



Subkinematic and growth strata sequences in the deepwater Niger Delta – Insight from OPL 250

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Abstract

Keywords:

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reservoirs

Six sub-kinematic and three growth strata sequences have been described from the deepwater Niger Delta region using seismic and well log data sets from oil and gas industry. The goal was to create a preliminary overview and a base framework for tracking stratigraphic sequences within the study area. The sub-kinematic sequences (Ks1 – Ks6) are third order sequences with time span ranging from 1 to 2 million year (Ma). Possibly three fourth order sequences occur in Ks5. From log signatures, the sequences generally consist of thick hemi-pelagic shales interspaced with thin sand prone intervals. The sand prone intervals represent gravity slump deposits such as basin flow fans and sand flushed from channels mouths at the onset of the lowstand system tract (LST). Growth strata sequences consist of thick hemi-pelagic sections with deeply incised channels and associated levee systems and possibly extensive reworked sand prone facies. Vertical communication is enhanced due to stacking of sand prone facies. Thrust initiation at 12.8 MA defines the boundary between charged sands in deeper sections and water filled sands in shallow section.

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INTRODUCTION

Sequence stratigraphy analyses sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of accommodation (space available for sediments to fill) and sedimentation' (Catuneanu, 2006). It therefore has tremendous potential to unravel the Earth's geological record from local to global changes, and identify the principal constraints forcing them. For the academia, it affords the opportunity to understand the genesis and internal architecture of sedimentary basin fills and in the industry, provides a platform for exploration for hydrocarbons, coal, and mineral resources (Catuneanu, 2006).

Sequence stratigraphic analysis provides the opportunity to integrate earth system data sets on multiple scales into a coherent subsurface model. The resulting models help to synchronize the understanding of the possible myriads of information about the evolution and development of sedimentary systems.

Sequence stratigraphic analysis has been applied to a variety of geologic settings; siliciclastic (Vail *et al.*, 1977; Posamentier and Vail, 1988) carbonate

successions (Bubb and Hatlelid, 1977; Sarg, 1988), and more recently to volcanic rifted margins (Spitzer *et al.*, 2008; Jerram *et al.*, 2009; Ellefsen *et al.*, 2010). In this study, preliminary sequence stratigraphic description of subsurface facies from seismic and well log data set is presented.

LITERATURE REVIEW

Study Area

The Niger Delta is situated in the Gulf of Guinea on the west coast of Central Africa (Figure 1a). Located in the southern part of Nigeria between latitudes 4° 00'N and 6° 00'N and longitudes 3° 00'N and 9° 00'N, its limits include the Gulf of Guinea (or the 4000 m bathymetric contour) to the south and older (Cretaceous) tectonic elements such as the Anambra Basin, the Abakaliki Uplift and the Afikpo Syncline to the North. The Cameroon Volcanic Line and the Dahomey Basin represent the eastern and western bounds of the Delta respectively (Tuttle *et al.*, 1999, Reijers, 2011).

