Structural Style and Reservoir Distribution in Deep-Water Niger Delta. 
A Case Study of “Nanny Field”

L. Adeoti¹*, T. Igiri¹, L. Adams², A. Adekunle¹ and M.A. Bello¹.

¹ Department of Geosciences, University of Lagos, Akoka - Yaba, Lagos, Nigeria.
² Department of Chemistry, University of Lagos, Akoka - Yaba, Lagos, Nigeria

ABSTRACT

The structural styles and its effect on reservoir distribution in deepwater Niger Delta was analyzed using information derived from 3D seismic data and well logs interpretation. This complimentary approach facilitates a better implication of faulting with respect to determining prospectivity potential within “NANNY” Field. The data analysis was carried out using Nanny-1 well log. Well tie to seismic was conducted and five (5) mapable sequence boundaries were identified and interpreted across “NANNY” Field. Fault interpretation and framework modeling was developed for the field. The results from seismic interpretation and well log data show that in the Inner Fold and Thrust Belt synthesis of that the structural province is characterized by complex; broad scale thrust cored anticlines and imbricates structures that are widely spaced. This spacing creates accommodation space for reservoir development. This region also has multiple levels of detachment surfaces which improves hydrocarbon charge. The analysis of the Transition zone reveals that the structural province is typified by large areas of little or no formation. Prospects in the transition zone have well defined four way closures with large size of containers from drilled well results. The outcome of well log data analysis and fault interpretation on seismic reveal that the Outer Fold and Thrust Belt where “NANNY” Field lies, is dominated by smaller and less prominent sets of closely spaced imbricated thrust faults with shallow single detachment surface. This structural province is characterized by active and intense faulting style, some of which are still active as evidenced by the footprint on the sea floor. Active faulting increases the risk of fault breached traps that affects hydrocarbon accumulation. Furthermore, regional petrophysical study using data from thirty wells randomly selected across the three structural provinces shows that in deepwater Niger Delta, porosity decreases with depth. At depth range between 3,000 – 5,000 feet, porosity varies from about 33 – 28%. When depth ranges between 5,000 – 7,000 feet, porosity varies from 28 – 22% and between 7,000 – 10,000 feet, porosity varies between 22 – 17%. This result shows that shallow reservoirs have higher porosity and permeability than reservoirs that are emplaced deeper stratigraphically. Hydrocarbon charge or expulsion is not considered a major issue confronting reservoirs within the Outer Fold and Thrust Belt. However, this study reveals that thrust faults in the structural province are closely spaced and active with little or no seal strength thereby preventing the focusing of hydrocarbon. Hence, prospectivity within the “NANNY” Field area will likely have increasing geological risk arising from fault seals, limited fetch area, and small sizes of container and limited volume of source rock (Akata).

Keywords: Reservoir, structure, seismic, hydrocarbon, petro-physics, fold, fault, Porosity.

*Corresponding author: E-mail: lukuade@yahoo.com;
1. INTRODUCTION

The Niger Delta, located in the Gulf of Guinea on the margin of West Africa, is one of the most prolific petroleum basins in the world (Fig. 1). It is one of the largest regressive deltas in the world [1] and is considered a classical shale tectonic province [2]. The Delta consists of Tertiary marine and fluvial deposits that overlie oceanic crust and fragments of the extended African continental crust. Over the last decade, advances in drilling technology have opened the deep-water Niger Delta to exploration. At the deep-water toe of the delta, a series of large fold and thrust belts (Fig. 1) is composed of thrust faults and fault-related folds [3, 4, 2, 5, 6]. Recent discoveries in this fold and thrust belt include the Agbami, Bonga, Chota, Ngolo, and Akpo fields, all of which have structural traps formed by contractional folds. The contractual part of the deep-water Niger Delta is divided into three major zones [7, 6]. The inner fold and thrust belt, the outer fold and thrust belt, and the detachment fold province which is otherwise referred to as transitional province (Fig. 1). The inner fold and thrust belt is a highly shortened and imbricate fold and thrust belt, whereas the outer fold and thrust belt is a more classic toe-thrust zone with thrust-cored anticlines that are typically separated from one another by several kilometers [6]. The detachment fold belt is a transitional zone between the inner and outer fold and thrust belts that is characterized by regions of little or no deformation interspersed with broad detachment anticlines that accommodate relatively small amounts of shortening [5].

