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# Characterization of Laterally Continuous Reservoirs: Implications on Recovery of By-passed Hydrocarbon in "*Gerun*" Field, Onshore Niger Delt

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**Abstract**

Laterally continuous silici-clastic reservoirs within the Agbada formation in a field onshore Niger Delta were marked out and characterized using Well logs and 3D seismic data. Using Hampson Russell's seismic and Well log interpretation software (Geo View CE8\R4.4 version), marker-based formation evaluation yielded two intervals NL1 and NL2 spanning through a depth range of 5867ft – 5962ft (95ft) and 6142ft – 6239ft(97ft) respectively. Preliminary well log based petrophysical analysis, well to seismic tie, building of acoustic impedance model, a model based low frequency acoustic impedance inversion, generation of attribute slices, and ultimate reservoir evaluation were all implemented in processing of data and interpretation of results. Petrophysical analysis revealed that in Well RONA, sand dominated interval - NL1- with average porosity = 33.60%, average resistivity = 2.85 x $10^2$ Ωm, and average density = 2.10 g /cc has average water saturation of 5.00% and corresponding hydrocarbon saturation of 95.00%. NL2, a sandy lithology in Well RONB with average values of porosity, resistivity and density respectively at 31.00 %, 3.19 x $10^2$Ωm and 2.02g/cc had average water saturation of 4.00% and corresponding hydrocarbon Saturation of 96.00%. The lowest average hydrocarbon saturation (76.00%) is observed in Well RONC, within NL2 which is a shaly-sand interval with corresponding average values of density, porosity and resistivity respectively at 2.15 g/cc, 31.93% and 0.06 x $10^2$ Ωm. These results tied adequately with interpretations from the petrophysical attribute slices, which were generated for acoustic impedance, density, porosity and water saturation. The results are more optimal than the standard values required for hydrocarbon bearing intervals in the Niger Delta. These optimal results of petrophysical properties are attributable to the delineation of reservoir intervals with matching depth range across the well locations which aided the mapping of laterally continuous reservoirs and presented a simulation of spatial homogeneity and ultimately enhanced the recovery of by-passed hydrocarbon in the "*Gerun*" field.

***Keywords***: *Reservoir; By-passed hydrocarbon; Hydrocarbon saturation; Well data; Seismic data.*

## 1. Introduction

The global hydrocarbon reserve is being depleted daily, due to increasing demand for energy, the major end product of all hydrocarbon exploration ventures, despite increasing discouragement on the use of fossil-fuels. There is also a growing need to re-evaluate existing wells in prolific oil fields, to locate and recover by-passed hydrocarbon - hydrocarbon reserves that were by-passed during initial exploration ventures. Well log and seismic data, indispensable tools in hydrocarbon exploration are very pivotal in this quest to recover by-passed hydrocarbon. Myriad works have been carried out in recent times within the study area, especially with regards to quantifying the amount of hydrocarbon in place [3, 4, 18, 20-23]. Many researchers [1-3, 6, 7, 15, 19] utilized an integration of well log and seismic data in characterizing reservoirs within the Niger Delta.

However, these studies and many others had to deal with the complexities of the default reservoir heterogeneity, a situation which is responsible for the trapping of hydrocarbon in isolated pockets which ultimately end up being by-passed by conventional reservoir characterization approach, as observed by Bassiouni and Velic [8]. The spatial variation of properties within a reservoir has over the years been known to be responsible for the increased degree of unpredictability associated with the characterization of heterogeneous reservoirs. To mitigate this limitation posed by spatial heterogeneity of hydrocarbon reservoirs, we have shown that marking out laterally continuous reservoirs during the well conditioning greatly reduces spatial heterogeneity, and ultimately enhance the recovery of by-passed hydrocarbon within the study area.

## 2. Location and geology of the study area

The study location – Alpha field- lies between latitudes 3°N and 6°N and longitudes 5°E and 8°E, situated in the Gulf of Guinea, and extending throughout the Niger Delta Province, within a Basin identified as the Niger Delta Basin (Figure 1). With a major petroleum system identified as the Tertiary Niger Delta Petroleum System, majority of which lies within the borders of Nigeria, with some access to Cameroun and Equatorial Guinea [6, 11, 13]. Three main stratigraphic subdivisions dominate the subsurface in this oil rich basin, namely – the Akata, Agbada and Benin formations (Figure 1). The Akata formation, a combination of turbidite sand, thick marine shales, minor amounts of clay and silt, is about 7km thick [9] and forms the base formation of the Niger Delta Basin and has been identified as the major source rock in the province. Overlying the Akata formation is the main petroleum bearing unit in the Niger Delta - the Agbada formation. This section is an approximately 3.7km thick silici-clastic formation, with the base part which is in direct contact with the underlying Akata formation having an equal combination of shale and sandstone depositions, while the upper section of the Agbada formation is mainly dominated by sandstone and minor intercalations of shale [9, 10, 12]. At the shallowest section of the basin lies the Benin formation, comprising of about 2km thick deposits of alluvial and upper coastal plain sands.