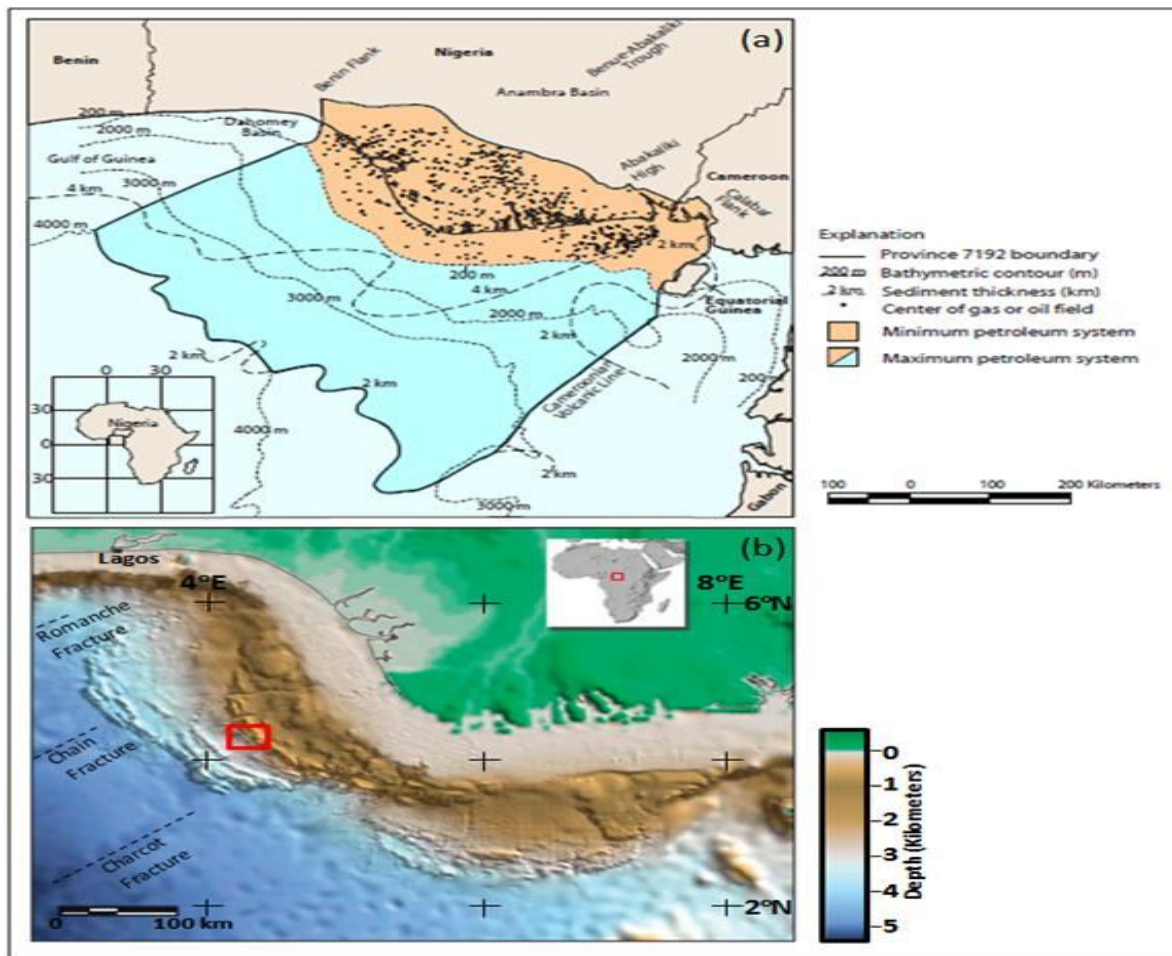


Fig. 1: The Niger Delta. (a) Province outline of the Niger Delta region showing bounding structural features and Oil and Gas Field centers (Modified from Tuttle *et al.*, 1999). (b) High resolution bathymetric image of the Niger Delta region indicating major structural elements (Modified from Corredor *et al.*, 2005). The study area location is indicated in red polygon.

The lithostratigraphy of the Delta consists of three stratigraphic units of Cretaceous to Holocene origin (Short and Stauble, 1967; Frankl and Cordry, 1967; Avbovbo, 1978; Reijers, 2011); the undercompacted and overpressured foraminiferous Akata marine source rock, the paralic Agbada reservoir rock and the continental Benin Formation. It is speculated that syn-rift clastic deposits, fragments of the pre-rift oceanic crust, underlie the Akata formation (Corredor *et al.*, 2005; Sahota, 2006). The shape and internal structure of the Niger Delta are controlled by two principal factors: (1) gravitation induced collapse of sediments on the continental shelf which are consumed by contractional structures in the more outboard regions and; (2) the original configurations of the post-rift oceanic basement beneath the Delta with its assay of major fractures such as the Romanche, Chain and Charcot fractures (Figure 1b) of Early Jurassic–Cretaceous origin (Corredor *et al.*, 2005). This has led to the evolution of five tectonic belts within the Delta, each with its characteristic structural style. These zones have been identified by Corredor *et al.* (2005) as: [1] a proximal to land extensional province beneath the continental shelf; [2] a zone dominated by

active and re-active mud diapirs beneath the upper continental slope; [(3) the inner fold and thrust belt; [4] a transitional detachment fold zone beneath the lower continental slope; and [5] the outer fold and thrust belt. Pronounced seafloor expression of structures not covered by recent sediments indicates ongoing deformation across these structural belts. The study area is located in the deepwater Niger Delta (Figure 1b) in OPL250 and in water depths generally in excess of 2000 m.

MATERIALS AND METHODS:

Data

Data available for this study included seismic data volumes, well logs suite for a single well and age marker from a field in the deepwater Niger Delta. The seismic data volume is a post-stack time migrated volume consisting 940 inlines and 1050 crosslines. Total record length is 7200 msec. The data coverage is approximately 460 sq. Km. The inline and crossline intervals are 17.32 m and 26.94 m respectively. The field is generally in water depths of over 2 km. The suite of logs include the gamma ray log, resistivity log, interval transit time log, neutron density log, bulk

density log and caliper log. The logs generally cover the range 3079 m to 5689 m (10,100 - 18660 ft.). The logging interval for all logs is 0.15 m (0.5 ft.). The time-depth survey extended from 0 to 5351.4 m (0 - 17552.5 ft.) and has interval spacing of 50 m (164 ft.). The well also came with time markers.

Methodology

The well was tied to the seismic data using the provided check-shot survey and analyses carried out in Petrel. The study was severely limited by a number of factors: (1) Only one well, the Whale 01 well, was available in the study area and this totally hindered the correlation of sequences across the field; (2) extensive tectonic deformation and possibly diagenesis in the eastern province also made near impossible, the identification of sequence boundaries and stratigraphic terminations from seismic data. This region constitutes more than 80 % of the field and; (3) within the western undeformed province, sequences boundaries were also difficult to decipher from the seismic data. This probably is as a result of the well documented and reported general conformability of the sedimentary succession of the Niger Delta (Doust and Omatsola, 1990). The only observable sequence boundary signatures in the seismic data are confined to growth sediments which have accumulated in piggyback basins behind thrust related anticlines in the eastern province. For the sub-kinematic section, sequences boundaries and stratigraphic features, have been obtained mostly from well top information provided along with the well data. Description of the sequences in the 'WHALE' Field is therefore undertaken under two headings: (1) Sub-Kinematic sequences and (2) Growth strata sequences. Description of sedimentary style for the sub-kinematic section was based primarily on the Gamma Ray log. Other logs utilized include the resistivity log, transit time log, bulk density log, neutron porosity log and a synthetic seismogram computed for the only well in the field.

RESULTS AND DISCUSSIONS

Sub-Kinematic Sequences

Sequence boundaries were located at the highest gamma ray log peak separating a lower fining upward pattern from an overlying overall coarsening upward pattern. This location correlates with maximum flooding surfaces which mark the boundary between the Transgressive System Tract (TST) and the overlying Highstand System Tract (HST). This scheme corresponds to the Galloway (1989) Genetic sequence model (see Figure 2) and has been found to be very applicable within the Niger Delta (Magbagbeola and Willis, 2007). Six sub-kinematic sequences were identified from well top information. Starting with the deepest (oldest), these sequences are designated $K_s1 - 6$ and are discussed below (Figure 3). The sequences are third order sequences (age range between 1-10 million years [Ma]) but sometimes appear to contain perturbations of fourth

order sequences. High gamma ray log values (curve deflections to the right) are regarded as marine shales while significantly lower gamma ray log values (curve deflections to the left) were identified as sands. Generally, the sedimentary pile is made of very thick shale sequences interrupted by much thinner sandy intervals. Sand prone intervals are thicker at deeper levels but become thinner in upper sections of the sedimentary pile. It is expected that sands are confined to entrenched channels and their overbanks and have largely been deposited by gravity induced turbidity flows which cut and fill pathways in the thick hemi-pelagic fallouts of the low energy environment. Table 1 provides depth ranges and computed sedimentation rates for Sub-Kinematic sequences for the 'WHALE' Field.