The deformation in the contractual toe of the Niger Delta is driven by updip, gravitational collapse of shelf sediments. Basinward motion of these shelf sediments is accommodated by normal faults that sole to detachments within the prodelta marine strata that lie above the basement (Fig. 2). Slip on the detachments is transmitted to the deep water, where it is diverted onto thrust ramps and consumed by contractual folds in deep-water fold and thrust belts (Fig. 3). This style of gravitationally driven, linked extensional and contractual fault systems is common in passive-margin deltas [8], including the Gulf of Mexico basin [9]. The Niger Delta fold and thrust belts occupy the outboard toe of the delta in water depths ranging from 100 to 400 m (0.6 to 2.5 mi) below sea level (Fig. 1).

Several works have been done on the Niger Delta region ranging from the hydrocarbon habitat of the province [10]; the patterns of incidence of the oil reserves [11]; the tertiary lithostratigraphy of the Niger Delta [12]; the tectonic setting, sequence and stratigraphic setting, the fault pattern – Niger Delta [1], and structural setting and the geochemistry of the hydrocarbon in the province [13]. The Niger Delta is located in the Gulf of Guinea, central West Africa, at the southern culmination of the Benue trough.

The NANNY-1 well which was drilled in 2006 was classified as an uncommercial discovery. This was not different from the results of wells drilled across the Outer Fold and Thrust Belt where NANNY Field is located. It was discovered that a total of seventeen (17) wells have been drilled across the Outer Fold and Thrust Belt to date but none was proved to be of commercial discovery. Thus, the problem informed this research work to properly interpret 3D Seismic data to correlate the reservoir distribution trend with other structural provinces that have commercial discoveries with a view to achieving prospectivity potential within the study area.
Fig. 1. Map of the offshore Niger Delta showing the location of the study area, bathymetry, and major offshore structural provinces modified from [13] and [5].

Fig. 2. Regional structural transect through the Eastern Niger Delta.
2. GEOLOGY OF THE STUDY AREA

The study area (Fig. 1.) falls within offshore Niger Delta which comprises Cretaceous through to recent marine clastic deposits overlying a continental-ocean transition [14]. In the Paleocene, a major transgression began with the Imo shale being deposited in the Anambra Basin to the northeast and the Akata shale, being the basal Niger Delta formation, deposited to the southwest [15]. The Tertiary section of the Niger Delta is divided into three formations. Akata, Agbada and Benin, representing prograding depositional facies that are distinguished mostly on the basis of sand-shale ratios [16].

3. MATERIALS AND METHODS

3.1 DATA ACQUISITION

The primary source of the data was from Chevron Nigeria Limited. Well log data comprising Nanny-1 well logs from “NANNY” Field and other wells from Demo Field were used. Past block wide regional work data as well as 3D seismic lines were also supplied and used.

3.2 DATA PROCESSING AND INTERPRETATION

The first step taken was to quality-check (QC) the seismic data. The processing and interpretation of seismic data was done using SeisWorks software in OpenWorks version 2003.12.1.4 environment while the Well log data were processed and interpreted using StratWorks in OpenWorks version 2003.12.1.4 environment.

The procedures for data analysis are as follows:

(a) The major and minor faults were picked from high quality 3D seismic data along dip section. Names were assigned to both major and minor faults as shown in Fig. 4. Correlation of faults was
carried out by transferring the dip line faults onto the strike section using the intersection points of the dip and strike lines. Minor faults that could not be found on the dip section were drawn on the strike section and later transferred same to dip section.

(b) Synthetic seismogram was generated from Nanny-1 well using Syntool software in OpenWorks environment and later tied to seismic as shown in Fig. 5.

(c) Well markers were interpreted as sequence boundaries from reservoirs of interest as shown in Fig. 6.

(d) The events or mappable sand identified assisted in the picking of horizons which were representative of strong and continuous reflectors on the seismic section.

