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Research Paper

THE PROSPECTIVITY AND EXPLORATION POTENTIAL OF ONSHORE SLOPE FAN PLAY, NIGER DELTA BASIN, NIGERIA

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The need to replace oil/gas production reserves cannot be over-emphasized, especially in areas with production facilities and ullage capacity, as in the onshore setting of the Niger Delta, where familiar and proven play types have been heavily drilled and tested. Any successful exploration effort on the onshore Eocene-Oligocene Slope Fan play, should have attractive economics, provided reserve replacement volumes and cost effective analogue for better understanding of such play exists in present-day deep-water setting. These views necessitated the present study. The Slope Fan objective was defined by mapping seismic reflector terminations, application of seismic and sequence stratigraphic principles, to well and 3D data set in the Eastern part of the Northern Depobelt. This provided a better understanding of the reservoir, seal facies and related Geologic risks. The MIN, MAX and RMS attribute extractions of the mapped fan body were used to highlight the internal architecture and constrain quality sand-prone "sweet-spot" areas. Further analysis of the observed "Mound Deposit" geometry, revealed different unconnected stratigraphic "Deposition Lobes", separated by thin shale levels and the overall stacking pattern. In this study, the Geologic Chance Of Success (GCOS) was 0.14-0.35 for the "sweet spot" areas, where the P50 risked resources range of 2-36 MBOE was calculated. These exploration data should support a Near Field Wildcat strategy and development program. The methodology and technical understanding from this effort, have been applied to an opportunity which is currently producing some 3000 BOPD and at 35 Km from a high water-cut Field in the Niger Delta Basin.

Keywords: Niger delta basin, Onshore depocenters, Slope channels, Slope fan complex deposits

INTRODUCTION

Most exploration wells in the onshore setting of the Niger basin bottomed within "shallow" deltaic fluvial sediments from where oil and gas resources have been discovered, and are being produced. The national reserve base is currently about 37 BBO recoverable reserves (Allison-Madueke, 2010). At the current average of 2.2

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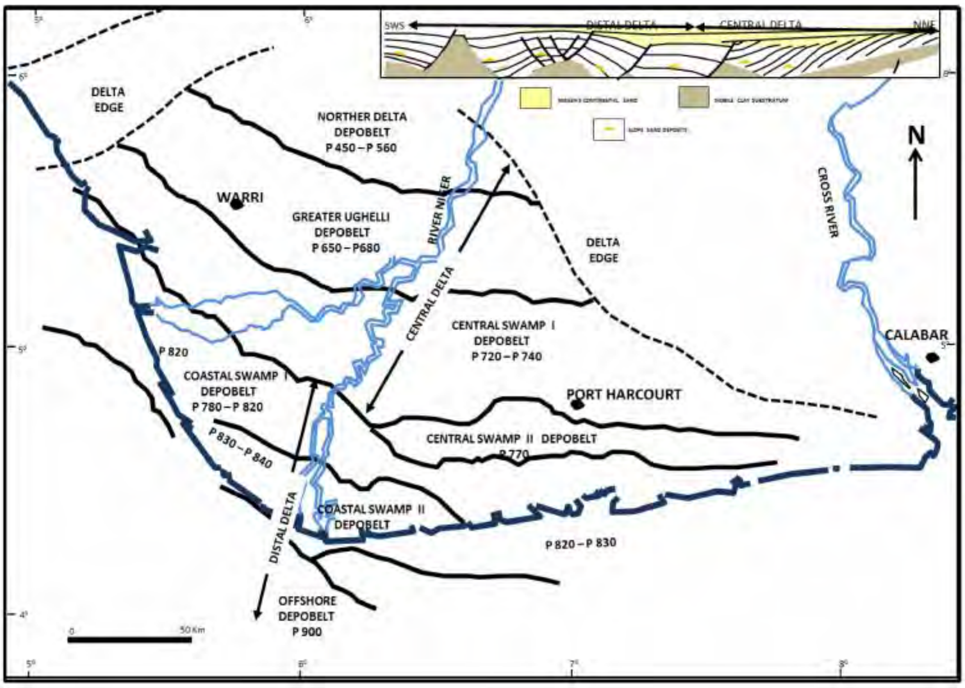
MBO daily production, the reserve base can only last some 40-45 years, if new reserves are not added to the Inventory. To increase the reserve base at both corporate and national levels, exploration efforts in the deeper medium-high overpressure slope domain, which underlies the current window of production, should be encouraged. Some private companies are already prospecting in this slope setting where oil-gas condensate bearing turbidite fans have been logged. More successes in such untested slope setting would contribute to reserve replacement and arrest fast reserve depletion.

There has been progressive southward progradation of fluvial sediments into the delta since Eocene times (Figure 1) (Olawoki, 2014) resulting in different time-bound building blocks (depobelts) of the basin. Stacking of sediments on the unstable over-steepened shelf edges would lead to slope failure and sediment slumping down dip into the upper-lower slope setting, where series of new and/or pre-existing channels and canyons would act as sediment conduits. These narrow-wide sediment fairways are known to connect the proximal fluvial sand-rich deposits, to the distal down-dip structural lows or depocenters on the continental slope where the sediments accumulate as quality reservoir and argillaceous deposits within the basin. This sediment supply-connection-deposition relationship is documented in the present-day slope setting, and it is believed to be a continuously and widely replicated process across the region from the Eocene times (Evamy *et al.*, 1978).