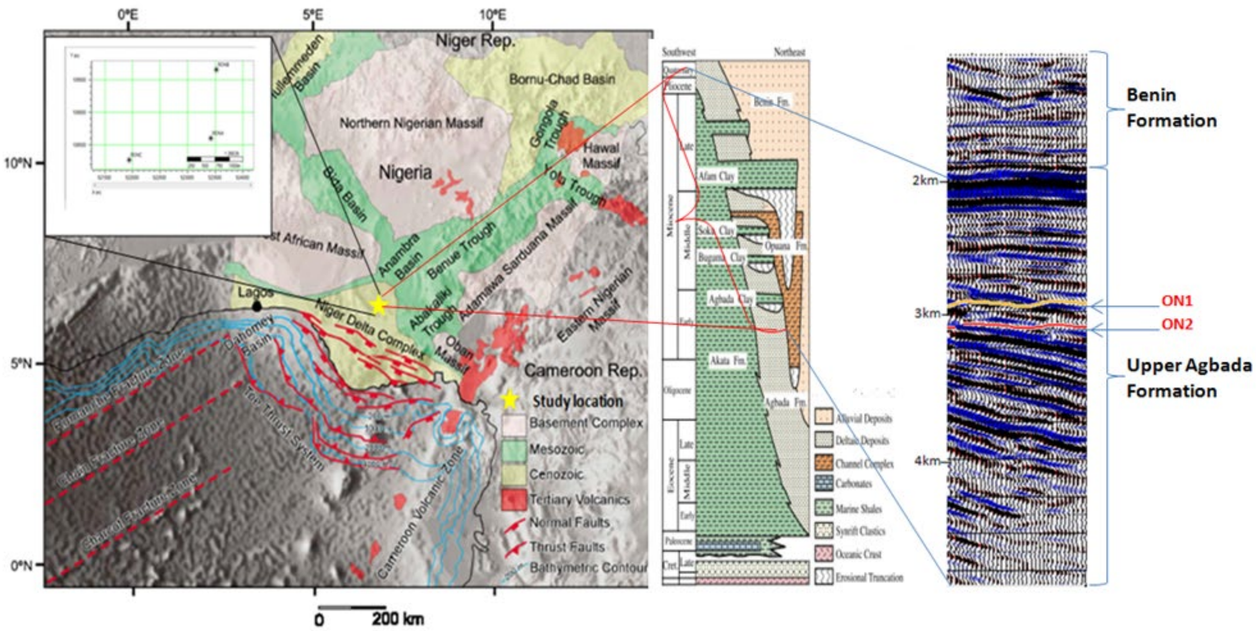


Figure 1. Location map of the Niger Delta region (left) showing the study location, the main sedimentary basins and tectonic features (Adapted from Ekwe and Onuoha [11]) with Inset showing Well locations on base map; Stratigraphic Succession map of the area (right) (from Doust and Omatsola [9]) and seismic section from the study location showing two stratigraphic units and two horizons ON1 and ON2 within the intervals of interest.

## 3. Methodology

Data conditioning and editing of the well log and 3D seismic data precedes other steps followed in achieving results in this work. These include creation of new (by-passed) markers, marking possible reservoir intervals that were not captured initially prior to production in the hydrocarbon field under consideration. Marker-based formation evaluation and preliminary petrophysical analysis, well to seismic tie, building of acoustic impedance model, a model based low frequency acoustic impedance inversion, generation of attribute slices, and ultimate reservoir evaluation. A workflow for the methodology is given in Figure 2.


Figure 2. Research work flow

## 3.1. Well Log conditioning and editing

### *3.1.1. Loading of Well logs:*

Logs from three Wells (RONA, RONB and RONC) were used for this study. RONA is located on X = 5233415.00m and Y = 108600.00m. RONB is located on X = 523517m and Y = 109658.00m and RONC is located on X = 521944.00m Y= 108265.00m. The three wells are oil and gas wells. The well logs were loaded into the Well Explorer panel of the HRS software in LAS format, with Imperial measurement system. Table 1 shows the available and unavailable logs in each well identified respectively with YES or NO.

Table 1. Check-list of logs in the suite of logs

| LOGS | WELLS | | |
|---|---|---|---|
| | RONA | RONB | RONC |
| Density | YES | YES | YES |
| Gamma Ray | YES | YES | YES |
| Porosity | NO | NO | NO |
| Caliper | NO | YES | YES |
| P-wave | NO | YES | YES |
| S-wave | YES | YES | YES |
| Resistivity | YES | YES | YES |
| Water Sat. (Sw) | NO | NO | NO |
| P-Impedance | NO | NO | NO |

Two markers (tops) tagged NL1 and NL2 spanning a depth range of 5867ft – 5962ft and 6142ft – 6239ft respectively were created by inspection of the gamma ray log and the resistivity log, taking into consideration, zones with gamma ray amplitudes tending more to the left, indicative of reservoir sand, and resistivity amplitudes tending to the right, indicative of hydrocarbon presence.

#### *3.1.2. Log transform generation*

For optimal interpretations, transform logs were generated from already existing logs. The generated logs of RONA, RONB and RONC are P-Impedance, Porosity and Water Saturation.

Equation 1 was used to generate the P-Impedance curve. This was generated from the product of the P-wave velocity and density.

$$Zp = Vp * \rho \qquad (1)$$

The porosity log was generated from density log using equation 2, involving the matrix density ($\rho_{ma}$), fluid density($\rho_f$), and observed log density($\rho_{obs}$).

$$\Phi = \frac{\rho_{ma} - \rho_{obs}}{\rho_{ma} - \rho_f} \qquad (2)$$

Water Saturation, the fraction of the pore that is filled with water, was calculated using equation 3 which combines the formation water ($R_w$) and true resistivity of the formation($R_t$), Porosity ($\Phi$), cementation factor (a) and cementation exponent (m)

$$S_w = \sqrt{a\Phi^m \frac{R_w}{R_t}} \qquad (3)$$

### 3.2. 3D Seismic data geometry conditioning

The 3D seismic volume which is a pre-processed post-stack data in time domain is handled in 'SEG-Y' format with Inline and Xline numbers in the trace headers as well as X and Y coordinates. SEG-Y format and Header and the geometry grid page is given in Figure 3.