(e) Isochron (time) map was generated. Also, the conversion of time map to depth structure map was done using checkshots from nearby well (Demo-Field).

(f) The root mean square (RMS) amplitude was extracted and posted on depth structure map to ascertain structural conformity

(g) Generation of prospects was carried out using trap identified within the study area.

(h) Regional Well log correlation was carried out using Nanny-1 well and nearby Demo-01 and Demo-01 wells.

(i) A cross plot of Depth Below Ocean Bottom (DOB) versus Total Average Porosity was generated to know the trend of the porosity.

(j) Determination of petrophysical parameters using was carried using stratworks in openworks.

(k) **Deduction of structural styles along the major zone within the study area.**

---

**Fig. 4.** A Regional Seismic line linking other prospects around the study area.
Fig. 5. Nanny-1 well synthetic seismogram tie to seismic. Nanny well has a good Time Depth tie with a trough to trough and peak to peak match.

Fig. 6. Seismic interpretation on a 3D seismic data and correlations from Nanny-1 well complex to a new prospect area. Good seismic data quality and accurate age control, sequence boundaries were carried from wells in Demo field.
4. RESULTS AND DISCUSSION

The results are presented in Figs. 7-16 and Table 1 and subsequently discussed as below:

4.1 Root Mean Square Amplitude Extraction on Depth Structure Map of 5.73 Sequence boundary

Fig. 7 shows little conformance at the base but none at the top. The red shows high amplitude with low amplitude at the pink colour areas. The area considered for prospectivity is so small. This is typical of the Outer Fold and Thrust belt.

![Fig. 7. RMS amplitude extraction draped on the depth structure map of 5.73 sequence boundary with plus 30ms (peak) and minus 10ms (trough) window.](image)

4.2 5.73 and 6.98 Sequence Boundary Regional Depth Structure Maps in Transitional zone

Figs 8 and 9 show pronounced similar structural trends. The surrounding fields in the Transitional zone have greater 4-way closures; they have little or no deformations. These fields are structurally higher than the Nanny Field which is within a province with closely spaced thrust system; this will affect sediment accumulation and reservoir distribution. The reddish areas are the structurally higher regions followed by the yellow and green. The Nanny Field is structurally lower within the blue coloured area. The big size of the 4-way closures will also give room for a big fetch area which means accumulation in such areas will also be big.

![Fig. 8. The 5.73 Sequence boundary regional depth structure map with surrounding fields](image)
Correlation of the Demo with Nanny Field.

Regional Well log correlation was done to examine the continuity and discontinuity of sands (reservoirs) and it was also carried out to understand the dipping trend in the area of study by correlating the NANNY-1 well with wells in nearby Demo field which have commercial discoveries as shown in (Fig. 10). Correlation is the demonstration of equivalence in sand packages across the correlated area. The Demo field wells are structurally higher to the Nanny-1 well. NANNY-1 well which was drilled deeper than the Demo wells encountered similar sand sequences as those encountered by the Demo field wells at same structural levels. This connotes continuity of reservoirs regionally, though the deeper reservoirs in the Demo field area appears to be massive than those in the NANNY complex while shallow reservoirs in the NANNY area are cleaner and bulky. The shallow intervals in both fields look shaly with some sands present meaning a discontinuous sand deposition pattern because some sands that logged by the NANNY well could not be identified by the Demo field wells.

Fig. 9. The 6.98 Sequence boundary regional depth structure map with surrounding fields

Fig. 10. Demo wells to Nanny well logs stratigraphic correlation. The sequence boundaries are carried from Demo well seismically into Nanny Area.
4.4 Depth below Ocean Bottom (DBOB) against Porosity

Fig. 11 reflects that when the depth below mud line ranges between 1,500 - 5,000 feet, the porosity varies from about 33 - 28%. When the depth ranges between 5,000 – 7,000 feet, porosity varies between 28 – 22%, and between 7,000 – 10,000 feet, porosity varies between 22 – 17%. This result tends to favour shallow targets because shallow regions have greater porosity and permeability. The nearby shallow high amplitude prospect to the NANNY Field will have porosity ranging from 20 – 33%. From the result of the regional study in Fig. 11, porosity decreases with depth in the deep-water Niger Delta. Prospectivity with respect to porosity in deep-water favours shallow reservoirs while decreases tremendously with deeper targets.

