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REVIEW ARTICLE

STRUCTURAL STYLE OF WABI FIELD, OFFSHORE NIGER DELTA NIGERIA, USING SEISMIC AND WELL-LOG DATA

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ABSTRACT

This study is focused on the interpretation of structural style in Wabi field in the Niger Delta Nigeria using seismic and well log data. From the results, faults and horizons correlated on Wabi wells tied perfectly to reflections on the seismic. The faulting pattern shows that the structural geometry over the Wabi field consist of an elongated N-W to S-E trending, collapsed crest, roll-over structure with two crests separated by a central saddle. Based on their lateral extent and throws Faults in Wabi Field is classified into boundary faults that confined the Wabi structure, synthetic and antithetic faults are within the crestal roll-over structure. The interplay of these faults, combined with the structural dip, provides the closure for the hydrocarbon accumulation within the field. Hydrocarbons in the field are encountered between 9,560 and 12,750ftss, and are contained within 3 stacked B, O, and R1 reservoirs in crestally collapsed rollover anticline. The reservoirs are predominantly shore face and are correlatable throughout the Field. Well correlation and sand analysis showed that sand R1 was the thickest sand unit by 320ft. Sand B is the thinnest sand unit in Wabi Field, it is 50ft. Results from this study provides interpretation and modelling of structural and stratigraphic interplays that would help in understanding of the feature and factors that control them reservoirs thereby creating room for predictive models that can be applied in other reservoirs at greater depth prospects. This helps to make informed decisions for optimum exploration and development of hydrocarbons in the field of study.

KEYWORDS

Well Logs, Seismic Data, Wabi Field, Faults, Horizons, Structural Style, Reservoirs, Niger Delta, Nigeria

1. INTRODUCTION

It is important to fully understand the subsurface structures for hydrocarbon production. The interpretation of seismic data is the fundamental method of determining the geometry and displacement of faults in the subsurface (Umunna et al., 2019). It involves the knowledge of structural geology, stratigraphy, tectonic settings as well as the physics behind the seismic image. Detailed mapping of geological features that are associated with reserves is very important in seismic exploration and interpretation. Although a lot of progress has been made in the areas of structural interpretation, there still exists challenges from conventional interpretation of seismic data especially in complex geological terrains such as poor resolution of sub-seismic faults and within stratigraphic features. Understanding the structures and proper mapping of the subsurface will reduce the risk of drilling for prospects and enhance the subsurface structural areas.

Well logs are an important tool in geophysics and is used extensively for detailed formation evaluation. It is also employed in the study of structural integrity; this helps progressive knowledge of the subsurface and is used to resolve major concerns in the reservoir and ultimately improve its efficiencies. Well logs are used to identify these reservoir rocks, to know if they are hydrocarbon bearing, discriminating hydrocarbon zones. It also determines the porosity, permeability, saturation of reservoir. In this study, an integrated approach of advanced processing technology using seismic and well log data are employed to enhance the structural complexity of subsurface image, to understand in detail the geological sequences around the field. The advantage of using integrated data analysis is that it provides a more detailed analysis which increase to a very large extent the reliability of the geological interpretation over using a single data. The aim of this study is therefore to carry out interpretation of structures in Wabi Field in the Niger Delta, Nigeria, using seismic and well-log data.

This study is significant in several ways. The Nigerian economy is largely dependent on exportation of oil and gas and the Government has always emphasized on an increase in reserves as the existing reserves had been depleted due to production. On the other hand, there is an ever-increasing demand for energy thereby giving rise to operators looking deeper for hydrocarbon to meet the demand for energy. Again, exploration activities in the Niger Delta for decades had been focused on shallow prospects and drilling within shallow depths had caused most field to be tagged as marginal fields which led to its abandonment for larger reserves. Most relatively, the geological basin of the Niger Delta has been exploited, leaving to explore areas of complex geology with fault planes, steep and dip structures (Beka and Oti, 1995). Applying pre-stack depth migration drastically improve on seismic images which resulted from improved understanding of the structural geometric (Mitchell and Toldi, 1998).