Figure 3. SEG-Y Format and Header (left) and The Grid Geometry (right) (Adapted from Hampson Russel Software - Geo View CE8\R4.4 version)

#### *3.2.1. Well to seismic tie*

Prior to the well to seismic tie, Two horizons ON1 and ON2 were picked at constant times (1580ms and 1640ms respectively), corresponding respectively to the mid-points of the markers (tops) RN1 and RN2 (Fig.4). Well-based wavelet extraction was done next, using the three Wells first, with offset selection option range of 4992m to 5771m. The extraction window ranged from constant time of 0-3000ms, utilizing the full volume. The wavelet parameters of length of 150ms, tapper length - 20ms, sample rate of 4ms with constant phase. Wavelet extraction was also done statistically for the full seismic volume, with a time range of 0-3000ms, offset range of 4992-5771m, X-line range of 1034-1529 (increasing by 1), and Inline range of 4992-5771. The wavelet parameters used are wavelet length of 200ms, tapper length of 25ms, sample rate of 4ms, and zero degree phase rotation at constant phase. The extracted response which was used as the current wavelet is shown in Figure 5. The well to seismic correlation was next carried out, with a maximum correlation of 0.763(76.3%) at time shift of 0ms obtained for RONA, a maximum correlation of 0.615(61.5%) at time shift of 90ms obtained for RONB, and a maximum correlation of 0.629(62.9%) at time shift of 49ms recorded for RONC.

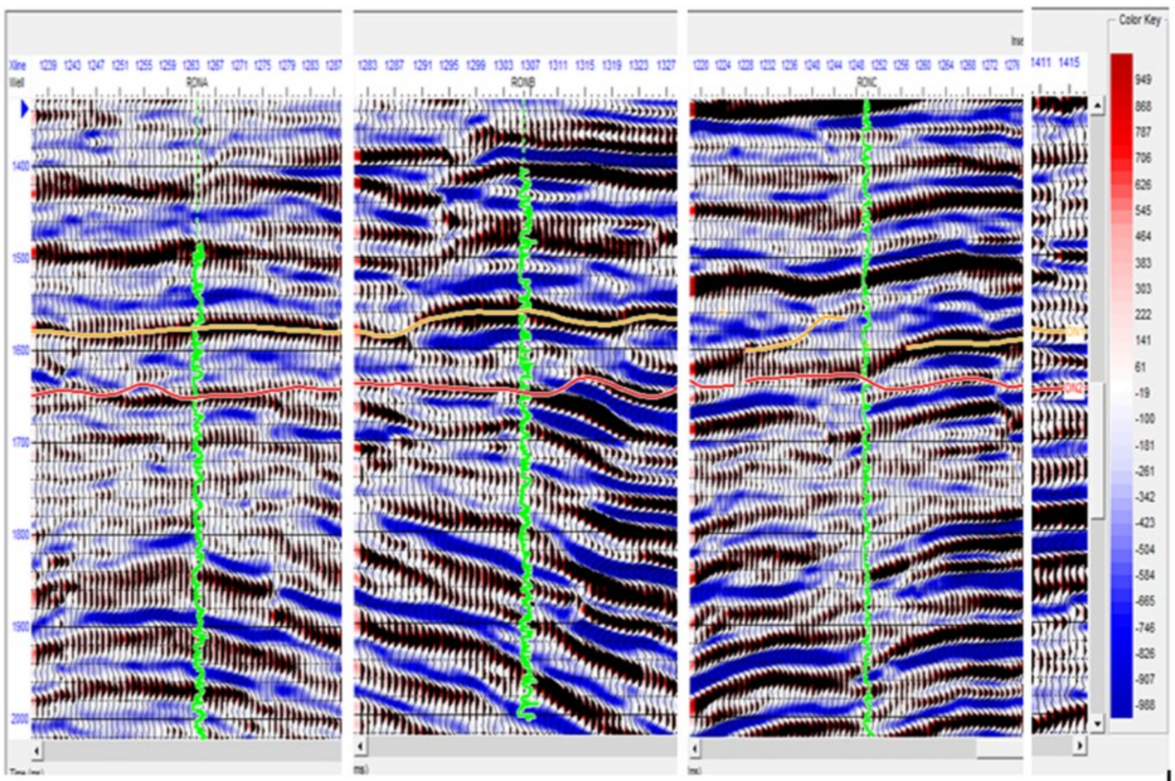


Figure 4. Seismic section showing the three Wells and the picked horizons

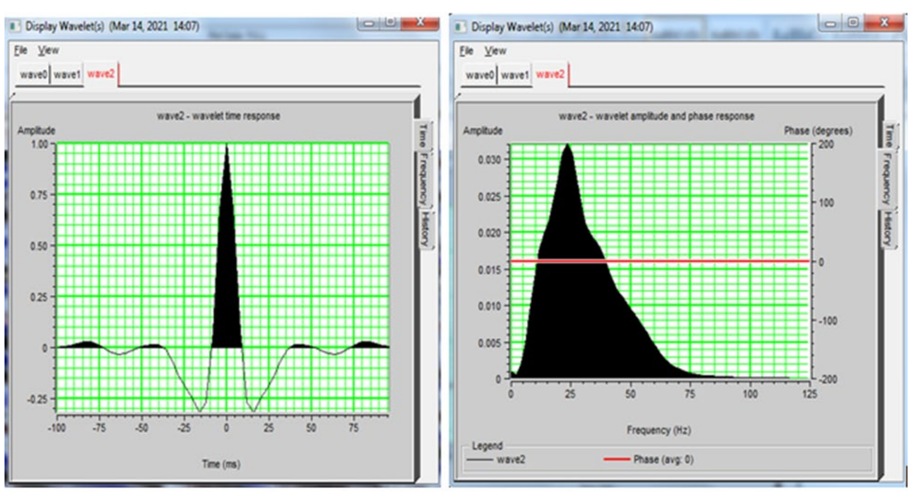


Figure 5. Wavelet time and frequency response

### *3.2.2. Low frequency acoustic impedance model building*

Acoustic impedance ($Z_p$) model was built using the typical setup for acoustic impedance inversion. The wells (RONA, RONB and RONC) were used as the source of amplitude data. The horizons ON1 and ON2 were included in the model. The model was not smoothened.