K_s1 Sequence

This sequence is the deepest (oldest) sequence penetrated by the Whale 01 well (Figure 3 and 4). The sequence extends from 5550 ms two-way travel time (tw) (5040 m) to the bottom of the well and represents strata with age predating 16.5 MA. The sequence consists mainly of massive shales representing hemi-pelagic sediments deposited in a low energy environment where there is a restriction of water bottom circulation. In the bottommost sections of this sequence (Figure 4), thin sand intervals displaying coarsening upward signatures punctuate the massive shales. Log curve shape of these sand intervals suggests para-cycles within this depositional cycle. Near the top of this sequence, thicker coarsening upward sands exist (e.g. Sand 1) and confer on the sequence an overall coarsening up character. The sands have relatively high resistivities indicating hydrocarbon saturation. The top of this sequence is capped by a thin shale section which possibly represents hemi-pelagic fallout as a transition from higher to lower energy depositional environment occurred. A facies change is indicated in the thick shale section between 5620 ms and 5730 ms where interval transit times and porosities are relatively higher than for adjacent shales. This could be due to pore pressure increases occasioned by gas build-up. Generally, synthetic seismogram signatures for the upper and lower boundaries of sand intervals show as strong negative and moderate positive polarity reflections respectively.

K_s2 Sequence

This sequence lies upon the K_s1 sequence and is bounded at its base and top by the 16.5 MA and 15.5 MA sequence boundaries. This confer on the sequence a 1 Ma deposition time span. The sequence extends from 5350 ms to 5550 ms (4740 m to 5040 m). At its near base is a 58 m thick clean sand interval (Sand 2) with a gradual coarsening upward log pattern at its base and an abrupt upward fining top (Figure 4). This sand interval possibly represents mass transport complex deposit in a high energy environment. Above this sand interval is a massive shale interval with thin sand intervals in its middle and top. Sand intervals are

associated with increased porosities and high resistivities.

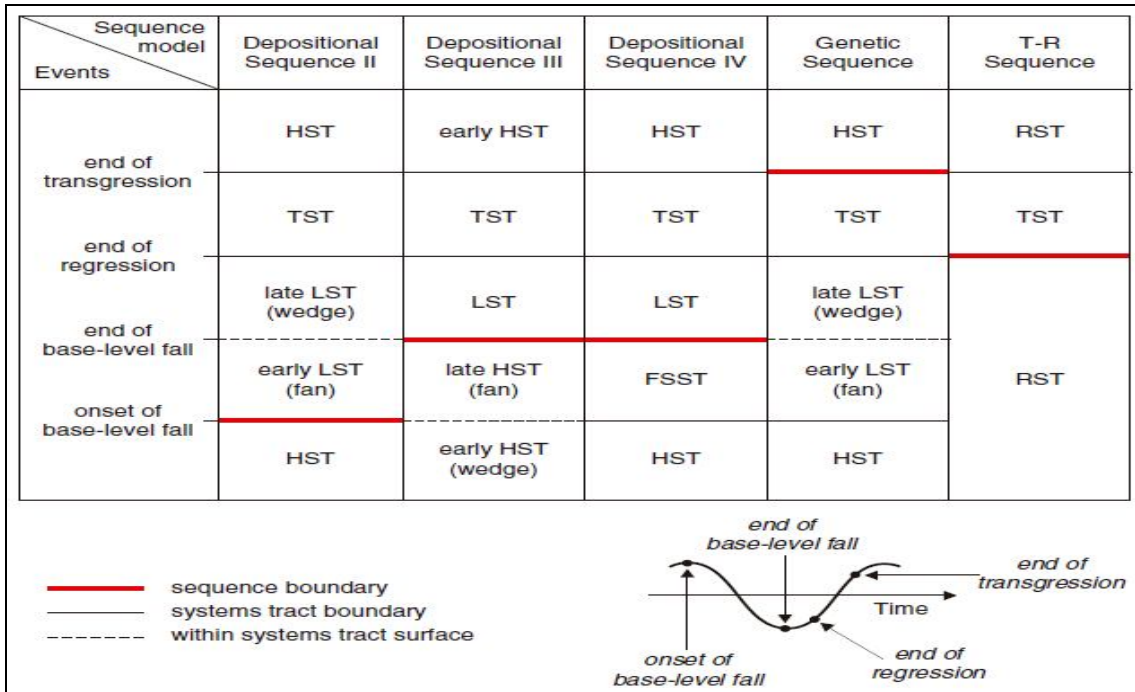


Fig. 2: Common System Tracts and Sequence Boundaries Models (Catuneanu, 2006). Credits: **Depositional Sequence II** (Haq *et al.*, 1987; Posamentier *et al.*, 1988); **Depositional Sequence III** (Van Wagoner *et al.*, 1988, 1990; Christie-Blick 1991); **Depositional Sequence IV** (Hunt and Tucker 1992, 1995; Plint and Nummedal, 2000); **Genetic Sequences** (Galloway, 1989; Frazier, 1974), **T-R Sequences** (Embry 1993, 1995; Curry 1964). Abbreviations: LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling-stage systems tract; RST—regressive systems tract; T-R— transgressive-regressive.

