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Research Article

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Lithostratigraphy and Sedimentation Models of TMG-C4 Well Offshore Eastern Niger Delta

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ABSTRACT

Analysis was carried out in TMG-C4 well by integrating well logs data that revealed three depositional sequences within the Agbada Formation of about 400ft thick. Three systems tracts identified include highstand systems tract, transgressive systems tract and lowstand systems tracts. The highstand systems tract is majorly stacked regressive shoreface sands that occurred in two parasequence sets, whereas the transgressive systems tract is a transgressive unit with both source rock and sealing potentials. The lowstand systems tract shows a boxcar log motif and is identified to be probably channel or barrier bar sand. Major shale units (maximum flooding surfaces) with regional significance mapped are designated MFS. This division is relevant to identifying genetic depositional units. Three genetic sequences occurred in the well. The transgressive shales represent interruptions in the overall regressive sequence that is related to sea-level rise. Three of these shales have been mapped and two of them correspond to the eleven genetic megasequences that occur delta wide. A predominantly marine and deltaic sequences strongly influenced by clastic output from the continent is inferred from the well logs. Paleo water depth is interpreted to fluctuate considerably and deposition occurred within a variety of littoral and neritic environments ranging from nearshore barrier sand complexes to fully marine outer shelf mudstones. The sediments are rapidly deposited within the shallow marine realm and reworked into longitudinal bars by wave action, strong longshore drift and tidal effects. The dominant depositional trend observed in the well shows progradation.

Keywords: Well Logs, Systems Tract, Shoreface, Barrier Bar, Depositional Trend

Introduction

Sequence stratigraphy is the study of sedimentary rock relationships within a chronostratigraphic or geologic-time framework. It is the basis for the identification of stratal surfaces, regional unconformities and their correlative conformities. Sequence stratigraphy is also the study of rock relationships within a chronostratigraphic framework of repetitive genetically related strata bounded by surfaces of erosion or deposition or their correlative conformities. The basic starting point for sequence stratigraphy is the sedimentary facies, which is a lithostratigraphic body characterized by distinct lithological or fossil characteristics, generally reflecting a certain origin [1]. The division of depositional packages into genetic units is well understood through the concept of sequence stratigraphy. This method is a relatively new concept developed from the traditional stratigraphy that has assisted to enhance the apprehending of sedimentary processes and deposits in most basins of the world [2]. The cyclical nature of stratigraphic successions (better simplified by sequence stratigraphic concept) is essential in the determination of reservoir architectures, and assist to predict the occurrence of reservoir rocks both at the regional and reservoir scales of investigation. Establishing a sequence stratigraphic framework for all the oil fields/depobelts in the Niger Delta is imperative, and will form a basis for establishing a regional sequence stratigraphic framework of the basin, and will be relevant to improved exploration techniques and the discovery of unidentified resources.

Classical sequence stratigraphy for deltaic successions assumes that depositional processes across linked system tracts produces an equilibrium offshore depositional gradient, that shifts in position as sediments fill accommodation generated by gradual subsidence and sea-level variations. Sequence stratigraphic analysis of these successions define key stratal surfaces at abrupt dislocations of system tracts to delineate broad-scale facies trends formed by along-basin shifts in depositional environments and changes in preservation within system tracts [3]. Higher-frequency progradation and transgression of deltaic systems tracts has been related to both random auto cyclic channel avulsion and associated delta lobe switching, and to allocyclic processes like sea-level fluctuations and climate changes [4]. The internal architecture of deltaic successions that prograde onto mobile shale substrates can be significantly complicated by structural collapse of the delta front. Despite extensive literature on large delta deposits, little attention has been focused on influence of mobile substrates on the resulting sequence stratigraphy. The Niger Delta has a distinctive structural

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and stratigraphic zonation. Momta and Odigi [5]. discussed sedimentation and shale tectonics of the north-western Niger Delta front. Durogbitan examined relationships between mobile shale structure and channel formation above the compressional toe of Niger Delta and highlighted the importance of transfer zones within the toe thrust belt as a control on the underlying structural framework [1,6]. Discussed transient fan architecture and depositional controls from near-surface 3-D seismic data of Niger Delta continental slope. Cook, et al. related structural styles in the deep-water fold and thrust belts of the Niger Delta and concluded that there are two complex, imbricate fold and thrust belt systems (the inner and outer fold and thrust belts) that are the product of contraction caused by gravity-driven extension on the shelf [7]. Evamy, et al. explained the role of deformation in controlling depositional patterns in the south-central Niger Delta, their work was however focused mainly at the compressional toe of the delta, and they concluded that structural elements are the primary control of accommodation changes on the slope and toe of the delta [8].