This study will also help in the characterization of subsurface structures, fault zones and physical properties of the formations through integration of geophysical and geological measurements. It will further provide better understanding of the subsurface leading to a better identification of optimum well placement position guide for economically viable well drilling activities. Delineation of subsurface structures, reservoir quality and lateral extents are of key importance in the determination of economic

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viability of Fields and exploration opportunities (Swan, 1991; Dong, 1996; Mahob et al., 1999; Larsen et al., 1999; Kelley et al., 2000; Jin et al., 2000). With limited well data control and the difficulty in resolution embedded in the seismic data, this study seeks to proffer ways of reducing uncertainty in the identification and classification of some subsurface structures by the integration of seismic and well log data.

2. Study Area and Its Geology

The study field location lies in the Eastern Niger Delta Northwest of Port Harcourt in the Niger Delta (Figure 1). The Niger Delta is located in the Gulf of Guinea in equatorial West Africa. It lies within the southern Nigeria between latitude 4°N and 6°N and longitude 3°E and 9°E (Klett et al., 1997). It is one of the most prolific deltaic hydrocarbon provinces in the world. And a major geological feature of significance petroleum exploration and production in Nigeria (Whiteman, 1982).

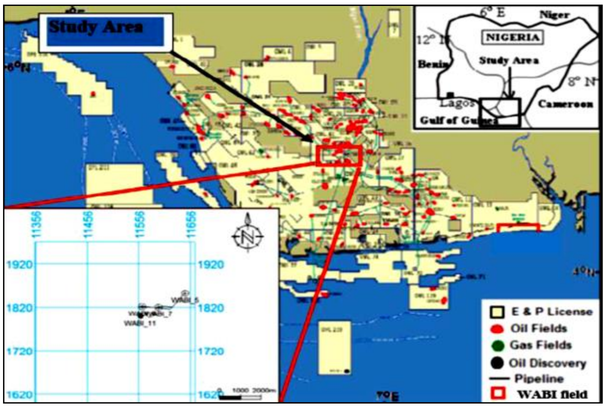


Figure 1: Map of Nigeria showing Wabi Field, Niger Delta, Nigeria

The Niger Delta area which is predominantly composed of sand, shale covers about 7500Km^2. It started to evolve in the early tertiary times when classic rivers input increased (Doust and Omatsola, 1990). This clastic wedge contains the 12th largest known accumulation of recoverable hydrocarbons, with reserves exceeding 34 billion barrels of oil and 93 trillion cubic feet of gas (Tuttle et al., 1999). The delta eventually prograded over the subsiding continental oceanic lithospheric zone and spread onto the oceanic crust of the Gulf of Guinea during the Oligocene (Figure 2) The prodelta developed on the northern part of the basin during the Camparian regression (Reymant, 1965). The modern delta formation comprises of marshy land masses intertwined by several rivers and creeks with banks of back swamps. Land mass formation here was as a result of sediment deposits. The Cenozoic delta basin developed during the cretaceous times from the triple joint and is bounded to the Northwest by the basin flank, the Calabar flank to the east west and the Anambra basin to the North (Burke, 1972). From Eocene to the present, the delta has prograde southward, forming depositional delta at each stage of its development (Doust and Omatsola, 1990). The Niger Delta is made up stratigraphically by these units: Akata formation, Agbada formation, Benin formation.

These formations become progressively younger farther into the basin, resulting in the long-term progradation of depositional environments of the Niger Delta onto the Atlantic Ocean passive margin. The Sy depositional collapse of the clastic wedge as shale of the Akata Formation mobilized under the load of prograding deltaic Agbada and fluvial Benin Formation deposits complicate the stratigraphy of the Niger Delta. Akata Formation is made up of an open marine facies unit donated by high pressured carbonaceous shales. It ranges in age from Palaeocene to Eocene and has a thickness of about 6500m, while suggested that it has a thickness of about 5000m for the deep fold (Corredor et al., 2001; Short and Stauble, 1967). Under its compacted shales with sandstone lenses, lies plant remains on top of the dark grey, sandy and silty shales. This formation is the oldest stratigraphic unit in the subsurface of the Niger Delta and the basal sedimentary unit of the delta and has been generally regarded as the main source rock for oil in the delta. According to a group researcher, the top of the Akata formation is the economic basement for oil (Ejedawe, 1981).