![Regional Depth below Ocean Bottom vs. Total Average Porosity](image)

**Fig. 11.** Regional Depth below Ocean Bottom vs. Total Average Porosity

4.5 Nanny Well Petrophysical Results

The effective porosity ranges between 15 to 33% as shown in Table 1. This corresponds to the result of the regional study which shows that in the deep water Niger Delta, porosity decreases as depth below mud line (DBML) increases in (Table 1). The reservoirs penetrated by the Nanny well are basically of good quality and ranges from weakly confined channel system to unconfined sheet system (Fig. 12). The gamma ray log in green shows areas containing sand and shale. The presence of reservoir rock was reaffirmed through running the V-shale log which appeared at the extreme right. A study was carried out to confirm the sequence boundaries which were correlated to those interpreted seismically from wells within the Demo field. From the deposition model, prospective reservoirs in the NANNY Field are within
the window of upper Oligocene to upper Miocene. Seismic evidence supports model of older sheet systems overlain by younger lower slope sand deposition (weakly confined / ponded). From NANNY-1 well result as shown in Fig. 12, the penetrated reservoirs that were hydrocarbon bearing (red and green circles) are within the Upper Oligocene to Upper Miocene series of sands which correspond to the interval of hydrocarbon bearing reservoirs in most fields with major discoveries within deepwater Niger Delta.

Table 1. Petrophysical parameters of Nanny-1 well

<table>
<thead>
<tr>
<th>Sand</th>
<th>Depth (m)</th>
<th>Dbml</th>
<th>Net Sand</th>
<th>Porosity (%)</th>
<th>Sw (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.26</td>
<td>9400</td>
<td>4172</td>
<td>45</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Stray</td>
<td>9802</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td>10110</td>
<td>4310</td>
<td>60</td>
<td>33</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>10300</td>
<td>4442</td>
<td>70</td>
<td>32</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>10400</td>
<td>4911</td>
<td>406</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>12.7</td>
<td>11410</td>
<td>6007</td>
<td>197</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Stray</td>
<td>11803</td>
<td></td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11915</td>
<td></td>
<td>21</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>14.8</td>
<td>12300</td>
<td>6512</td>
<td>41</td>
<td>22</td>
<td>26</td>
</tr>
<tr>
<td>17.3</td>
<td>12520</td>
<td>7746</td>
<td></td>
<td>17</td>
<td>35</td>
</tr>
<tr>
<td>23.8</td>
<td>13490</td>
<td>7989</td>
<td></td>
<td>15</td>
<td>62</td>
</tr>
<tr>
<td>33.2</td>
<td>13730</td>
<td></td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>older</td>
<td>14220</td>
<td></td>
<td></td>
<td>14.9</td>
<td></td>
</tr>
</tbody>
</table>
4.6 Structural style of the Extensional Province

Fig. 13 shows the seismic expression of the structural styles observed in the extensional province illustrating the presence of down-to-basin regional normal faulting present. This zone also exhibits prominent rollover anticlines in the hanging wall blocks of the regional and counter-regional normal faults represent the main targets for exploration. Plio–Pleistocene rollover features showing synthetic and antithetic normal faulting. Crestal grabens, synthetic and antithetic fault systems are also important structural traps. Foot-wall discoveries and opportunities are yet to be found in this province.
Fig. 13. Seismic expression of the structural styles observed in the extensional area of the Niger Delta showing down to basin regional and counter regional normal faults (Modified from [13]).
4.7 Structural styles of the Inner Fold and Thrust Belt

The Regional structural styles of the Inner Fold and Thrust Belt with observed seismic character are expressed in Fig. 14. These structural traps observed in the Deep-Water Niger Delta region are detachment folds, fault-related folds, fold-propagation folds, and imbricated thrust-sheets observed mostly in the Inner Fold and Thrust belt. Complex, broad scale thrust cored anticlines, includes duplexes, and imbricates structures that are widely spaced. Several pulses of deformation are indicated by multi-levels of detachments. Structures are poorly imaged.