Other examples of deltaic systems that rapidly prograde onto mobile substrates include: the Baram Delta, offshore Brunei Caspian Sea [2,9,10]. synthesized relationships between progradation, subsidence, basal under compacted shale wedge, growth faulting, shale diapirism and overthrusting within the Mississippi, Niger and Mackenzie Delta systems [11]. related shale tectonics to deformation associated with active diapirism within the Jerudong anticline, Brunei Darussalam [2]. They established that shale diapirs and associated growth faults exerted an important influence on large- and small-scale bedding geometries and facies changes of syntectonic shallow marine, shoreface and tidal strata for the area. Slatt reviewed the origin and significance of failed shelf margins of Tertiary northern Gulf of Mexico basin and recognized the role of slumping in forming unconformities of regional extent along retrograde failed shelf margins [11]. Evamy, et al. discussed a 3D Seismic study of a shale expulsion syncline at the base of the Champion Delta, offshore Brunei and its implications for the early structural evolution of large delta systems [8]. Most work on depositional sequences above mobile substrates has focused on slope and deep-water environments. The Niger Delta clastic wedge is complicated by listric normal faults that formed as prograding deltaic sediments loaded underlying under compacted prodelta and deeper marine shales. Over pressured shale has been related to some combination of burial compaction, diagenesis of clays, kerogen maturation, and compressive tectonics. The active fluid for migration is necessary to maintain shale movement can form vents for hydrocarbon migration from deeply buried source rocks to shallower reservoirs and traps [8]. A sequence stratigraphic framework is developed for TMG_C4 to interpret long-term patterns of deposition along this deltaic margin. This framework is used to examine relationships between sequence boundary erosion, spatial changes in sequence thickness and internal facies trends, and patterns of syndepositional deformation.

The main tool used in sequence stratigraphic analysis is the stacking pattern of strata and the key surfaces that bound successions defined by different stratal stacking patterns.

Location of the Study Area

The TMG-C4 well is located in the eastern part of the Niger Delta Basin, where thick Late Cenozoic Clastic sequence of Agbada Formation was deposited in a detalic fluvio-marine environment. The TMG_C4 well is situated within the Central/Coastal Swamp Depobelts of the Eastern Niger Delta (figure 1). The well is located 30 km off the South eastern part of the Niger Delta at a shallow offshore depth of about 40m. Conventional stratigraphic interpretation from seismic data has been predominantly qualitative and is based on visual inspection of geometric patterns in post-stack reflection data. This study aims at providing a stratigraphic framework consistent with the 3-D seismic interpretation that will not only aid in determining types of systems tract occurring in the field but also identify those systems tracts that are associated with hydrocarbon reservoirs using sequence stratigraphic approach. This will provide a model for stratigraphic interpretation of seismic data that addresses distribution of lithofacies, depositional environments as well as location and continuity of reservoirs.

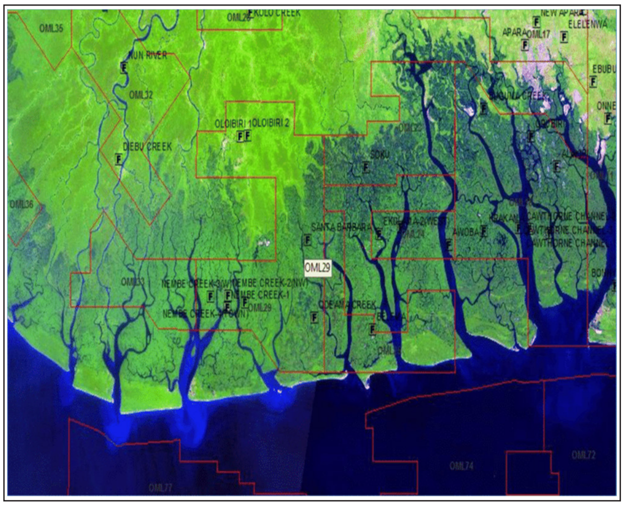

Figure 1: Location of TMG-C4 well on the Niger Delta Map [5].

Since inception in the early Cretaceous time, the southern basin of Nigeria has been the scene of at least three major depositional cycles [12]. The first, possibly a double cycle, commenced in the Albian time to Coniacian times and involved mainly marine deposition within the whole basin; between Albian to Lower Cenomanian and Turonian to Coniacian time. It was terminated by a brief phase of folding in Santonian formation, which consists of continental and fluvial sands, gravel, and back swamp deposits (2500m thick).

Outcrop sediments in the northern reaches of the Niger Delta Basin, range in age from Eocene to Recent. The Eocene outcrops occur in south of the Benin Flank and the basin areas in the northern fringe of the delta. The recent outcrops are the present coastlines. Surface evidences of Oligocene and Miocene deposits are limited and much of the age determination is uncertain. The approximate surface boundaries of th4e Eocene-Recent sediments have been indicated. The three major lithostratigraphic units defined in the subsurface of the Niger Delta (Akata, Agbada and Benin Formations) decrease in age basin ward, reflecting the overall regression of depositional environments within the Niger Delta clastic wedge. Stratigraphic equivalent units to these three formations are exposed in Southern Nigeria [12]. The formations reflect a gross coarsening-upward progradational clastic wedge deposited in marine, deltaic, and fluvial environments [12,13].

Materials and Methods

Two important models are adopted in this research in identifying sequences in the field. The Vail, et al. and Galloway models Galloway [3,14]. Vail considers unconformity surface (sequence boundary) as a criterion in subdividing sedimentary fills within a basin into sequences (depositional sequences). Sequence boundaries develop when the rate of sea level fall is a maximum or when relative sea level begins to fall at some specific break in slope, thereby initiating the incision of valleys by head-ward erosion. Galloway's model uses the flooding surfaces as a means of identifying genetic sequences. Applying the Galloway model is significant to establishing the continuity of key regional marker shales within the field. One shallow well (TMG_C4) was used for the sequence stratigraphic and depositional environment interpretations.

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

Materials

1. Well logs
- Gamma Ray
- Permeability
- Porosity
- Netgross

Petrel software

Methods

Well logs obtained from a well TMG_C4 were used for the study. The logs comprise of gamma-ray, porosity, permeability and fluvio-facies logs. The approach adopted for the study is shown in figure 2.

Data Editing, Correction and Import

Quality control was applied to the data. Thereafter, ASCII data importation and loading into Schlumberger Petrel software 2017.1TM platform were done. It is from here that well logs were loop-tied to assure consistency.