### *3.2.3. Model based acoustic impedance inversion*

Analysis setup for post-stack inversion of the acoustic impedance model involved a processing time of 0-300ms and processing sample rate of 4.0ms. The inversion of acoustic impedance model was run for the full seismic volume of the acoustic impedance model volume, with a hard constraint inversion option, average block size of 4ms, 1% pre-whitening, 10 iterations, processing sample rate of 4ms, and seismic volume sample rate of 4. The inversion trace scalar was calculated by applying user defined scalars. The inversion was run for Acoustic Impedance, Density, P-wave, Porosity and Water saturation, with the data constrained to a two way time range of 1000ms – 2000ms.

## 4. Presentation of results

The results presented in this work capture results of the marker-based formation evaluation and petrophysical analysis, low frequency acoustic impedance model based inversion, analysis of petrophysical attribute slices, and ultimate reservoir evaluation of the by-passed reservoirs RN1 and RN2, delineated at the same depth range across the three well locations – RONA, RONB and RONC.

### 4.1. Formation evaluation and petrophysical analysis

The suite of logs showing the "generated" rather than "imported" markers from previous analysis of the data set are given in Figures 6, 7 and 8.

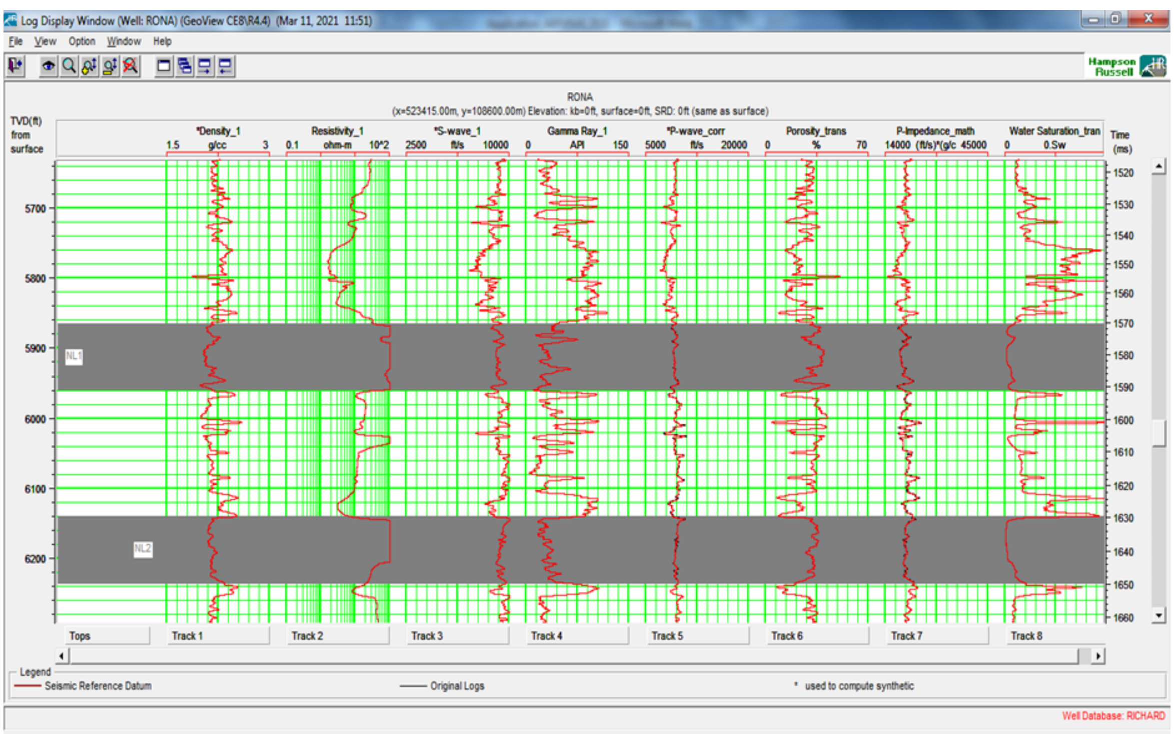


Figure 6. Suite of Logs in Well RONA showing markers NL1 and NL2

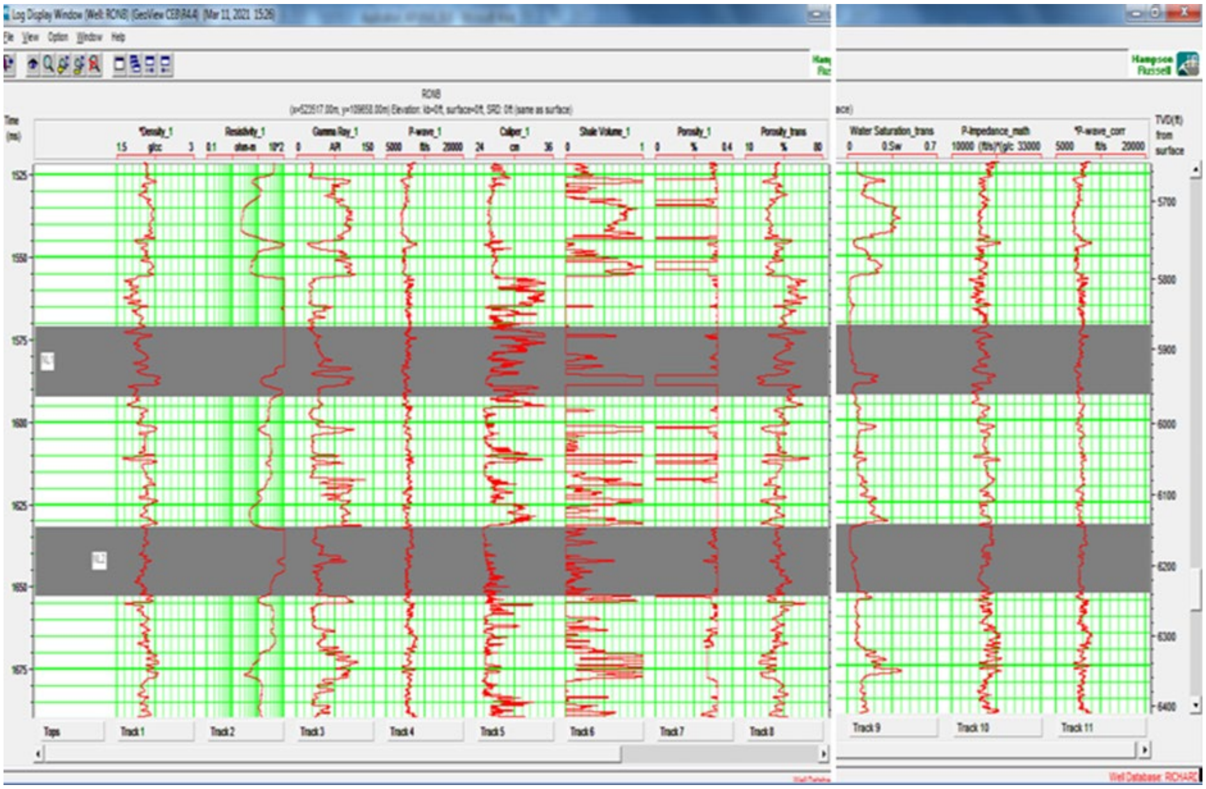

Figure 7. Suite of Logs in Well RONB showing markers NL1 and NL2

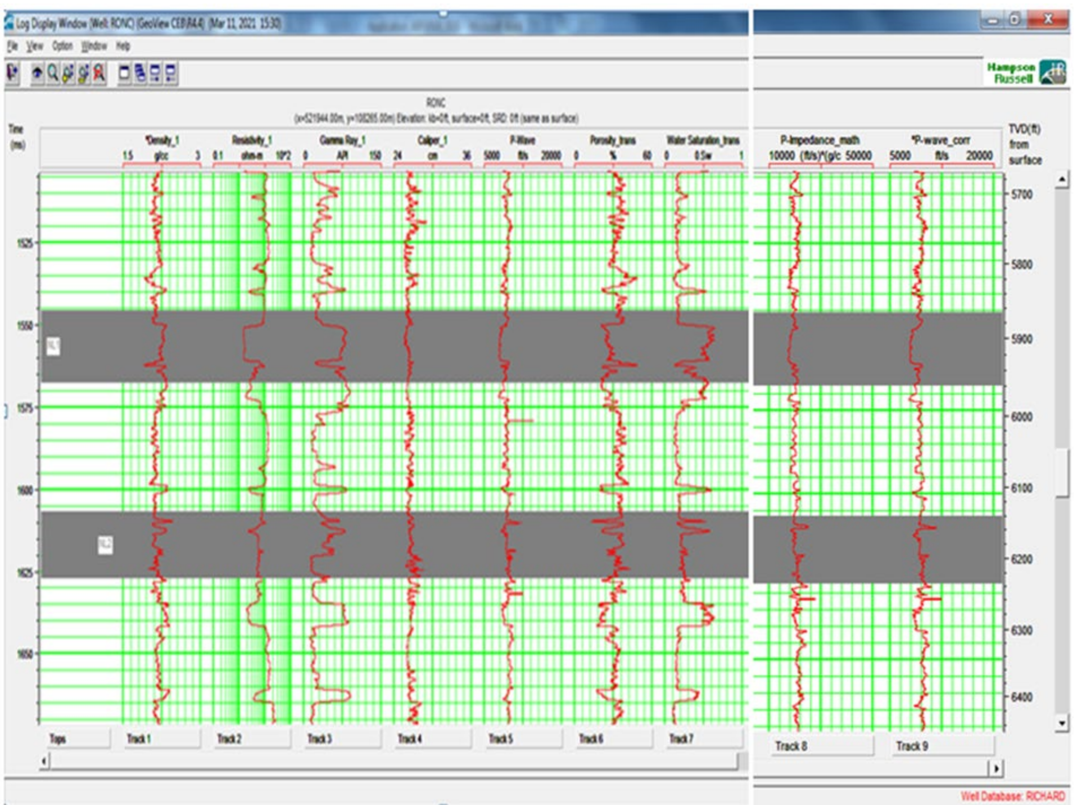

Figure 8. Suite of Logs in Well RONC showing markers NL1 and NL2

Table 2 shows the average numeric values of selected rock properties whose log responses are shown in the delineated markers (RN1 and RN2) in the suite of logs in the Wells – RONA, RONB and RONC. From Table 2, we can deuce that the sand intervals – NL1 and NL2 - delineated in Wells RONA and RONB