The objective of this study is to highlight the occurrence, associated geologic risk and prospectivity of slope fan deposits in the lower section of Agbada Formation and upper part of

Figure 1: The Depobelts of Niger Delta Basin



Source: Doust and Omatsola (1990)

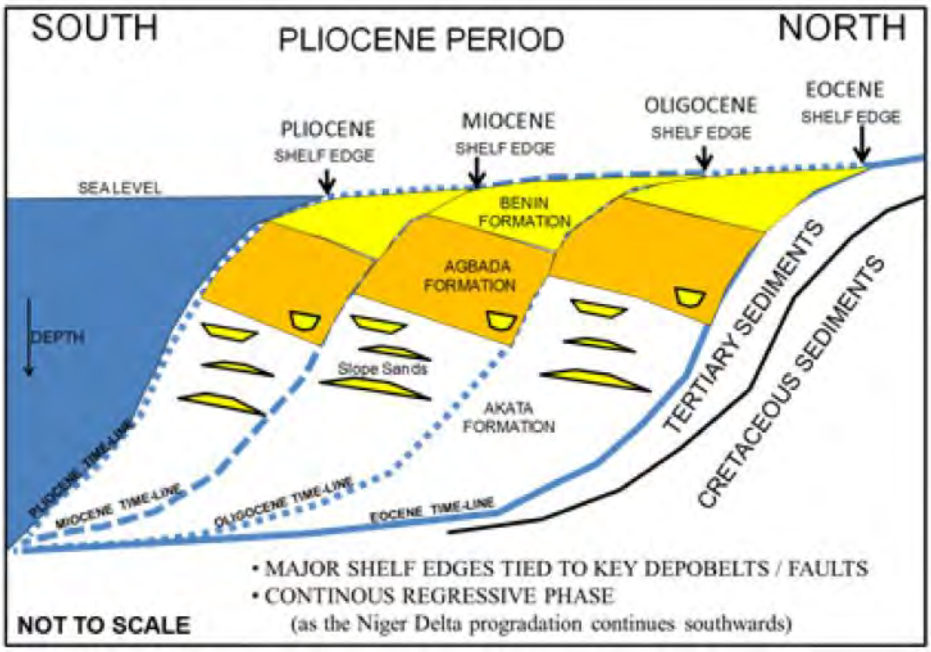
Akata shales in the onshore setting of basin, by the application of seismic stratigraphy principles.

GEOLOGIC SETTING

Based on lithostratigraphic units, the basin can be subdivided into three main formations, namely the Akata Formation, Agbada Formation and Benin Formation (see Figure 1). The stratigraphy of each Formation is well described in Short and Stauble (1967) and Weber and Daukoru (1975) publications. In summary, the Akata Formation is primarily under-compacted shales which are mobile where the overburden is thin as in the deepwater offshore setting; the Agbada Formation is mainly the paralic alternating sand and shale series with most of the oil and gas discoveries; and the Benin Formation is overlying reddish continental sands and gravels with few thin shale breaks. From the combination of the GR(Gamma Ray) – Res(Resistivity) – Sonic – Density well logs, the deepest marine shale tied to overpressure development is generally termed the "Top" of Akata Formation. The top of the first marine shale below the deepest thick freshwater bearing or transition saline water – freshwater zone sand, is often termed the "Top" of Agbada Formation, while the base of the same overlying thick freshwater sand level is mostly picked as the "Base" of Benin Formation.

The application of sequence stratigraphy principles and the different key time lines do not conform to the defined lithostratigraphic boundaries (Figure 2). However, the depositional relationship (as the sands grade into the shales) between the three different Formations are well defined by the sequence stratigraphic understanding of the evolution of the basin. Recent exploration efforts apply more of the

Figure 2: Contrasting Lithofacies and Chronofacies Limits of Niger Delta Basin



Source: Olawoki (2014)

sequence stratigraphic and seismic stratigraphic approaches to leads and prospect definitions in order to reduce the associated geologic risk, and ensure technical and possible economic successes.

STUDY AREA

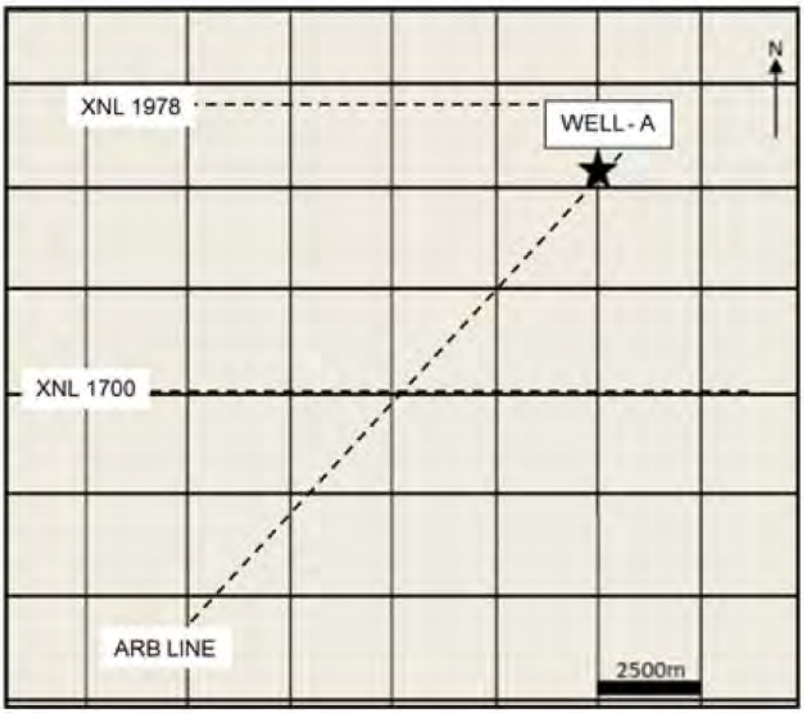
The study area is in the eastern part of the Northern Delta Depobelt (Oligocene age), bounded by regional growth faults. There is no oil and gas production in the area, but some few nearby exploration wells were reported dry with some hydrocarbon shows.