Determination of Lithology and Reservoir

Gamma ray log was used for lithology identification. It measured the natural radioactivity component of the formation in API value. The scale of the gamma ray log ranges between 0-150API. High API values indicate shale while low value is sand. Deflections of the gamma ray log to the right and left is interpreted as shaly and sandy formation respectively.

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

Determination of Maximum Flooding Surfaces from Well Logs

The Maximum Flooding Surfaces (MFSs) were identified as shaliest part of the section. It represents the points with the highest gamma ray values.

Determination of Transgressive Surface from Well Logs

The Transgressive Surface (TS) is a prominent flooding surface. It represents the first major flooding surface to follow the sequence boundary and is usually identified on the gamma ray log by fining upward. This is an indication of the beginning of rise in relative sea level at an increasing rate.

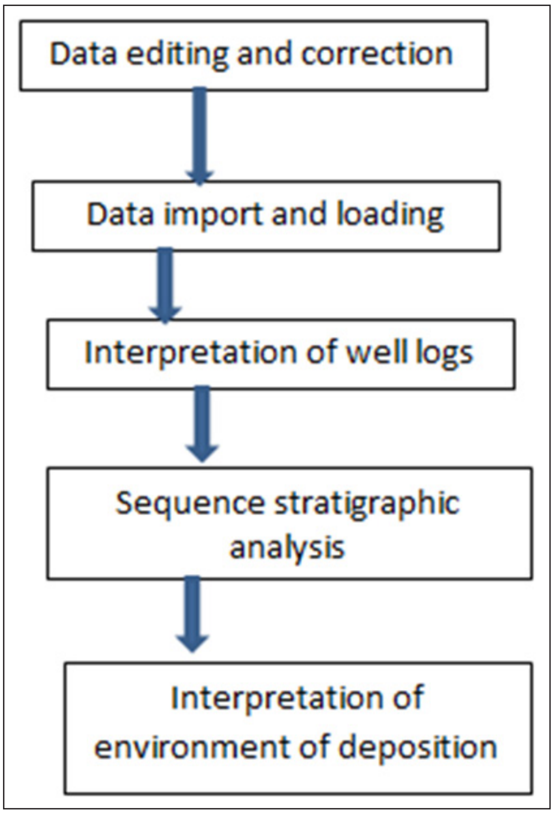

Figure 2: Flow chart of the research work

SB = Sequence Boundary
HST = Highstand Systems Tracts
MFS = Maximum Flooding Surfaces
TST = Transgressive Systems Tracts
LST = Lowstand Systems Tracts

Figure 3: Hierarchy of bounding surfaces

Determination of Depositional Sequence from Well Logs

Depositional sequence was determined by the cycle of sea level changed. In vertical succession, depositional sequences were identified in the well logs by using the order (Figure 3).

Determination of Environment of Deposition Using Well Logs

The environment of deposition was identified using gamma ray log responses. A funnel log response (progradational) represents a change from mainly shale into high sand lithology. It also indicates a gradual change from clastic to carbonate deposition. A bell log response is an indication of lithology change from sand to shale (waning of submarine fans-reducing sand contents).

It is predominant within meandering or tidal channel deposits in a non-marine setting. A cylindrical response indicates fluvial channel sands, turbidites and aeolian sands.

Results and Interpretation

The Lithology of well TMG_C4 in X-field revealed sand horizons (Figure 2). The Well occurred on the Eastern part of the field. Top and base of key sand have gamma ray values corresponding to the sand base line (25º API). The top and base of key marker shales form the base and top of suspected sand bodies. The sands are better developed towards the top part of the well than at the bottom (Figure 2) with a large lateral extent. The gross thickness of the reservoir ranges from 1859m to 2500m with a layer-cake architecture and large lateral extent. Significantly, stratigraphic framework of the reservoir and can be used in building 3-D petrophysical, dynamic modeling, and flow unit demarcation. Greater sand development was observed between 1845m-1970m of the well, whereas thick shales are noticed between 1965m-2065mof the well. Thicker sand units are observed in the reservoir unit (Figure 1) occurring towards the middle to the lower parts of the well section. The upper section shows thick sand horizon. These two sections may represent sediments deposited within both the coastal plains and the deltaic front environments. The upper section (possibly coastal plain) may be associated with more channels (amalgamated) whereas deltaic front with thick sand accumulations is characterized by thick continuous shoreline regressive deposits.

