the depositional and post-depositional structures discussed by Evamy, *et al.*, (1978); Elliot, (1986); Hudson, 2005. The well correlation showed that the vertical profile of the wells are comprised of cyclic succession of sands and interbedded shales at shallow depths while the shale thickness increased in intermediate sections. The geological observations from well logs reflects the Niger Delta sedimentation patterns (Reijers, 2011). The facies associations are interpreted as fluvial distributary channel, tide dominated fluvial channels, abandoned channel or switching and the flood plain deposits. The results of the facies analysis was matched with corresponding depths of the well log motifs and compared to the results of Nduaguibe and Ideozu (2019).The sedimentological model shows that the environments of deposition may have had a tidal influence and ranges from tide-dominated fluvial channels to estuarine (Frazier, 1974; Elliot, 1986; Galloway, 1989; Van Wagonner *et al.*, 1990; Catuneanu, 2006; TotalEnergies, 2021). The long column of shale was interpreted from well log as facies of the transgressive systems tract using the Frazier, (1974) and Galloway, (1989) approach for genetic sequences.

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