MATERIALS AND METHODS

Only about 400 Sq. Km. of 3D seismic data and one well log are available for the project (Figure 3). Below a regional "peak" reflector which runs across the area, the seismic data is very poor. Therefore the study efforts were concentrated in the 1500-2600 msec window. The subtle but critical seismic reflectors such as the down-laps, top-laps, on-laps, amplitude anomaly definitions and their preservation were not in the primary objectives when the 3D seismic data was acquired and processed. These seismic reflector characteristics are very critical for the mapping and areal definition of potential modest-high risk/ high reward slope opportunities. Rather, the 3D seismic data was for the usual railtrack reflector continuity and the easier structural lead and prospect definition.

In the slope setting, the issue is generally about reservoir definition, quality and continuity as against the experience in the shallow fluvial setting where sheet reservoirs are known to have appreciable area coverage. Therefore, a more focused approach was made to delineate the slope sand facies. The application of seismic and

Figure 3: 3D Seismic Grid, Well Location and Referenced Seismic Sections of the Study Area



sequence stratigraphy principles in the Northern Delta Depobelt of the Niger Delta, was used to define sand-prone Eocene-Oligocene slope fan complexes. Seismic data quality in the study area is fair, as some of the subtle reflectors are not well-imaged. However, concerted efforts were made to understand the seismic expression, reflector continuity, strength, amplitude and anomalies where present. These reflectors were carefully mapped principally to define their stratigraphic limits, structural setting and internal stratigraphic variations (Figures 4-6).

A package of 'peak' reflector (black), with bi-directional down-laps, which bounds a strong 'trough' reflector (red) on a strong 'peak' reflector, was interpreted as slope sand level on an unconformity surface. In parts of the study area, some top-lap reflectors were noted below the strong basal 'peak' unconformity reflector. The exploration Well – A did not penetrate the mapped slope deposit (Figure 6), as the top seismic reflector downlaps before getting to the well location. The objectives then were to test the familiar growth wedge and stacked four-way structural closures in the hanging wall setting. With purely lithostratigraphic/structural lead definition approach, the slope opportunity would be by-passed or missed out entirely if it was part of the well program. Detailed seismic and sequence stratigraphic mapping methodology showed the fan shape and limit of the sedimentary deposit (Figure 7). To appreciate the anomalous attributes distribution within the fan body, the Minimum (MIN), Maximum (MAX) and Root Mean Square (RMS) attributes extractions were generated to provide critical information on the

Figure 4: Objective Slope "Mound" Fan Complex Deposit (Note the Bi-directional Downlaps)

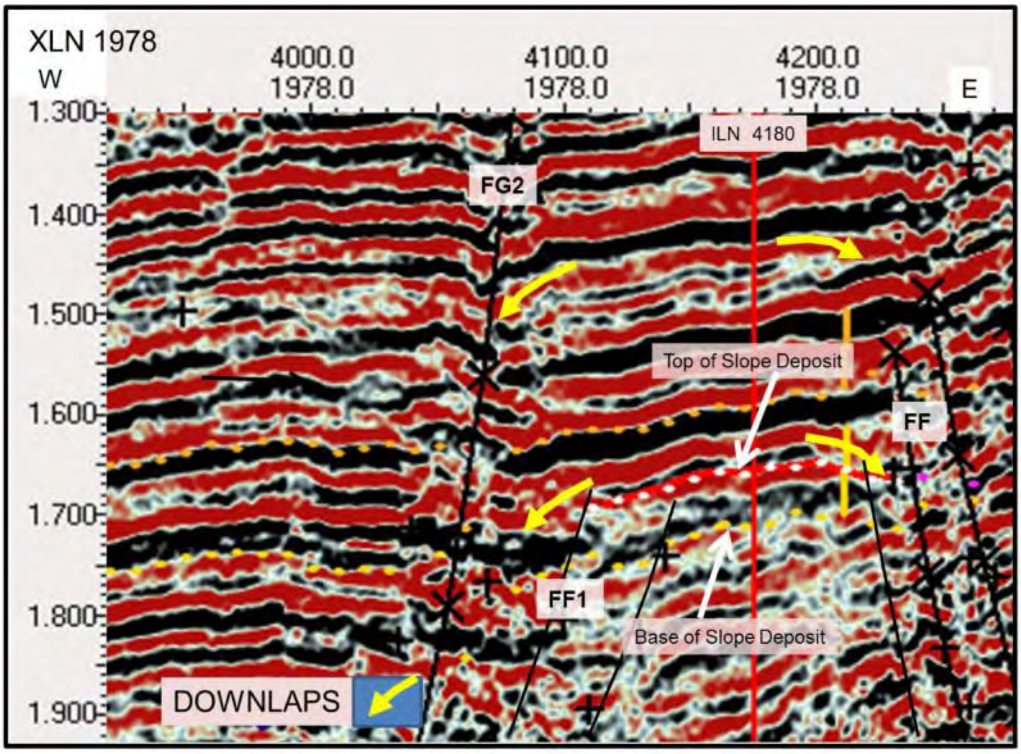


Figure 5: Slope Fan Complex Deposit in the Strike Direction (Note the Bi-directional Downlaps)