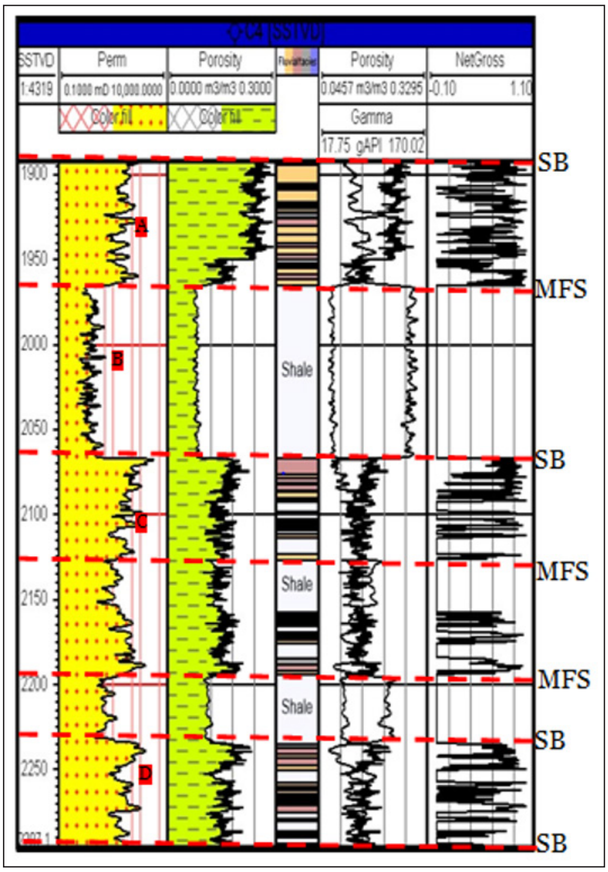

Figure 4: Sand and Shale Boundaries

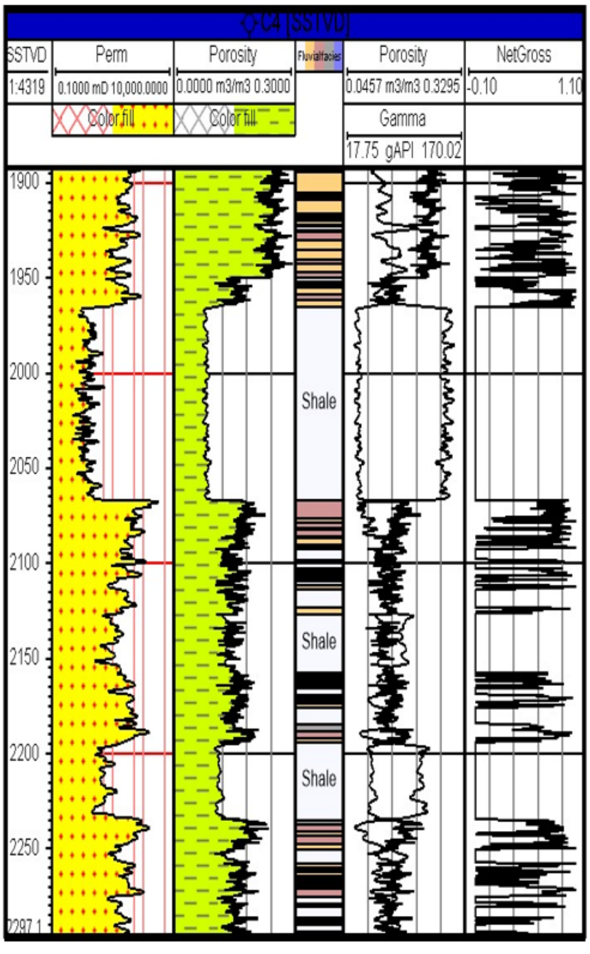

Figure 5: Sand and Shale horizons

From the perspective of facies models, layer A, caked shore-parallel facies have been assumed to form homogenous, uniform reservoirs with high production capacities. Wave-influenced coastline deposits possess distinct facies with homogenous beach and shoreface sands accumulating on the updrift side of the river mouth with significantly more heterogeneous facies on the downdrift side. The heterogeneous unit is noticed towards the lower parts of the reservoirs in the well (Figure 4). Well log interpretation shows that, predominantly the formation is made up of sand and shale occurring in alternate sequences especially within the Agbada Formation. The QIS base (Qua Iboe Shale) on the well log (Figure 5) occurring at about 2000ft represents the regional unconformity separating the onset of paralic sedimentation from the overlying continental Benin Formation. The Qua Iboe Shale (QIS) forms the regional marker shale delimiting the continental sediments of the Benin Formation from the parallic Agbada sequence.

Recognition of Systems Tracts

Systems tracts are three-dimensional assemblages of lithofacies that are genetically linked by sedimentary processes and environments, and are bounded by discrete, recognizable surfaces. Systems tracts are arranged laterally and vertically in a predictable manner, within the majority of clastic depositional sequences. Sequences are subdivided into systems tracts based on types of bounding surfaces, position within a sequence, parasequence set-stacking patterns, geometry, and facies associations. Sequence stratigraphy and parasequence stacking patterns exert a strong control on recovery at large scale architecture because they determine the distribution of laterally extensive, parasequence and sequence bounding surfaces and hence the degree of hydraulic communication between successive shoreface-shelf sandstones, while the facies and facies association within each parasequence, are key factors controlling fluid flow during production, and control the smaller scale distribution of petrophysical properties such as permeability and porosity. Three systems tracts identified based on log stacking patterns include; highstand systems tracts (HST), transgressive systems tracts (TST) and lowstand systems tracts (LST).

Highstand Systems Tract (HST)

The HST in sequences 1 to 6 each consist of a progradational parasequences and parasequence sets (Figure 6). It consists of coarsening-upward successions of marine sandstones overlain by alternating marine shale beds. The shoreface sandstones displayed typically gradational base with sharp upper contacts (Figure 5) separated by marine shales. Coarsening upward successions generally depict deposits resulting from falling sea level and constitute widespread, normal regressive systems tracts in the well. More repetitive units (parasequence sets) are observed in the lower sequences (sequence C and D) as shown in Fig. The highstand systems tract is bounded at the base by the maximum flooding surface and at the top by the overlying sequence boundary (Figure 6).