have very high values of average hydrocarbon saturation, corresponding to low values of average water saturation, while the sand interval in Well RONC having intercalations of shale and thus described as *shaly –sand* has lower values of average hydrocarbon saturation. High values of average resistivity corresponding to the high average hydrocarbon saturation values are also observed from Table 2 and vice versa. The average Gamma ray values validate the designated lithology of the intervals in the lithology column of the table, with NL1 in Well RONC having an average API value indicative of fewer shale intercalations than what is obtainable in interval NL2 of Well RONC.

Table 2. Average values of selected petrophysical properties within by-passed probable hydrocarbon sands in Wells RONA, RONB and RONC

| Markers (Intervals) | Wells | Start Depth (Ft) | End Depth (Ft) | Petrophysical Properties (Average) | | | | | | Thickness (Ft) | Lithology |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Density (g/cc) | Porosity (%) | Water Sat. (0.Sw) | HC Sat. (1-Sw) | Gamma Ray (API) | Resistivity (Ohm-m) | | |
| NL1 | RONA | 5867 | 5962 | 2.10 | 33.60 | 0.05 | 0.95 | 33.67 | 285.21 | 95.00 | Sand |
| | RONB | 5867 | 5962 | 1.98 | 30.00 | 0.05 | 0.95 | 52.13 | 288.97 | 95.00 | Sand |
| | RONC | 5867 | 5962 | 2.21 | 28.24 | 0.40 | 0.60 | 59.33 | 3.96 | 95.00 | Shaly- Sand |
| NL2 | RONA | 6142 | 6239 | 4.30 | 31.20 | 0.06 | 0.94 | 32.73 | 853.30 | 97.00 | Sand |
| | RONB | 6142 | 6239 | 2.02 | 31.00 | 0.04 | 0.96 | 45.41 | 319.07 | 97.00 | Sand |
| | RONC | 6142 | 6239 | 2.15 | 31.93 | 0.24 | 0.76 | 37.92 | 5.59 | 97.00 | Shaly-Sand |

### 4.2. Generation of Petrophysical Attribute Slices

Using amplitude plotting, the data slices were selected at constant times corresponding to the picked horizons ON1 and ON2. Attribute slices are for Acoustic Impedance, Density, Porosity, P-wave, and Water saturation, are generated and shown in Figures 9 to 13.