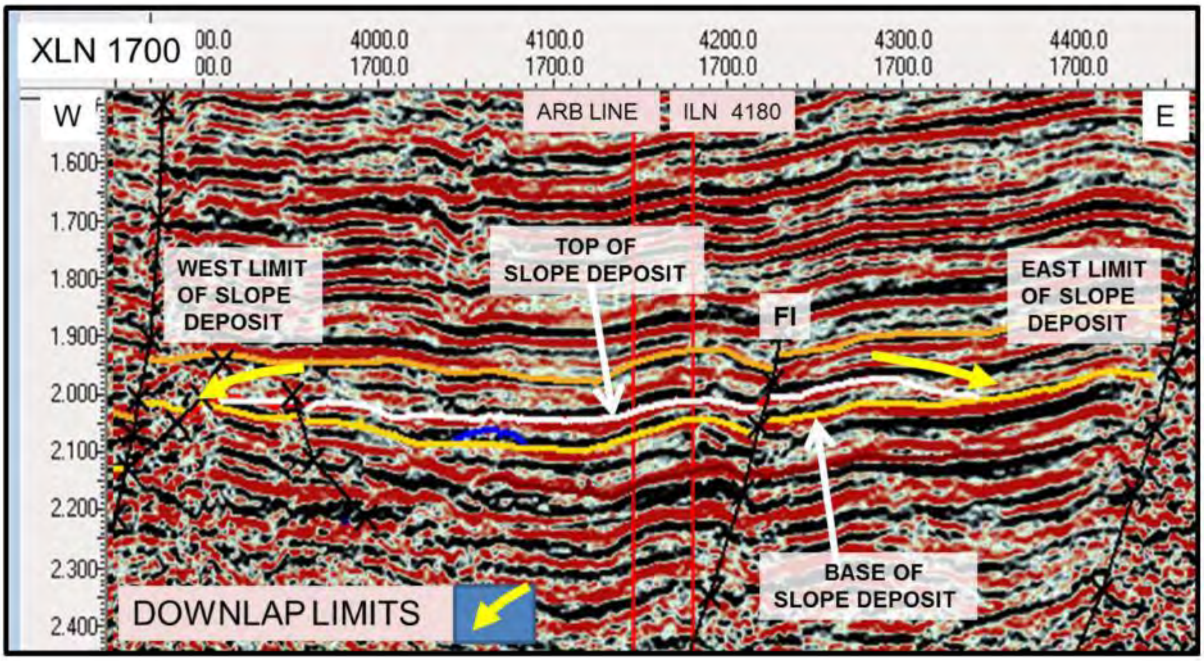


Figure 6: NE-SW 3D Seismic Line Over the Slope Fan Complex Deposit Thinning to the Edges