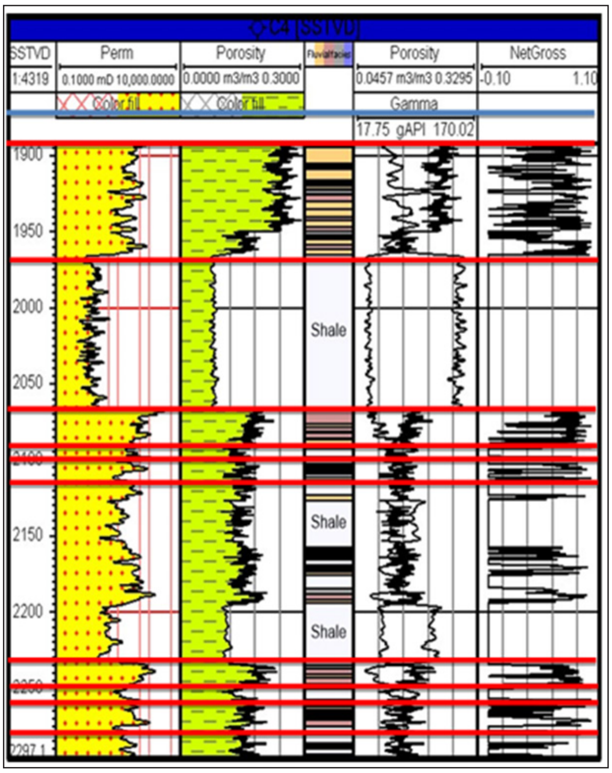

Figure 6: Sand units within the well

The best potential reservoirs of the highstand stage tend to be associated with the shoreline to shoreface depositional systems, which concentrate the largest amounts of sand, with the highest sand/shale ratio (Figure 4). These reservoirs are in feets (1895ft, 1965ft of sand), and display very good lateral continuity along strike in the field (Figure 5). Both sand-plains (open shorelines), deltas (river-mouth settings) prograde and downlap the maximum flooding surface, which marks the lower boundary of the highstand normal regressive package.

Highstand sands are highly productive and occupy the first terrace on the creaming curve where there is a rapid increase in production with potential for greater exploration/exploitation success in any sedimentary basin. The HST forms the dominant systems tract that stacked into parasequences and parasequencesets in the well. Sequence D contains three consecutive HST that stacked into parasequence set (Figure 6). This stacked HST is common to younger sequences, and may indicate rapid sedimentation of younger sediments onto the shelf.

Transgressive Systems Tract (TST)

Transgressive systems tracts are bounded at the base by the first major marine flooding surface and at the top by the maximum flooding surface (MFS) (figure 8). It is a deposit that results from transgression which indicates the landward migration of the shoreline. The transgressive systems tract comprises a well-developed back stepping succession of marine mudstones and heteroliths. Transgression occurs when accommodation is created more rapidly than it is consumed by sedimentation. That is, when the rates of base-level rise outpaces sedimentation rate at the shoreline. The TST is observed in sequence 2, 4, 5, 6 and 7 (Table 1). The transgressive sands form reservoirs with fair to good quality.

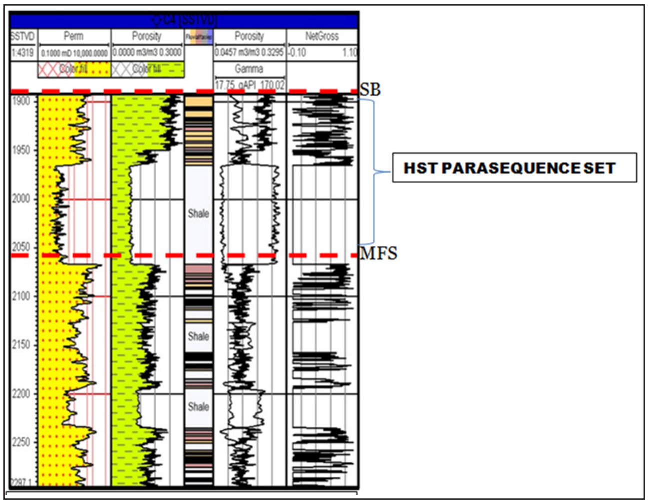

Figure 8: Sequences and systems tracts in the TMG-C4

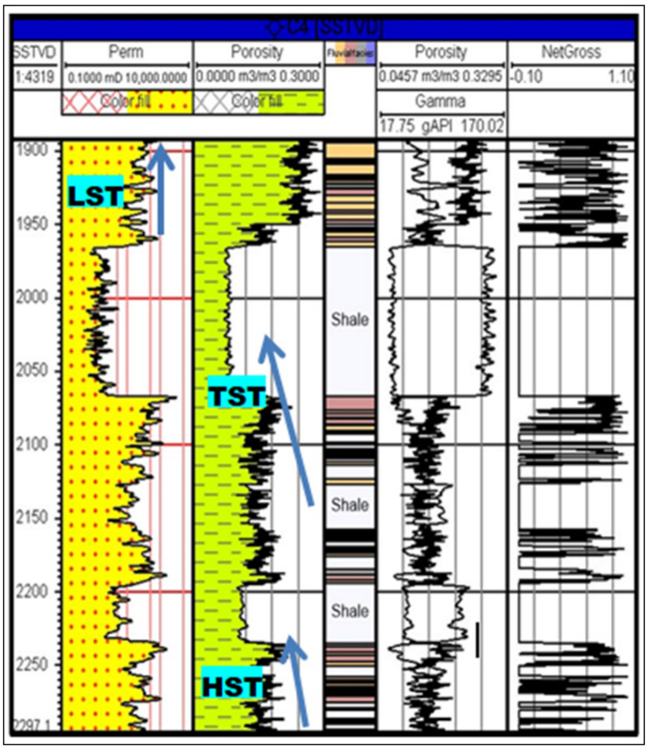

Figure 9: Sequences and systems tracts in the TMG-C4

Table 1: Systems Tracts and Sequences (Well TMG-C4)