#### *4.2.1. Analysis of Petrophysical Attribute Slices*

Figure 9 is an event time structure map taken at the shallower horizon - ON1. Corresponding to deposition time, the green colorations dominating the Well RONB location are indicative of younger deposition time than the red, blue and purple colorations symbolic of progressively older depositions at wells RONA and RONC. In Figure 10, low to intermediate values (corroborated by the inset of the acoustic impedance log from Well RONA) and intermediate to high values of acoustic impedance (Zp) are respectively observed within the black loop encircling the well locations at ON1 and ON2. Generally, higher values of acoustic impedance are observed in ON2, with Well RONC having the highest Zp value in both ON1 and ON2. These higher values of Zp are also seen surrounding the location of the wells within the North-Eastern and central section of the field.

Picked at constant times corresponding to Horizons ON1 and ON2 respectively, the inverted density response in Figure 11 reveal low to intermediate values of density ranging from about 1.65g/cc in Well RONB to about 2.45g/cc in Well RONC. The inset density log from Well RONA ties very well with the intermediate density values dominating Well RONA location on the attribute slices. These observations in the well locations within the black circles closely match the average values of density in Table 2.

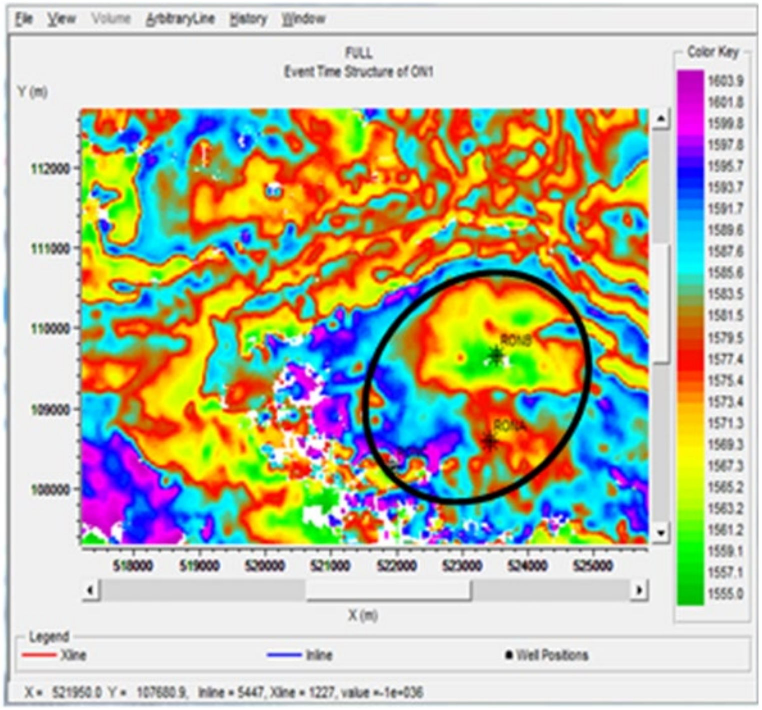


Figure 9. Attribute slice of event time structure

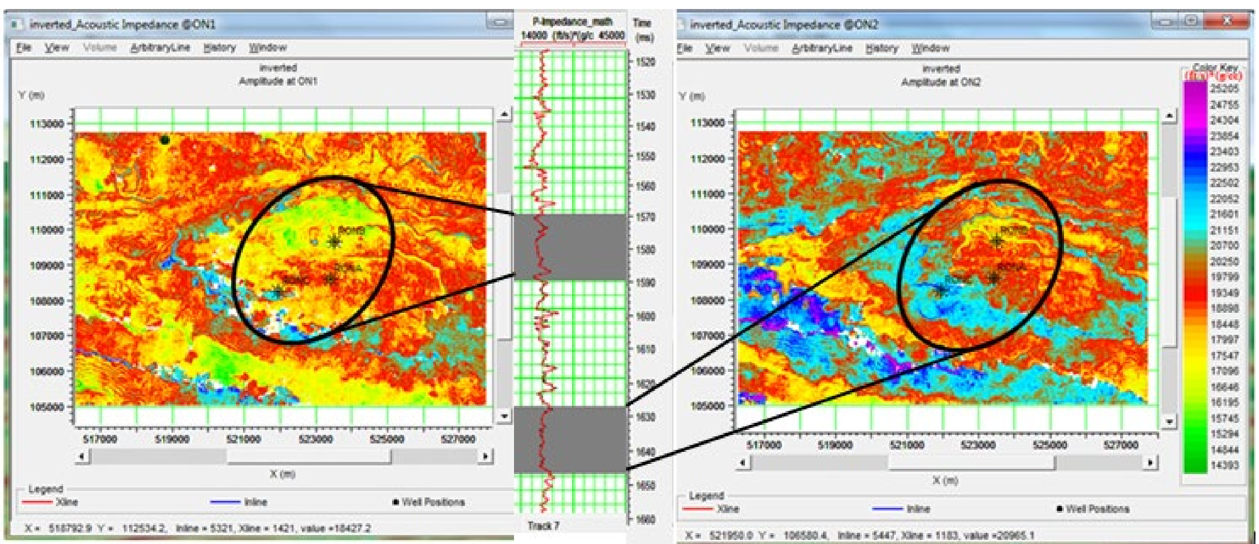


Figure 10. Attribute Slice of Acoustic Impedance (Zp) at ON1 and ON2, with an inset of the acoustic impedance log from Well RONA