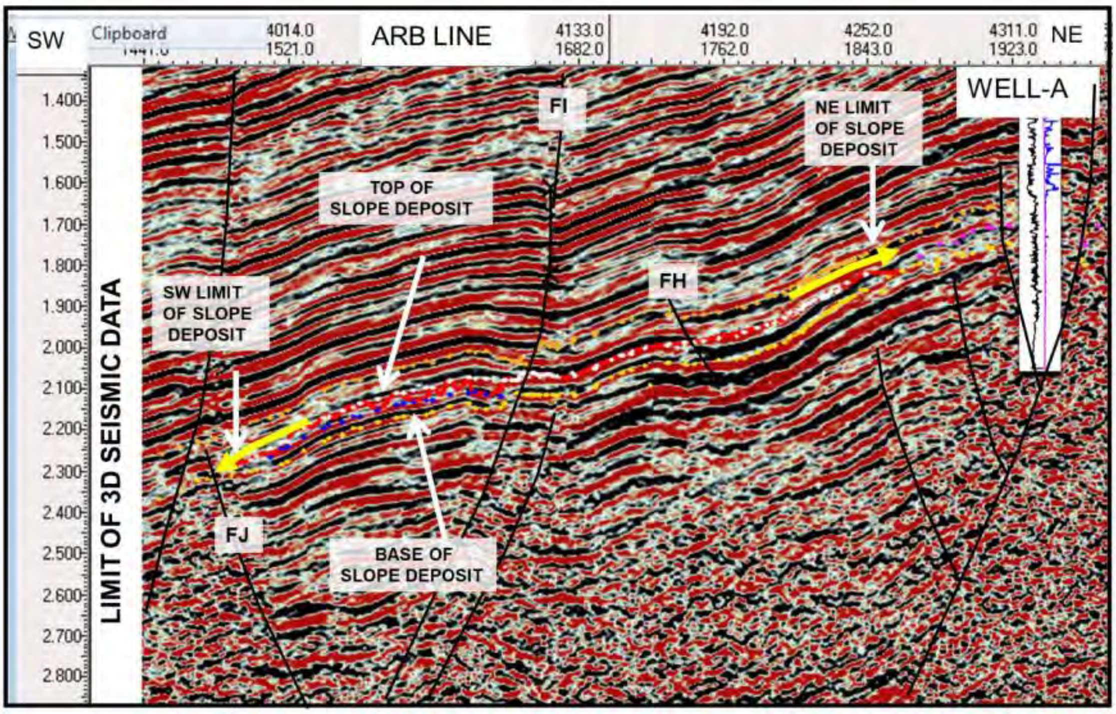
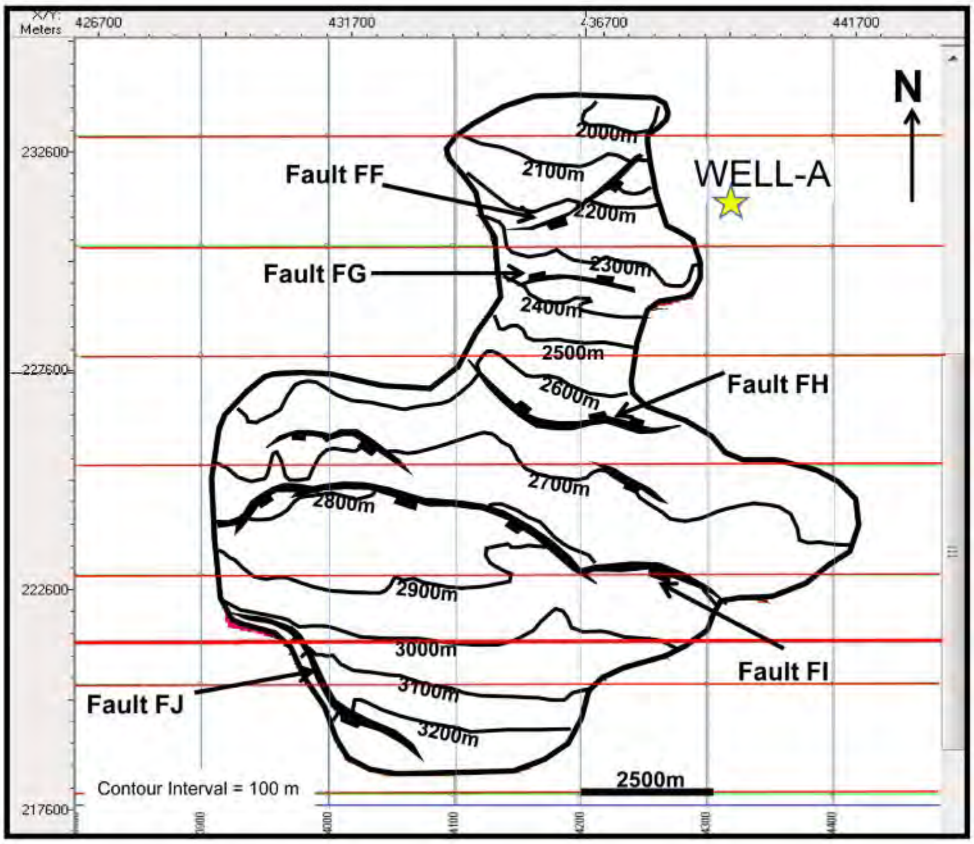


Figure 7: Top of Slope Fan Complex Depth Structure Map



internal architecture of the slope fan complex deposit.

RESULTS AND DISCUSSION

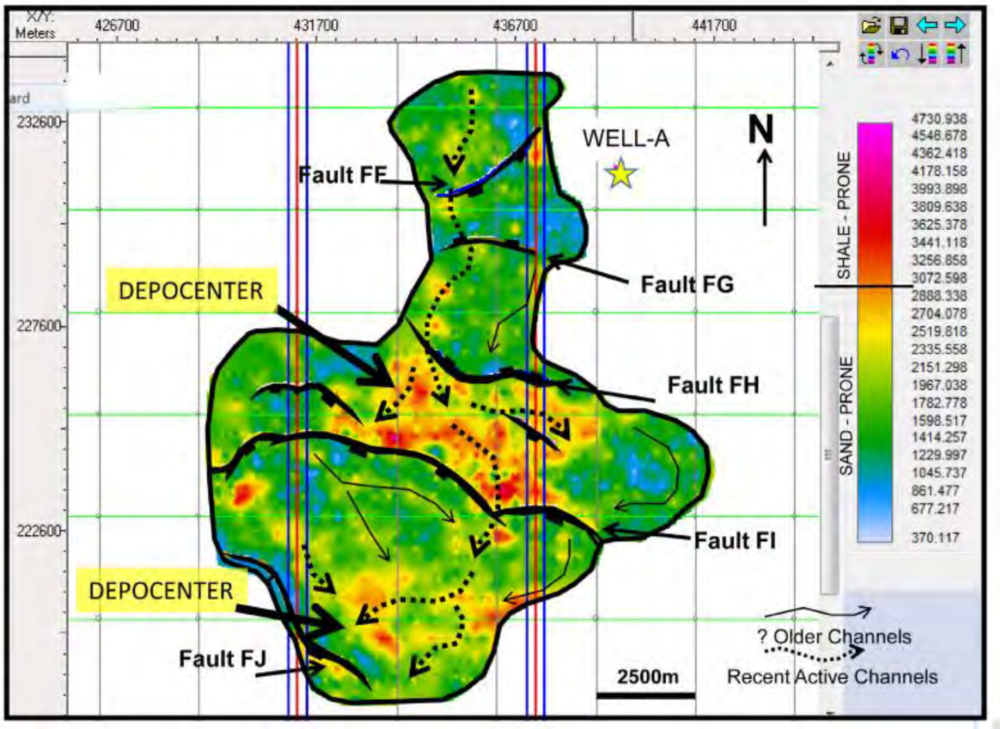
The definition of the slope fan complex package started with the mapping of the top horizon, particularly the subtle bi-directional downlap reflector terminations (Figure 4), which mark the limits of the slope deposit. There were many instances where the downlap limits were not well defined, as the top reflector would just "float" and end abruptly. This is possibly due to the acquisition and processing parameters which did not consider the preservation of such subtle terminations as very critical for opportunity or prospect definition and evaluation. Carrying the top horizon across faults was also challenging to some extent as the seismic reflector characteristics sometimes change or even get very discontinuous making correlation almost impossible, without the application of seismic stratigraphy principles. With time – depth information from "Well A" (Figure 6), appropriate velocity function was generated to and used to convert the top time structure map to top depth structure map. The slope fan complex occurs within 1980 – 3260 m ss depth interval (Figure 7) in the lower part of the Agbada Formation. It is observed that the depth contours are closely-spaced in the "channel" section, while they are widely-spaced in the "lobe" section, suggesting different slope gradients in the two systems.