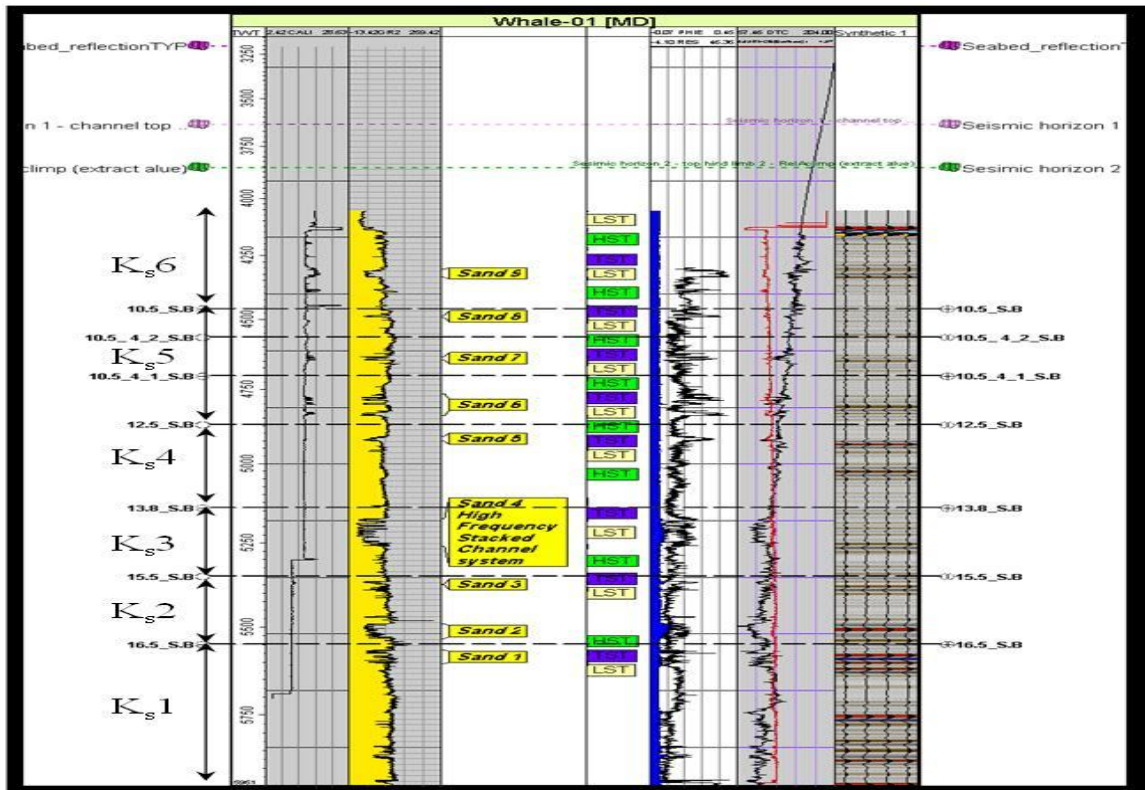


Fig. 3: Sub-Kinematic Section Sequences of the 'WHALE' Field from Well Logs and Synthetic Seismogram of the Whale 01. Log Panels from Left to Right are: Time (Ms), Caliper, Gamma-Ray, Comment, Deposition Environment, Resistivity/Sonic, Density/Sonic, and Synthetic Seismogram.

Table 1: Depth Ranges and Sedimentation Rates for Sub-Kinematic Sequences in the 'WHALE' Field.

Sequence ID	Age Span (MA)	Depth (m)	TWT Time (ms)	Sedimentation Rate ft./MA
K _S 1	Not computed	Below - 5040	Below -5550	Not computed
K _S 2	1	4740 - 5040	5350 - 5550	984
K _S 3	1.7	4440 - 4740	5140 - 5350	582
K _S 4	1.2	4072 - 4440	4870 - 5140	926
K _S 5	2	3564 - 4072	4458 - 4870	838
K _S 6	Not computed	3274 - 3564	4160 - 4458	Not computed