Intermediate to high values of porosity ranging from about 37.0% to about 41.2% in are observed in both ON1 and ON2 at Well RONB in Figure 12. Wells RONA and RONC show low to intermediate values of porosity ranging respectively from about 25.9% to about 34.4%. These values tie closely with average porosity values in Table 2 for both wells and horizons (ON1 and ON2) and the porosity values in the Well RONA inset in Figure 12. In figure 13, very low water saturation values are seen in Well RONB, in constant time slices ON1 and ON2, while in Wells RONA and RONC intermediate to high water saturation values and high to very high water saturation values are respectively observed. These observations correspond to average water saturation values in Table 2 as well as observations in Well RONA as seen on the inset log response.

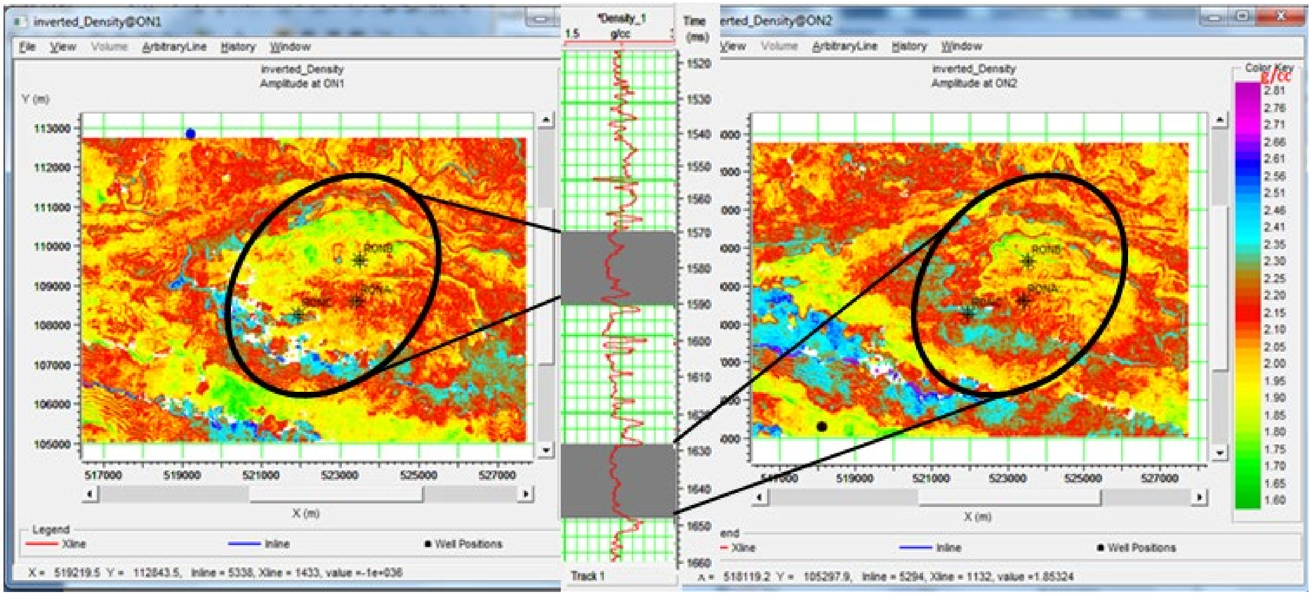


Figure 11. Attribute Slice of Density at ON1 and ON2 with an inset of density log from Well RONA

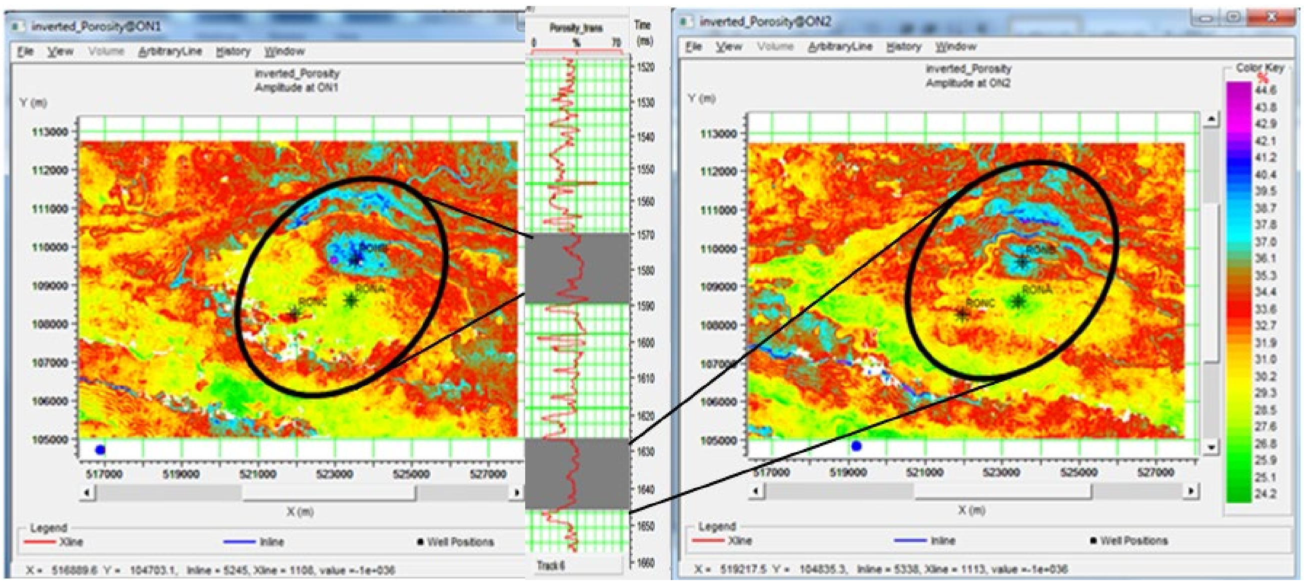


Figure 12. Attribute Slice of Porosity at ON1 and ON2 showing an inset of porosity log from Well RONA