Steep gradient generally supports turbidity system, basal erosional activities and gravity flows (Pickering and Corregidor, 2005), while the gentle gradient often favors sediment deposition in the depocenters or structural lows.

Within the slope complex, most of the faults are synthetic faults located in the "lobe" section, this is contrary to observed antithetic faults in the "channel" arm. Antithetic fault, FH is located at the tail end of the slope channel, and provides a footwall opportunity in the lobe setting.

In order to define the internal architecture of the slope fan complex deposit, series of interval attribute extractions were done. The minimum (MIN), maximum (MAX) and the Root Mean Square (RMS) extraction products were generated and interpreted with the understanding of slope depositional facies characteristics and evolution. The RMS attribute extraction was further constrained by careful and series of 3D workstation interpretations/iterations on the color scheme and seismic attributes, to enhance the salient critical geological features such as the slope channels and depocenters from the seismic data background (Figure 8). It is evident that faults FF-FJ are post-depositional structural features, otherwise the hanging wall structural lows of faults FH and FI should have been areas where reservoir facies would have preferentially developed to form intraslope basins or depocenters. On the Arb Line (see Figure 6), no thickening of the objective 2000-2200 msec stratigraphic interval across fault FI is observed, while a depothick is noted especially in the deeper section. Subsequent younger activities and movements of fault FI would enhance hydrocarbon migration especially through this

Figure 8: Internal Stratigraphic and Structural Architecture of the Slope Fan Complex Deposit



deep-seated fault into the slope reservoir deposits. With sand-shale sections juxtaposition across fault FH and adequate shale smear potential across the short-lived fault, there should be adequate up-dip sealing potential to trap hydrocarbons in the slope reservoir facies.

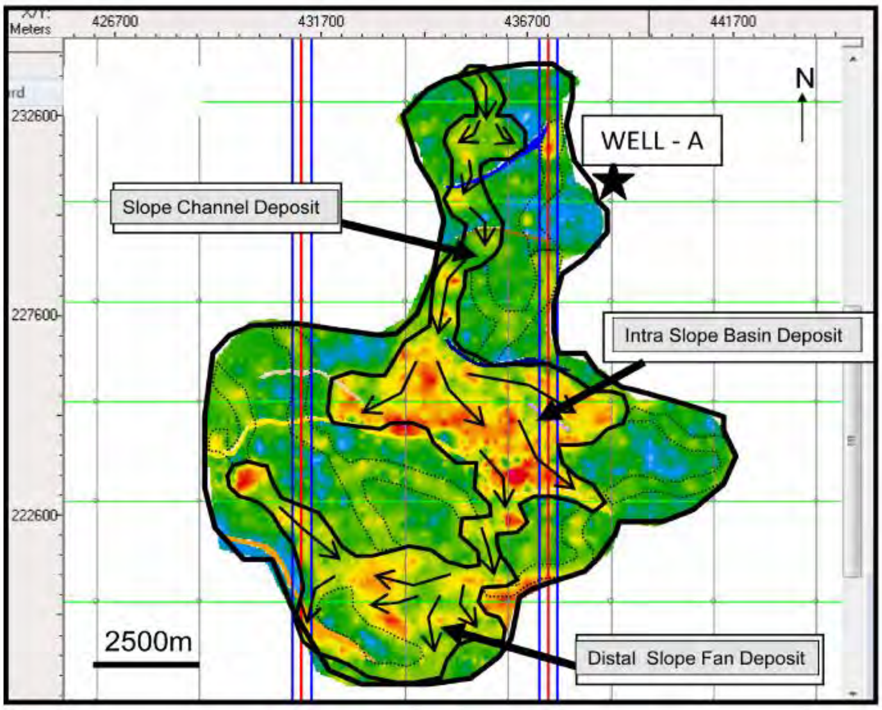
The RMS extraction showed that the mapped slope fan complex of about 100 Sq. Km which can be subdivided into two major sectors, namely the confined “channel” area and unconfined “lobe” area. This complex can also be sub-divided into Slope Channel, Intra-Slope Basin and Floor Fan components (Figure 9). On the average, the dimensions of the components range from 500-1500 m wide, 10-15 Km^2 and 12-16 Km^2 area respectively within the study area, where the slope fan complex lies within 2000-3200 m subsea depth range (see Figure 7).