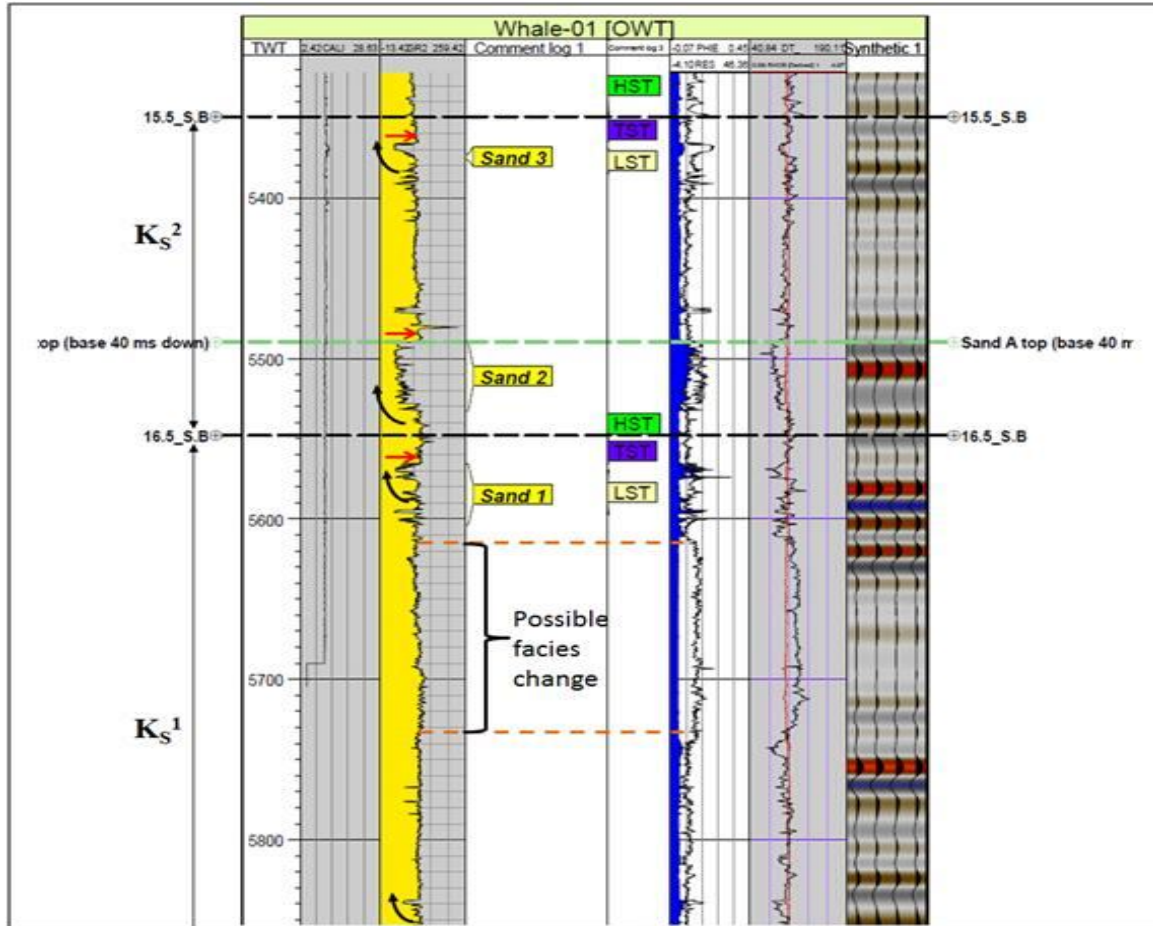


Fig. 4: Close-Up View of the K_S1 and K_S2 Sequences of the 'WHALE' Field. Panels are same as in Figure 3.

K_S3 Sequence

This sequence lies above the K_S2 sequence and is bounded by the 15.5 MA and 13.8 MA sequence boundaries at its base and top respectively (Figure 5). The age of this sequence spans 1.7 MA. It occurs between 5140 ms and 5350 ms (4440 m and 4740 m), a two-way listen time span of 210 ms (300 m). The lower section of this sequence consists of thick hemipelagic marine shales often punctuated by very thin (order of 2 m thick) sand intervals. At the near summit of this sequence is a thick approximately 120 m sand section with highly jagged (serrated) gamma ray log signature (Sand 4) with associated high resistivity response. This pattern indicates a

considerable period of alternating high energy and low energy deposition environments. In the deep water settings as the study area, this most possibly indicates a cyclic alteration between gravity slump deposits (turbidites) and hemi-pelagic sedimentation. The base of this sand unit shows a gradual coarsening upward pattern which indicates gradual increase in the energy of the environment.

K_S4 Sequence

This sequence overlies the K_S3 sequence and is bounded at its base and top by the 13.8 MA and 12.5 MA sequence boundaries, a time span of 1.2 MA (Figure 5). The sequence occurs between 4870 ms and

5140 ms (4072 m and 4440 m), a two-way listen time span of 270 ms (368 m). The lower section of this sequence consists of massive hemi-pelagic marine shales of the High-stand System tract (HST). The thickness of this shale indicates a very long hiatus in

sand deposition. At shallower levels, a sand interval with a symmetrical wedge shape (channels fill) gamma ray log pattern occurs. The lower and upper parts of this sand unit have linear coarsening

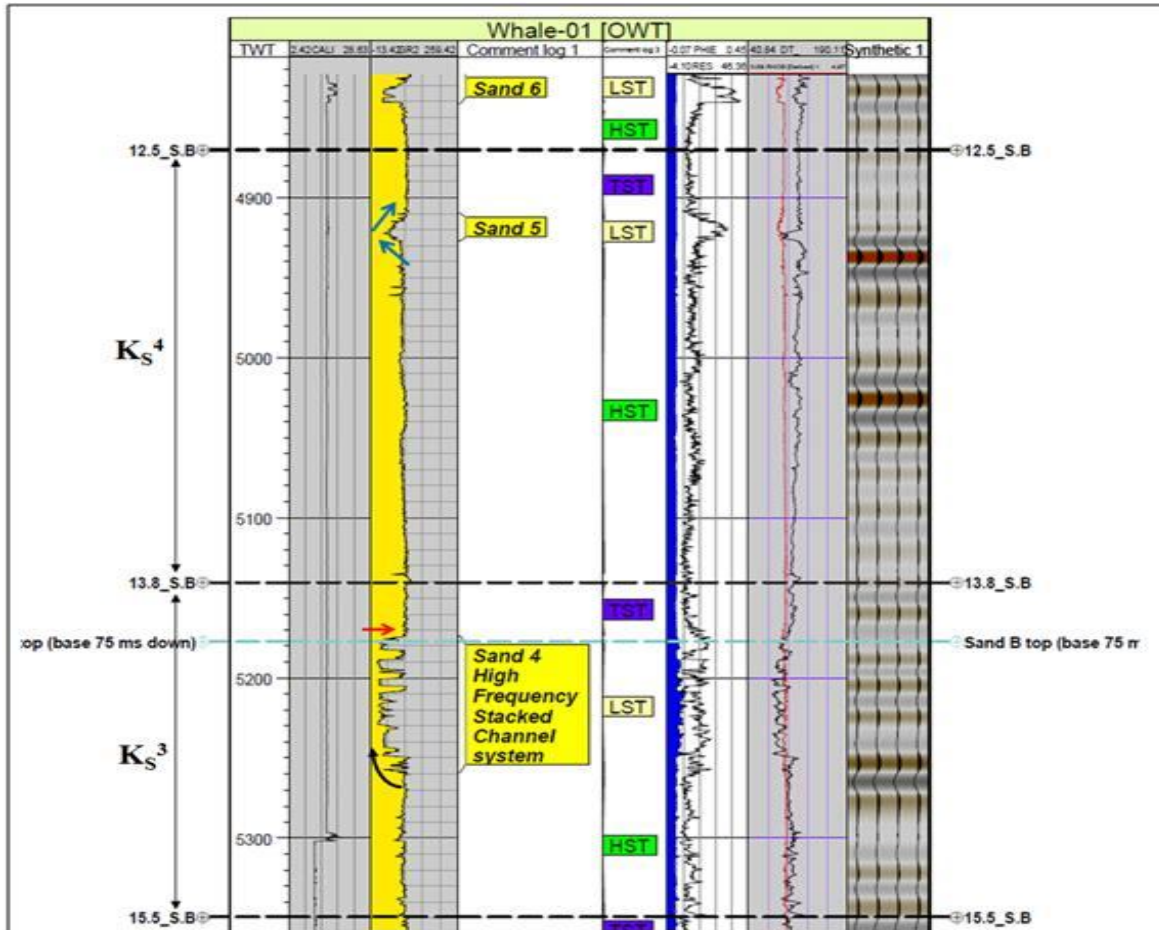


Fig. 5: Close-Up View of the K_{S3} and K_{S4} Sequences of the 'WHALE' Field. Panels are same as in Figure 3.

upward and fining upward log patterns respectively. These indicate that the increase in depositional energy marking the onset of deposition and the decrease in energy which marked the end of deposition of this unit were of constant rates. Sand intervals have low resistivities.