## 5. Discussion of results

Spatial reservoir heterogeneity leaves considerable volumes of by-passed hydrocarbon in isolated pockets, according to Bassiouni and Velic [8]. Thus, the approach used in this work, which involved the delineation of intervals RN1 and RN2 at the same depth range across the three well locations aided the simulation of a spatially homogenous reservoir system. Log responses within the selected intervals RN1 and RN2, having gamma ray value below the mid-line and tending more towards the sand line, correspond to standard responses for hydrocarbon bearing reservoirs, with regards to porosity, resistivity, water saturation, density and acoustic impedance. Specifically, in agreement with Nwankwo *et al.*, [16] the high porosity observed within the intervals in the well locations are indicative of high permeability, such that is required of any prolific hydrocarbon reservoir in the study area. The reservoir delineation approach utilized in this work revealed pockets of prolific reservoirs, having high hydrocarbon saturation ($S_h$), as high as 0.96(96%) in reservoir NL2 across Well RONB. These high hydrocarbon saturation values far outclass the $S_h$ values obtained by Amulu [5] who worked with the same data set, but utilized already generated markers (intervals) provided in the data set.

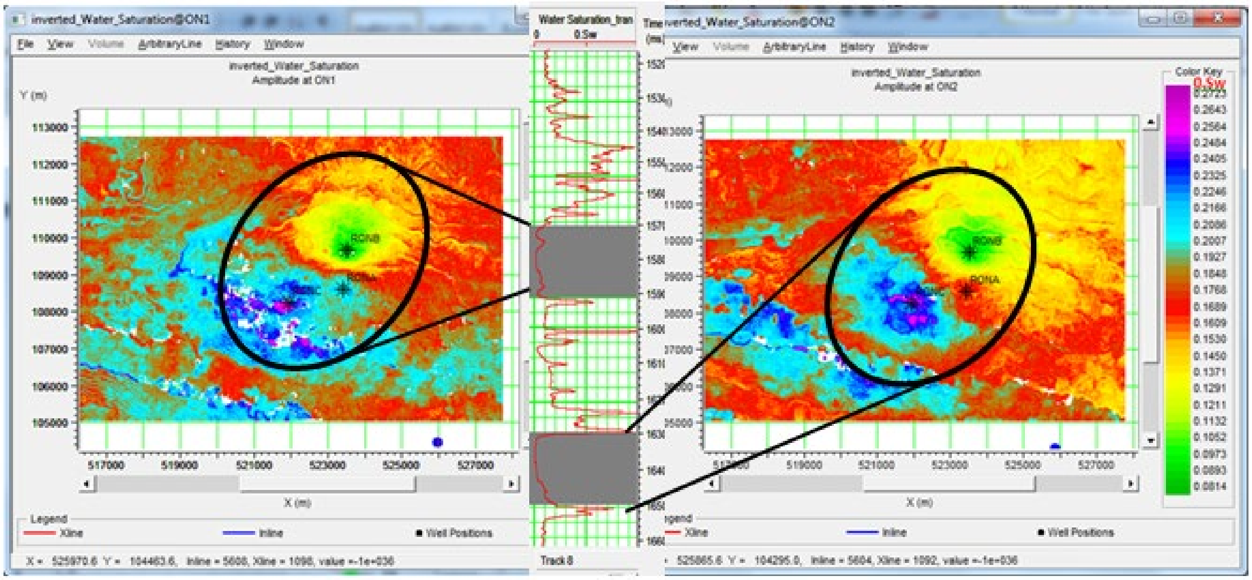


Figure 13. Attribute Slice showing water saturation at ON1 and ON2 and an inset of water saturation log from Well RONA

Structurally, the wells within the field sit on an anticline structure, evidenced by the event time structure slice, with Well RONB cutting through the crest of the anticline. This structural trend when tied with the varying colorations on the event time structure which are indicative of unequal layering within the horizon yield the picture of a fault infested anticline, which forms the main trapping mechanism for hydrocarbon within the Niger Delta. In the attribute slices the observed very low acoustic impedance values are indicative of gas sands, while low to acoustic impedance values correspond to oil sands. The high acoustic impedance values seen in Well RONC corroborate the average low hydrocarbon saturation recorded in the petrophysical analysis table. These observations are also in agreement with the density slice. Tying the intermediate density value in Well RONB at both ON1 and ON2 to the high hydrocarbon saturation observed in these horizons further validates the presence of by-passed oil sand in the two intervals NL1 and NL2. The very low density values observed in Well RONA are indicative of gas sand. The porosity and water saturation slices also show values that exceed the standard values of these two rock properties in hydrocarbon bearing intervals in the Niger Delta [14, 17, 5].

## 6. Conclusion

From the results obtained in this work, well and seismic data based acoustic impedance inversion is optimal in the characterization of by-passed hydrocarbon trapped in isolated pockets. Delineation of reservoir intervals within the same depth range across well locations aids the simulation of a spatially homogenous reservoir which reduces reservoir heterogeneity, and ultimately enhances the recovery of by-passed hydrocarbon. Data sets could be reprocessed and re-interpreted for an optimal reservoir characterization and recovery of by-passed hydrocarbon. Thus, to recover by-passed hydrocarbon within silici-clastic reservoirs, reservoir delineation should fundamentally involve detailed inspection of well logs for log responses that corroborate standard petrophysical requirements for prolific reservoirs in the study area, while ensuring that the selected markers cut through the wells within the same depth range across the wells in the field.

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### *Conflict of Interest*

*The Authors do not have any conflict of interest to declare in this research.*

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