In the confined “channel” area, one major channel system and other subtle and/or older channels were defined (see Figure 9). Some of these channels are suspected to be filled with more shales than sands, thus there is minimal contrast between them and the slope shale background. Along the major well-defined slope channel section, series of isolated bright seismic anomalies were observed within the meandering pathway. They were interpreted as detached compact sedimentary blocks sliding, gliding or rolling down dip on the shale substratum. Alternatively, they could be smaller sand-rich mini-basins filled by “fill and spill” processes as sediments were transported along the slope channel section (Gong *et al.*, 2013). Many factors can contribute to the dimensions of these deposits. These include size of the pre-existing structural low, quantum of sediment input, configuration of substratum and energy of sediment transport.

The confined sediment fairway is about 3000-3700 m wide and 6000-7500 m long range, within which the major intraslope channel is located in the western part, possibly the most recently active and is averagely 60 m wide and 7000 m long. In some cases, this fairway is connected to the sand-rich shelf setting which is often represented as a stratigraphic wedge in the hanging wall setting of a regional growth fault. To the North of the project area, the growth wedge is heavily faulted making horizon correlation very tedious coupled with the limit of available 3D seismic data. Though the down-lapping seismic reflectors terminated before the wedge, it is clear that the slope fan complex was not detached. Possibly outside the 3D seismic coverage area, the slope fan complex is connected to the fluvial setting for the sand supply. Examples of detached sand-rich slope packages are well documented in deltaic settings.

Within the unconfined “lobe” component area, the well-defined proximal intra slope and distal slope basins are connected by a narrow wavy channel fairway (see Figure 9). The slope basins and the short channel are 9.25 Sq. Km and 5.00 Sq. Km, while the short channel is 50 m wide by 2500 m long. Other smaller channels are noted to be connected to the distal slope basin. The proximal slope basin is in footwall structural setting, as it is bordered to the North and South by normal faults almost spanning across the entire breadth of the slope fan complex. Laterally, the postulated reservoir sands grade to the encasing shale section. In the background, series of slope channels are noted, and interpreted as the network of pre-existing sediment conduits cutting into each other in the area. The “bright” network should be sand-prone, while the “dull” network is expected to be shale-filled.

Figure 9: Major Slope Channels and Intraslope Basins Within the Slope Fan Complex



GEOLOGIC RISK ANALYSIS

Considering each major component of the slope fan complex as a potential exploration lead, the associated Geologic Chance Of Success (GCOS) was estimated. The process involved the understanding of the presence, effectiveness and rating of each key element of a petroleum system: the (a) source, (b) migration pathway, (c) reservoir, (d) seal and (e) trap. These were convolved to determine the GCOS which was estimated to be within 0.14-0.35 limits, and in the global range of 0.11-0.36 for exploration opportunities.

Out of the key petroleum elements, the seal potential is rated lowest. Generally in the slope setting, where reservoir facies are transported and deposited under turbidity and energy waning conditions respectively, lithofacies gradation towards the provenance is expected. There are instances where good quality sands would gradually grade to silt and not completely shale out, this "thief" zone may not be easily defined or located in the quality 3D seismic dataset, and would eventually compromise the effectiveness of the sealing capacity of the encasing quality marine shale interval (Figure 10). Where high-confidence Direct Hydrocarbon Indicator (DHI) anomalies are documented, then the seal efficiency can be rated high. In many cases, technology supports hydrocarbon accumulation, but drilling activities still result in dry holes. Understanding the geologic risks associated with these slope opportunities, helps to manage expectations.

Reservoir facies were observed to occur as "mound" deposits, which often thicken at the center and thin to the flanks. Detailed investigation show the mound to contain series of individual "lobes" separated by thin marine shale levels but

Figure 10: Schematic Geological Cross Section of Intraslope Fan and Slope Channel Deposits