Sequences	Depth interval (ft)	SB depth (ft)	Thickness (ft)	System tracts
1	1890-1975	1890	85	HST, MFS
2	2065-2215	2065	150	LST, TST
3	2065-2195	2195	130	MFS

Lowstand Systems Tract

This is a component unit of a sequence defined by a correlative conformity (CC) and its correlative surfaces as the lower boundary and a maximum regressive surface (MRS) and its correlative surfaces as the upper boundary [8]. In this study, lowstand systems tract (LST), transgressive systems tract (TST) and highstand systems tract (HST) are used to partition sequences. The lowstand systems tract forms when there is a significant sea level fall and results in extensive subaerial exposure and/or widespread fluvial incision (incised valley). Lowstand systems tract is bounded at the base by a sequence boundary and above by the first major marine flooding surface (transgressive surface). It shows an aggradational depositional trend (Figure 7). All processes of aggradation or erosion are linked to the shifting balance between environmental energy flux and sediment supply (i.e. aggradation occurs only where sediment supply outpaces energy flux, and erosion occurs only where energy outpaces sediment load). With high rate of sediment supply as noticed in top sequence in the well TMG-C4, there is the likelihood of potential unconformity traps and buried channels in the field. The LST forms excellent reservoirs and constitutes the first exploitation phase in the field. The LST type common in the field may be due to fluvial incision and also deepwater/slope turbidite sands especially within the Akata Formation.

Recognition of Sequences

A sequence is the primary unit of sequence stratigraphy. It is subdivided into component units called systems tracts. The stacking patterns of systems tracts couple within distinct chronostratigraphic surfaces (sequence boundaries and maximum flooding surfaces) (Figure 10) forms the major criteria for the recognition of a sequence either depositional or genetic stratigraphic sequence. Two dominant depositional trends observed on the well log are regression and transgression. Regression is indicated with a shallowing upward trend, whereas a deepening upward represents transgressive process (Figure 10). Using the regressive-transgressive approach of mapping sequences, six depositional sequences are clearly observed in Figure 6.

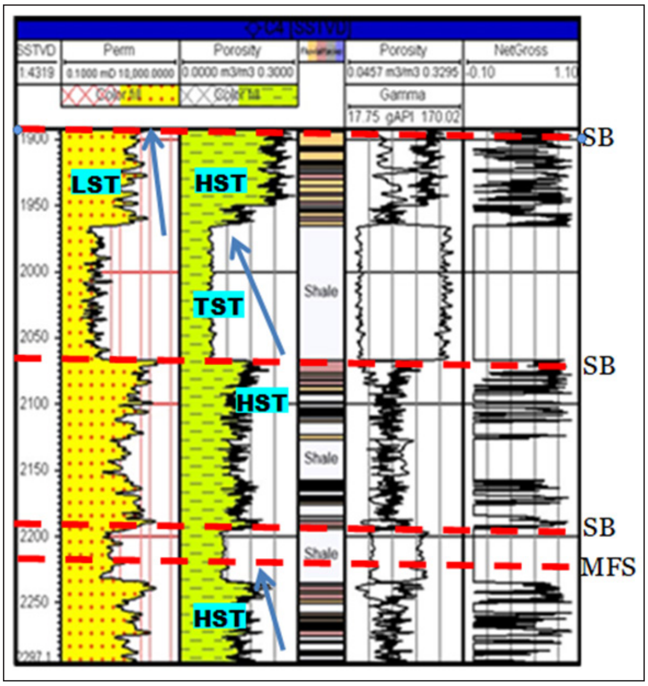

Figure 10: Sequences and systems tracts in the TMG-C4

Sequence 1

Sequence 1 is the oldest penetrated by the TMG-C4 well of the X-field (Figure 11). The base (SB1) of this sequence is not seen. The top sequence boundary (SB2) is at 2235ft in the well, and contains MFS1, a minor flooding surface older than MFS2 and

MFS3 (possibly Middle Miocene) (Figure 11). Three major sand bodies and three 3rd-order marine flooding surfaces occur in this sequence. The sandbodies comprise of three Highstand Systems Tracts (Figure 6) occurring above the maximum flooding surface (MFS1). It displays a coarsening upward (progradational parasequence) trends with thicknesses of about 65ft. Other sand bodies occurred below shale to form a complete depositional sequence.

Sequence 2

This occurs between SB2 and SB3 from 2200ft and 2250ft. The top boundary (SB3) is possibly a parasequence set boundary (Figure 11). Three sand bodies comprising of Transgressive Systems Tract (TST) and HST occur in this section. The TST unit is overlain by MFS2, whereas the twoparasequence sets of the highstand systems tract downlap the MFS2. Some marine flooding surfaces cap the repeated HST showing abrupt increase in water depth. The log pattern of the TST shows a thickening upward transgressiveparasequence, while the HST shows a regressive shallowing upward trend. The thickness of this sequence is 2050ft (Table 1).