K_{S5} Sequence

This sequence overlies the K_{S4} sequence and is bounded by the 12.5 MA and the 10.5 MA sequence boundaries (Figure 6). It spans 2 MA and lies between 4458 ms and 4870 ms (3564 m and 4072 m), a listen range of 412 ms (508 m). This sequence is the longest (time relative) of logged sequences within the 'WHALE' Field. It possibly consists of three 4th Order (smaller) sequences (K_{Sa}^5 , K_{Sb}^5 , K_{Sc}^5) with time spans of 0.5 – 1 MA. The internal boundaries of these sequences are indicated by the 10.5_4.1_S.B and 10.5_4.2_S.B markers. Sand intervals within this sequence generally have an abrupt coarsening upward base and a gradual fining upward upper boundary. This indicates that the onsets of sand depositions were instantaneous while cessations were gradual. The

sands could represent sands flushed from channel mouths at the onsets of LSTs or slump gravity flows which were sorted during the downslope transport. Sand 7 appears to be composed of two distinct incidences of sand deposition interjected by a relatively short period of hemi-pelagic sedimentation. The lower section of this sand has a bell shaped log signature with an abrupt coarsening upward base and a gradual fining upward top. This section possibly represents a basin floor fan. The upper section has a funnel shaped log signature with a gradual coarsening upward base and an abrupt fining upward top. The upper section possibly derives from sand flushing from the mouth of a channel. Sand intervals have low resistivities.

K_{S6} Sequence

This sequence occurs between 4160 ms and 4458 ms (3274 m and 3564 m) (Figure 6). It is bounded at its base by the 10.5 MA sequence boundary and is the shallowest sequence logged in the field. A sand prone interval (Sand 9) occurs in the middle of the sequence

between 3398 m and 3425 m, with a thickness of 27 m. The base of this sand interval indicates an abrupt

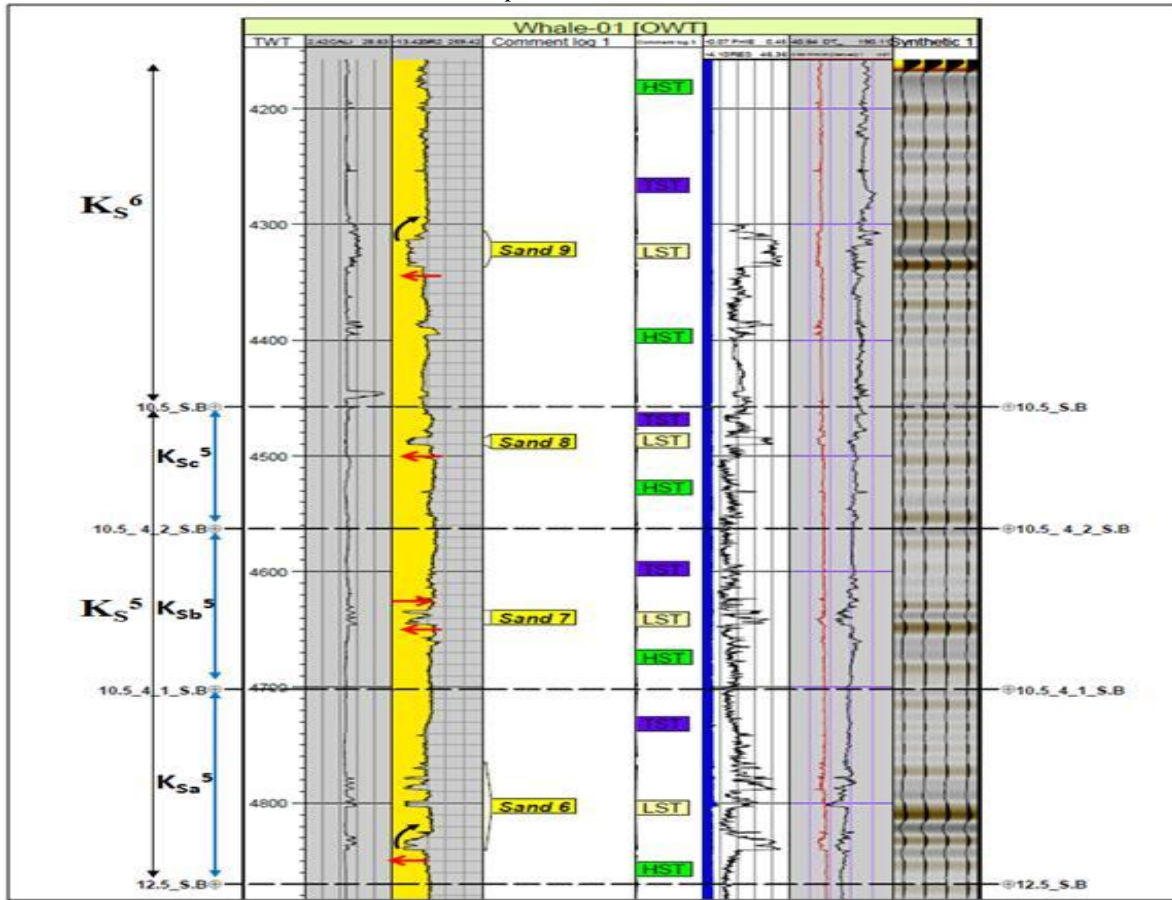


Fig. 6: Close-Up View of the K_{S5} and K_{S6} Sequences of the 'WHALE' Field. Panels are same as in Figure 3.

change from fine grained hemi-pelagic deposition to coarse grained sediments. This transition in deep-water setting is characteristic of basin floor fans resulting from a high rate of sand flushing from the mouths of previous channels (Mitchum *et al.*, 1993) during the low stand system tract (LST). The top of this sand interval has a fining upward pattern and indicates a transgressive system. The HST above this transgressive regime grades upward quite rapidly into very clean LST coarse sediments (Figure 6). Sand intervals have low resistivities.