Fig. 14. Regional Structural styles with observed seismic character within the Inner Fold and Thrust Belt with widely spaced imbricated thrust faults as observed on seismic with multiple levels of detachment surface (Modified from [13]).
4.8 The Transitional or Detachment Fold Zone

Fig. 15 is an illustration of regional structural styles with seismic observation within the transitional detachment fold zone. The transitional detachment fold is beneath the lower continental slope that is characterized by large areas of little or no deformation interspersed with large, broad detachment folds above structurally thickened Akata Formation [5]. There are individual and isolated detachment folds. There are areas of no deformation associated with shallow to deep detachment surfaces. This zone contains broad age of activation (Middle Miocene to recent). Little internal deformations are also present in this zone.

Fig. 15. Regional Structural styles with seismic character within the Detachment Fold Province. Structure within this province has little or no deformation (Modified from [13]).

4.9 The Outer Fold and Thrust Belt structural style

Fig. 16 shows the Outer fold and thrust belt common shallow detachment level. This less oil prolific belt is dominated by smaller and less prominent sets of closely spaced imbricately. It is the outermost structural setting to the Niger Delta coastline. Growth sequences capping this province are also much thinner, which makes difficult to properly correlate among individual trends. The deformations in this province are very recent. The belt is also observed to exhibit small amplitude structures with smaller trap anticlines.
5. CONCLUSION

The structural styles and reservoir distribution in deepwater Niger Delta was carried out on three different structural settings namely: Inner Fold and Thrust Belt; Translational or detachment Fold Zone and Outer Fold and Thrust Belt. In the “NANNY” Field, five (5) mapable reservoirs were identified from the Nanny-1 well and were interpreted across “NANNY” Field as sequence boundaries. The field is dominated with shallow normal faults while down dip proves the presence of thrust faults. The result of regional petrophysical studies shows that in the deep-water Niger Delta, porosity decreases with depth. A regional plot of depth below ocean bottom (DBOB) against porosity shows that there exists a regional porosity trend at various depth intervals. When the depth below mud line is within 1,500 - 5,000 ft, the porosity varies from 33 - 28%. At a depth window of 5,000 - 7,000 ft, the porosity decreases from 28 – 22% and from 7,000 – 10,000 ft below ocean bottom, the porosity value reduce from 22 – 17% respectively. This result shows that deeper reservoirs will have lower porosity values than up shallow reservoirs. The excitement surrounding hydrocarbon exploration in the Niger Delta Deepwater basin following several commercial discoveries seems to have reached its peak. From observed data, most of the discoveries made to date are situated within the “translational” and inner fold belts. The outer fold and thrust belt appears to be less prolific in terms of commercial discoveries. The Outer Fold and Thrust Belt is a high risk play area. The geologic risks: fault seals, source rock (Akata), thermal maturity (charge) and small sizes of the container (resources) are very high. Also observed is a scarcity of well data and nearby
infrastructures to commercialize marginal discoveries. Four (4) way closures with Direct Hydrocarbon Indicator (DHI) are low risk but three (3) way fault dependent closures are high risk in the outer fold and thrust belt. It is believed that deformation across these structural provinces is still active till today.

ACKNOWLEDGEMENT

The authors wish to thank the Department of Petroleum Resources and Chevron Nigeria Limited for releasing the data for this research.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

AUTHORS’ CONTRIBUTIONS

‘Author A’ worked tremendously in ensuring a well-designed research study. He was relentlessly engaged in acquiring the research data from a relevant company (Chevron). He was the leading head during data validation, processing and interpretation, simply for his in depth technical contributions. He also ensured a critically reviewed project for this paper publication.

‘Author B’ participated in the study design, data gathering, analysis and interpretation. He also played a leading role in terms of technical contribution.

‘Authors C, D and E’ participated in the research project. They were fully occupied with critical reviewing of the project work to produce a technically robust paper for publication. All the authors read and approved the final manuscript.

REFERENCES