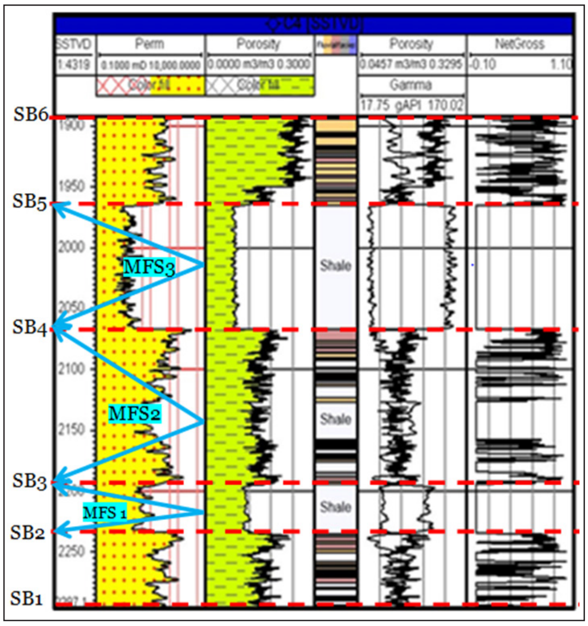

Figure 11: Stacking patterns and key surfaces identified in well TMG-C4.

NOTE: SB - Sequence Boundary; MFS - Maximum Flooding Surface.

Sequence 3

Sequence 3 lies between sequence 2 and 4 with a thickness of 2200ft in the well, between 2020ft and 20500ft. This sequence contains one transgressive parasequence set of two TST; one highstand parasequence set with three HST and one LST underlain by a sequence boundary. The TST displays a retrogradational trend and downlaps the lowstand sand. The thickness of both the TST and LST forming the sand reservoir is about 100ft and thicker towards well top than in the well bottom (Figure 6). This may be as a result of decrease in transgressive force/ sand development marking the onset of transgression. The channel fill size decreases as we move in the basinward direction.

Sequence 4

Sequence 4 occurs between SB4 and SB5. The thickness is about 100ft between the intervals of 1965ft to 2065ft. It contains one TST, HST and MFS4 (Figure 6; Table 1).

Sequence 5

This sequence is thicker than the sequence below it. SB5 is a possible parasequence set boundary, bounding stacked successive prograding highstands (Figure 6). Sequence 6 is the thickest unit of about 150ft thick (Table1); occurring between1956ft and 1800ft. It has series of stacked highstand systems tracts (Figure 6). In these younger sequences there are sets of fourth order highstandparasequences capped by marine flooding surfaces. These parasequences stack to form the systems tracts in the well (Figures 5-11). The dominant trend noted in the well is the shallowing upward, which represents a progradational phase of delta outbuilding in a lower coastal plain setting.

TMG-C4 Well Sequences and Sequence Boundaries

Three major depositional sequences have been inferred in theTMG-C4. They are separated by sequence boundaries, which form in response to falls in base level.

A sequence is bounded by non-depositional unconformities and typically defined to be marked by a basin ward shift in facies including abnormal subaerial exposure basin ward shift in facies is interpreted to form in response to a relative fall in sea level. Many flooding surfaces can exist within a sequence but a sequence deposited during the same cycle of relative changes of sea-level is bounded by a sequence boundary. There are at six (6) sequence boundaries identified in the TMG-C4 well. The criterion for the identification possible sequence boundaries included basically changes in parasequence stacking pattern from progradational to retrogradational (Figures 5 and 6). Because sequence boundaries form in response to base level fall, siliciclastic sequence boundaries are often marked by fluvial incision into previously deposited subtidal strata and abnormal subaerial exposure, whereas parasequence boundaries form in response to base parasequence boundaries are conformable and lack the incision often associate with sequence boundaries. There are possibilities of incised valleys, barrier bar, channels and estuarine-controlled sedimentation in the TMG-C4 well that provides opportunity for hydrocarbon accumulation and stratigraphic traps. The sediments are mostly regressive deposits showing fast deposition of fluvial sediments into the shallow marine realm. The upper sequences display stacked regressive parasequence sets (Figure 11). The processes and their responses show sediments supplied by river action and reworked into barrier deposits, beaches and shoreface deposits through the action of marine energy flux (wave action), longshore currents and tidal action. The fluvial influence and rapid sedimentation seems to be more active in the upper sequences (4, 5 and 6), and this accounts for the stacked prograding sand units of great thickness. The various sequence boundaries cut across the well and have potential for stratigraphic traps. Incised valley may be associated with the LST and channels. Depositional trends portray a highly regressive sediments basinward. This provides opportunities in adjacent areas because these sand deposits can be traced towards the deep offshore location.

Importance of the Sequences in TMG-C4 Well

The overall depositional trend of sediments in TMG-C4 well shows a prograding delta. Common depositional units that form hydrocarbon habitat occur within the Agbada Formation. These sediments were deposited within the shoreface to shallow marine shelf environments (Figure 1). Genetic units that form the reservoirs are barrier bar sand, beach sand, shoreface and channel deposits (Figure 6). The barrier complexes are locally punctuated by transgressive shale beds. The thickness of the sequences decreases with depth probably due to the intensity of both autogenic and allogenic controls as at the time of deposition of the sediments and also the effect of diagenesis (compaction).

TMG-C4 Well Depositional Architecture

Facies of the well displayed distinctive shallow marine and nearshore depositional elements throughout (Figures 1 to 11). These are primarily controlled by delta progradation and deposition of sediments within the shoreface and shallow marine realm. Fluvial, wave, longshore currents and tidal processes are the major forces that may have contributed in the systemic distribution and redistribution of sediments in the well. Typical depositional architectures identified based on the stacking patterns include; beach, barrier, shoreface, mouth bar, and channels (Figures 10, 11). Depositional architecture is defined by three major controls. They include; sediment influx, subsidence, and sea level changes that provides space for sediment accumulation (accommodation). Three depositional trends that occur in the well include; progradation, aggradation and retrogradation (transgression) (Figure 6). Each of these events has unique products that aid the reconstruction of their depositional systems.