Growth Strata Sequences

Three distinct sequences were identified from growth strata deposited in piggyback basins behind trust related anticlines (Figure 7). These sequences are younger than the Kinematic section sequences. These sequences are denoted (starting from the oldest) G_{S1} – 3. Sequence boundaries are identified according to the criteria of Mitchum *et al.* (1977) as surfaces of non-deposition marked by stratigraphic unconformities or their correlative conformities. These boundaries are essentially typified in erosional surfaces and surfaces across which the lapout patterns differ (e.g. downlapped, onlapped and toplapped surfaces). Table 2 is a summary of the characteristics of sequences within the growth strata for the 'WHALE' Field.

G_{S1} Sequence

This is the oldest of the growth strata sequence. It overlies, onlaps and pinches out on the top of the Kinematic section (Figure 8). It fills structural lows on the top of the Kinematic section and generally represents strata deposited after the cessation of tectonic activity for most of the field. The exceptions are two; (1) in the extreme northeast above the hinterland anticlinorium where recent tectonic activity has arched upward and faulted this sequence; (2) in the southernmost foreland thrust region where this sequence pinches out against the backlimb of the foreland thrust anticline and; The top of this sequence is defined by concordant reflections although erosional truncation occurs locally at incised channels locations. Reflection amplitude for this sequence is low at the base and increases to moderate to high amplitudes at its top.

Reflections are parallel to sub-parallel at the base and become more divergent towards the top. Reflection cycle breadths are fairly large. Within the sequence, extensive erosional channels are observed and possible reworking of deposits near the top of the sequence. The sequence is capped by a strong, fairly continuous reflection which possibly represents hemipelagic shales deposited as the energy level of the system waned.

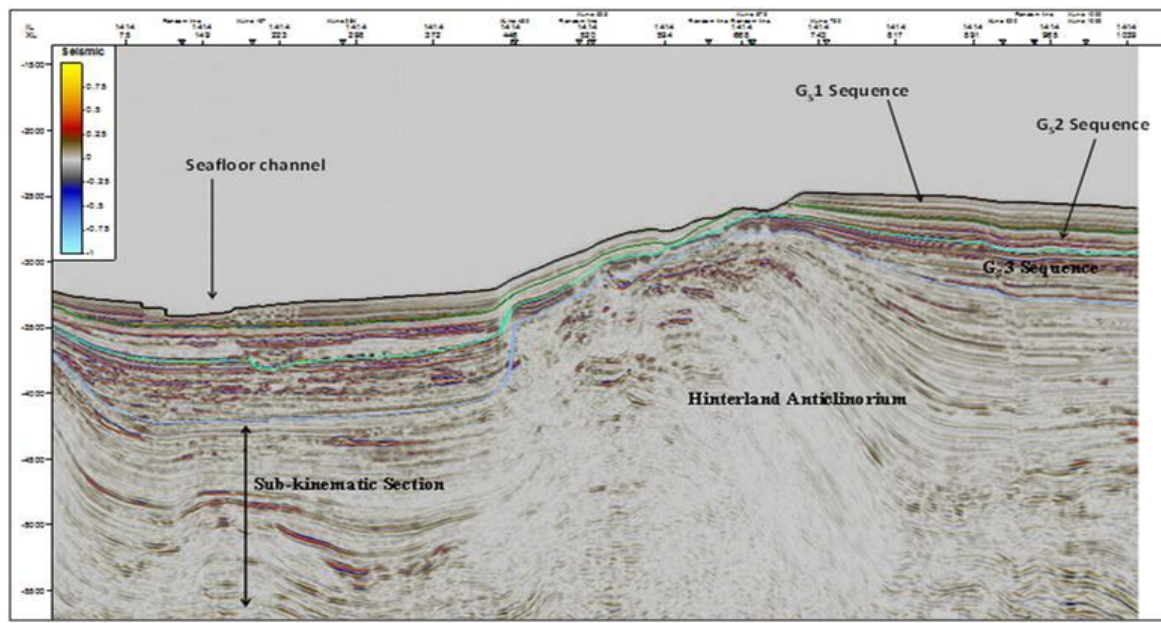


Fig. 7: Growth Strata Sequences G_S1-3 of the 'WHALE' Field above the backlimbs of Thrust Related Anticlines.