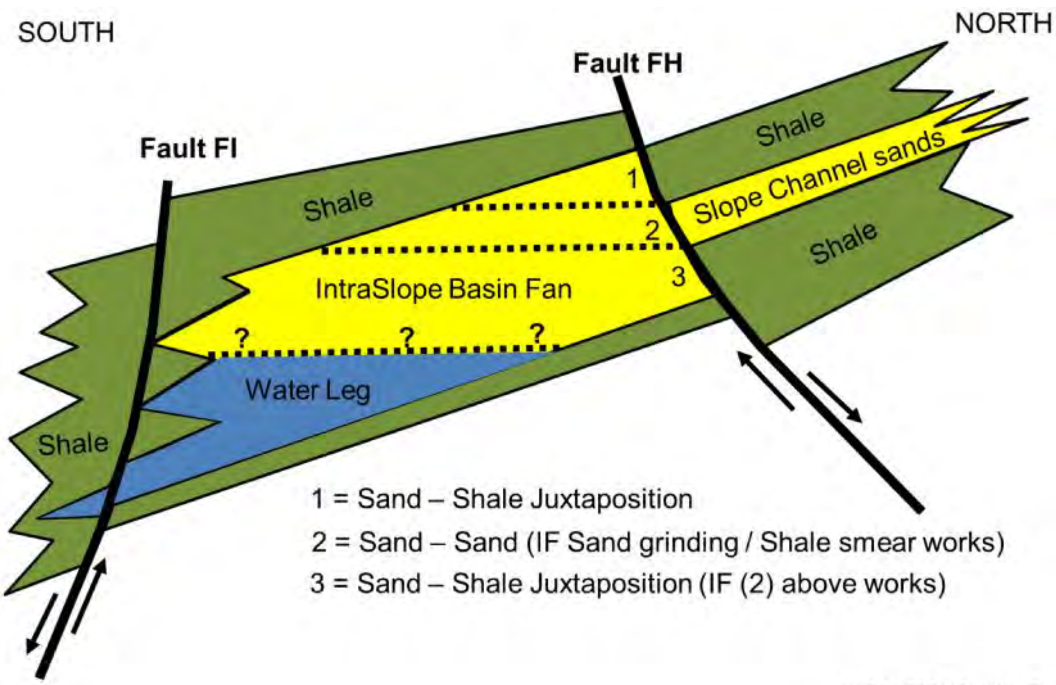
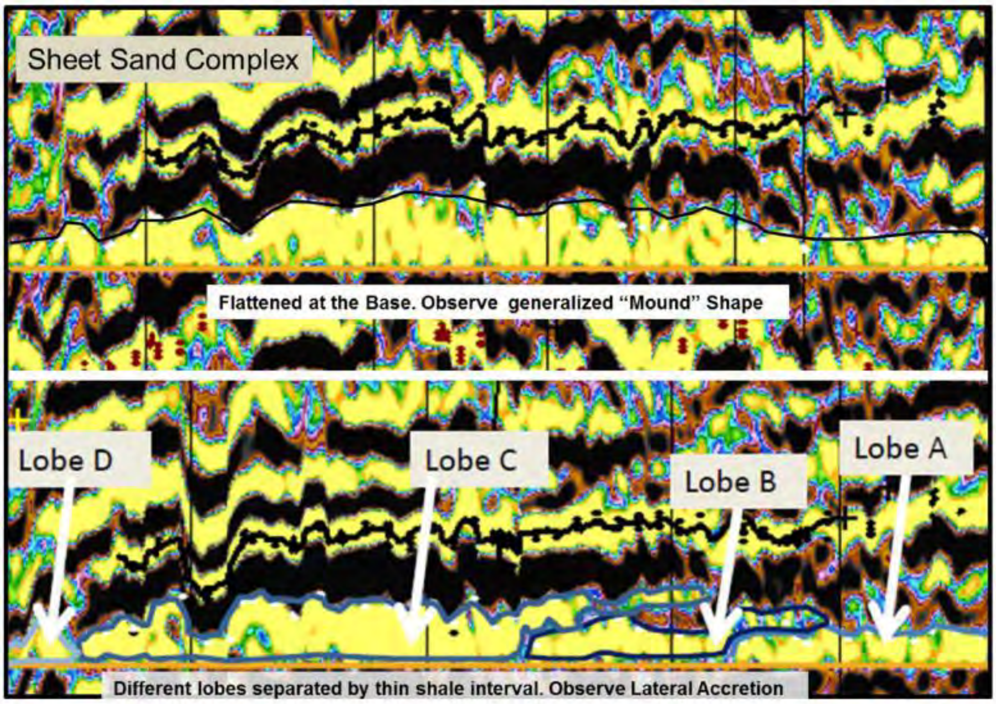


Figure 11: Slope Fan "Mound" Complex with the Different "Lobe" Components



stacked with lateral accretion pattern (Figure 11) as also observed by Bouma (2004). Understanding the stacking pattern always helps to have a more realistic sand-to-sand correlation, steady fluid communication and lasting hydrocarbon flows from productive reservoirs.

HYDROCARBON RESOURCE ESTIMATION

For probabilistic hydrocarbon resource computation, all the key parameters such as area, net pay thickness, porosity, oil saturation, formation volume factor, recovery factor and the Geologic Chance of Success (GCOS) were considered covering the P10 (Minimum), P50 (Most Likely) and P90 (Maximum) percentiles in the log normal distribution. The P10 value is constrained by the effective sand-shale juxtaposition sealing (Scenario 1, Figure 10), while P50 value goes with the reservoir section with sand-sand juxtaposition section where the sealing potential is due to sand-to-sand-to-clay grinding each other to provide lateral seal (Scenario 2, Figure 10). The P90 value is where the effective shale—and juxtaposition is working, but hydrocarbon retention in the reservoir is fully dependent on the shallow sand – sand-clay seal efficiency (Scenario 3, Figure 10). When the GCOS factor was applied, the risked recoverable oil/gas resources of 2-36 MBOE range was estimated mainly for the Intra Slope and Basin Floor Fan deposits, with P50 (Most Likely) estimates of 15 and 10 MBOE respectively. The slope channel deposit was too risky to be considered. This size of hydrocarbon resource range will fit a Near Field Wildcat (NFW) exploration strategy where 3D seismic data and production facilities are already existing, with pipeline ullage capacity.

Analogs of the slope fan complex are well documented in Ghana, Equatorial Guinea and Nigeria deepwater discoveries where hydrocarbon resources in the 150 MBOE-1.0 BBOE range have been reported (Bruso *et al.*, 2004).

CONCLUSION

In areas where the familiar trap styles have not been found and/or in the deeper onshore setting, slope channel, fan complex opportunities could be rewarding, if adequate attention is paid to their detailed technical evaluation. Integration of seismic and sequence stratigraphy principles, key petroleum system elements and understanding from proven analogs have been used to define the slope fan complex sand. The component slope channel, intra slope basin and basin floor fan deposits are attractive potential exploration objectives. If tested and successful, they will stimulate another round of exploration activities, and provide the necessary additional “new-find” oil and gas resources which will be booked to increase the corporate and national hydrocarbon reserve bases.

It is interesting to share that the methodology and understandings from this effort, have been applied to an opportunity which tested and is currently producing about 3000 BOPD from 100 ft. gross slope sands at about 10,000 ft. ss., and some 35 Km distance from a high water-cut field.

ACKNOWLEDGMENT

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