Progradation in TMG-C4 Well

Progradation is the basinward (seaward) migration of facies belts (shoreline), when sediment supply exceeds the rate of creation of accommodation space. It implies a basinward shift in clinoforms. Progradational patterns form when the rate of deposition exceeds the rate at which accommodation increases. Stacked progradational parasequences have been identified in the X-field (Figure 5). Repeated progradational patterns (parasequence sets) are observed in the well indicating a prolong migration of the shoreline, controlled by the larger-scale balance between the rate of sediment supply and accommodation space creation. The architecture generated when the rate of sediment supply is greater than the rate of creation of accommodation space is described in the work of the stacking pattern is typically of the highstand system tract. Most siliciclasticparasequences are progradational in nature, resulting in an upwardshoaling (upward-coarsening and cleaning) association of shallow marine lithofacies. If the rate of sediment supply to a shoreline area exceeds the rate of water deepening as a result of subsidence and/or sea level rise, then sediments will prograde in the basinward [12].

There was rapid and repeated increase in water depth as sediments were supplied leading to regular marine flooding isolating the sandstone intervals. This is a typical progradational parasequence set where each parasequenceprogrades progressively farther basinward than does the preceding parasequence (Figure 6).

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

The environments of coarsening upward successions can be put into three general categories: (1) regressive barrier bars, (2) prograding submarine fans, (3) prograding deltas or crevasse splays. The first two environments, regressive barrier bars and prograding submarine fans are commonly deposited with glauconite and shell debris [1]. The paleoenvironments of funnel shape facies belongs to regressive barrier bar sand. However, one of the main differences between a prograding delta and a crevasse splay is the deposition scale; the prograding delta is comparatively large. According to the identification system of the paleoenvironment of funnel-shaped successions with carbonaceous detritus can be identified as a prograding delta or a crevasse splay [1,15].

Aggradation in TMG-C4

An aggradational pattern develops when sediments stack vertically as a result of a balance between sediment supply and rate of creation of accommodation space. Log facies of this unit has sharp upper and lower contact (blocky) (Figure 6). Mudlog report shows that the lithologies of these sections are mostly sandstones (light brown to creamy brown, dark in part, translucent to transparent, very fine to fine, occasionally medium grained, subrounded to rounded, sub-spherical, primarily argillaceous in part poorly to moderately sorted). In the well, the boxcar shaped gamma-ray log occurs in the well with average thickness of 20ft.

Retrogradation

Retrogradation is landward migration of facies belts when the rate of sediment supply is less than the rate at which accommodation space is generated. The log characteristic of this unit shows a sharp lower contact with a gradational top (Figure 6). It is a transgressive unit. The bell shaped succession usually occurs in three types of environments: tidal channels, turbidite fills and fluvial or deltaic channels.

TMG-C4 Well Sequences and Depositional Architecture

Thought drawn from the stacked HST signifies mostly regressive sediments of fluvial origin deposited within the shallow marine realm. The uppermost sequence displays the highest stacked regressive parasequence sets of highstand systems tracts (HST) (Table 1; Figure 5), with an overall shallowing upward trend towards the top of the Agbada and base of the Qua Iboe Shale Member. The processes and their responses show sediments supplied by river action and reworked into barrier bars, beaches and shoreface deposits through the action of marine energy flux, longshore currents and tidal action. The various sequence boundaries cut across the field and have potential for stratigraphic traps. Incised valleys may be associated with the lowstand systems tracts (LST) and channels. Depositional trends portray a highly regressive sediments basin ward. There is high potential of successful exploration and exploitation for hydrocarbon in the highstand sands within the field and adjacent areas. These marginal to shallow marine reservoirs are typically laterally continuous, and in good stratigraphic relationship with the transgressiveshales to enhance accumulation and entrapment of hydrocarbon in the field.

Conclusion

The use sequence stratigraphy in this study has helped in the demarcation of the various stratigraphic intervals in the well into six complete depositional sequences with their component systems tracts. Sediments are still prograding into the offshore areas and will provide opportunities in the adjacent fields offshore. A predominantly marine and deltaic sequences strongly influenced by clastic output from the continent is inferred from the well log. Paleowater depth is interpreted to fluctuate considerably and deposition occurred within a variety of littoral and neritic environments ranging from nearshore barrier sand complexes to fully marine outer shelf mudstones. The lower part of the Agbada Formation penetrated by the well is interpreted to have been deposited in the outer shelf or upper slope setting. Six complete depositional cycles occur in the Field, representing sediments deposited probably during the Late Middle Miocene to Upper Miocene. The dominant depositional trend observed in the well shows progradation. The sediments are rapidly deposited within the shallow marine realm and reworked into longitudinal bars by wave action, strong longshore drift and tidal effects. The rapid deposition may not be unconnected with the late Miocene catastrophic event associated with the Qua Iboe collapse; proximity of the adjacent Cameroun Mountain and the Oban massive as provenance sources, and the Kwa/Calabar Rivers providing conduits for constant sediment supply. This also, may have accounted for the proper development of parasequences and parasequence sets resulting from the rapid sediment deposition.

Recommendations

The research work has unravel that sequence stratigraphy is becoming veritable in sedimentology.
This will aid:

1. Depositional environment modeling
2. Petroleum exploration and exploitation
3. Reservoir characterization.

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