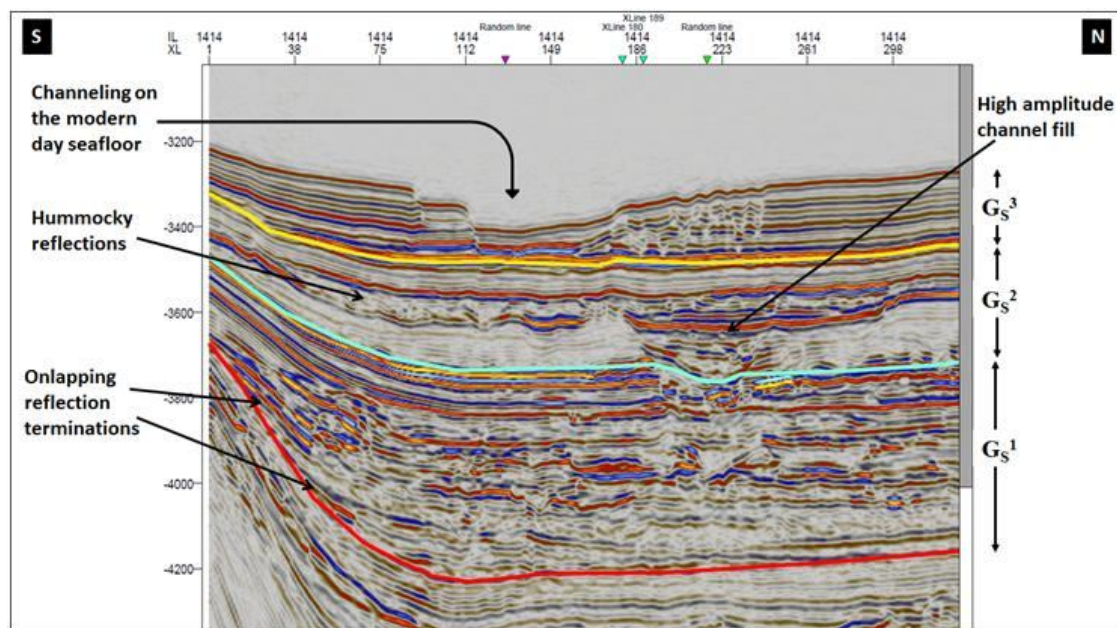


Fig. 8: Close-Up View of Growth Strata Sequences of the 'WHALE' Field.

G_S2 Sequence

This sequence appears to onlap and downlap onto the G_S1 Sequence (Figure 8). Reflections within this sequence are generally of low amplitudes and at the lower boundary are fairly continuous. Reflections become hummocky and of higher amplitudes towards the middle section indicating an increase in the energy of the deposition environment. Reflections become continuous and parallel at the summit of the sequence. Like the G_S1 Sequence, the G_S2 Sequence is also folded upwards and faulted by En echelon northeastwards dipping normal fault sets above the anticlinorium and thins and pinches out against the

foreland anticline. This sequence possibly consists of mud rich gravity driven mass transport complexes with the hummocky section representing intervening sand-rich reworked deposits. Behind the foreland thrust anticline, the sequence appears to fill a major channel way incised by bottom current into the G_S1 Sequence. This channels fill possesses high reflection amplitude which could indicate that the channels fills are sand-rich facies.

Table 2: Summary of Stratigraphic Characteristics for the Growth Strata Sequences of the 'WHALE' Field

Sequences	Base or Top	Boundary	Reflection Amplitude	Reflection Pattern	Reflection Frequency	Thickness	Deformation	Inferred Lithology	Environment of Deposition
G _s 1 Sequence	Base	Onlap onto top of kinematic section (Agbada Formation of the deep water delta)	Low to moderate	Sub-parallel and fairly continuous	High	Follows topographic lows	Normal strike-slip faulting and	Possibly hemipelagic shales grading into sand rich deposits at the top	Uniform rates of deposition in low energy environment.
	Top	Generally concordant but erosional at channel locations.	High	Divergent and discontinuous	Low		Normal strike-slip faulting and		Relatively high and variable energy.
G _s 2 Sequence	Base	Onlap and downlap onto G _s 1 sequence	Low	Sub-parallel and fairly continuous	High	Follows topographic lows	Normal strike-slip faulting and	Mud rich flow deposited rapidly in relatively medium to high energy deep sea environment	High energy possibly mud rich mass transport complexes.
	Top	Possible toplap	Low	Hummocky to parallel	High		Normal strike-slip faulting and		
G _s 3 Sequence	Base	Concordant	High	Parallel and continuous	High	Follows topographic lows	Normal strike-slip faulting and	Hemi-pelagic shales which have settled in relatively low energy deep sea environment	Uniform rates of deposition. Presence of some erosional channels
	Top	Present day seafloor	Moderate to high		High		Normal strike-slip faulting and		

G₅3 Sequence

This sequence shows concordant reflections at its boundary with the G₅2 Sequence (Figure 8). Its top is the modern day seafloor. The base is interpreted to represent a very short break in deposition between the emplacement of the G₅2 and the increase in hemi-pelagic fallouts. Reflection strength is generally high, parallel and continuous and cycle breadths very low. Reflection character becomes wavy and chaotic towards the backlimb of the foreland thrust anticline where preferred bottom current flow creates active channeling into earlier deposited sediments. This sequence most possibly represents hemi-pelagic sediment deposited in a low energy environment.

Discussion

A total of Nine (9) sequences have been described in the 'WHALE' Field, six (6) sub-kinematic sequences and three (3) growth strata sequences. There certainly exist at least one other sequence between the K₅6 sequence and the G₅1 sequence, which has not been described. It lies at the top of the sub-kinematic section but it has not been logged. The seismic quality here also does not permit the identification of its sequence boundaries, boundary terminations or reflection characteristics.

Stratigraphic sequences in the study area consist of thick hemi-pelagic shales indicating long periods of low energy deposition environments. Sand intervals are generally thin and are indicated to be often instantaneous. They consist of basin floor fans, reworked sand deposits and sand flushed from channels mouths at the onset of lowstand system tracts (LSTs). Sand intervals in deeper sections (K₅1 – K₅3) are charged with hydrocarbons while intervals in shallower sections (K₅4 – K₅6) are

water filled. This separation between hydrocarbon and water saturated sands roughly coincides with the onset of thrust activity at 12.8 MA (L. Lonagan, Personal communication, 2017) in the Niger Delta. This implies that the timing of hydrocarbon generation and migration within the field was synchronous with thrust fault initiation. Sands deposited prior to thrust initiation therefore received recharge while sands deposited post-thrust initiation failed to receive hydrocarbon charge. Though sand intervals are generally thin, vertical stacking increases net to gross ratios and possibly vertical communication between reservoir systems. Significant seal potential exists due to the thick shale sequences. Growth strata sequences indicate a cyclic process of hemi-pelagic deposition, channel incision followed by aggradation and levees development, sediment reworking, further hemi-pelagic deposition and finally sub-areal erosion. This process relates to transient thrusting episodes, with thrust growth at uneven rates within cycles (Shaw et. al, 2004).

CONCLUSION

A preliminary study of stratigraphic sequences from a field in the deepwater Niger Delta has been undertaken. Nine sequences have been identified and described. Depositional environments typify deepwater settings where low energy hemi-pelagic deposits dominate and sand systems consist of gravity driven slump complexes. The study provided insight into stacking of reservoir prone facies and timing of recharge with the field.

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