Agbada Formation is transitional between the upper Benin formation and the underlying Akata formation. It consists of a sequence of deltaic sands and shales. It is Eocene to Oligocene in age and consists of paralic siliciclastic that are more than 3500m thick (Short and Stauble, 1967). It has micro fauna at the top while the base is characterized by a body of sandstone. The coarseness of the grains and poor sorting inn this formation indicates its affluviatile origin. This formation serves as the main hydrocarbon reservoir due to hydrocarbon accumulation confined within it (Avbovbo, 1978).

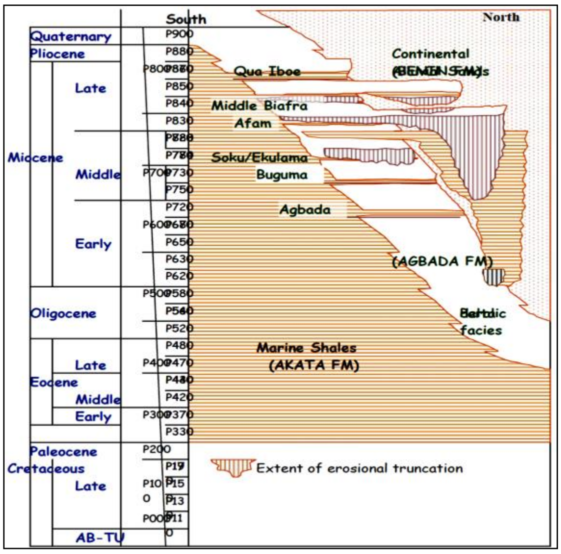


Figure 2: Stratigraphic Column Showing the Three Formations of the Niger Delta (Weber, 1971)

Benin Formation is the youngest unit in the Niger Delta. It is continental and consists of coastal plain sands, gravel with a few clay intercalations, consisting of late Eocene to recent deposits of alluvial and upper coastal plain deposits that are up to about 2000m thick (Weber, 1971). It is a continental deposit of probable upper deltaic depositional environment. It is Oligocene of age in the North on the subsurface and becomes younger progressively southward. Although this is the water bearing formation in the Niger Delta, very little hydrocarbon accumulation has been associated with this formation. Most growth in the Niger Delta are crescent in shape with the concave side facing down thrown seawards. They show a marked flattening with depth and instric shaped.

The Agbada and Akata formations are affected by these growth faults and dies out below the base of the Benin formation. Within the depobelts each growth fault is characterized by its own sand shale distribution pattern and structure. Growth faults constitute a migratory path for hydrocarbons generated in the Akata and Agbada formation giving room for migration and accumulation in the reservoir sands within the Agbada formation. It also acts as seals to migration. Weber identified four principal types of hydrocarbon traps associated with growth faults in the Niger Delta The anticlines associated with growth faults are known as roll-over anticlines (Short and Stauble, 1967). Roll over anticlines always occurs in associated with the growth faults and it is in these structures that oil and gas have been noted in the Agbada reservoir sands.

3. Materials and Methods

3.1 Data Sets

The materials used in the acquisition of the set of data employed in this study, include Seismometer and well logs, courtesy of Total Exploration and Production (E&P) Nigeria Limited with the assistance of the Department of Petroleum Resources (DPR). Seismic data consist of digitized 3D seismic data in Seg Y data format, and digitized conventional well-log suites are Gamma ray, sonic, neutron, resistivity, calliper, in LAS or ASCII file formats, check shots and image logs. Seismic data was processed using the sequence suggested by (Newman, 1973; Spratt et al., 2005; Leinbach, 1995; Yilmaz, 2001; Umoetok et al., 2020; Uko et al., 2013; Weber and Thapa, 1990). Well-log datasets used for the research are suite of logs from six wells that penetrated the reservoirs of interest. The data were assembled, quality checked and loaded. Out of the six wells, only well Wabi-10 has all the data complete. The well logs were carefully conditioned or edited prior to their use in a modelling workflow. This means that great care was taken to correctly treat the log data through shales, across drilling breaks, casing points, and washouts. In all cases, the log data were edited, normalized, and interpreted before they were used in a reservoir study. Specific analysis steps were followed de-spike and filter to remove or correct anomalous data points; normalize logs from all of the selected wells to determine the appropriate ranges and cut-offs for porosity, clay content, water resistivity and Saturation; and correct sonic and density logs for mud filtrate invasion if needed (Zorasi et al., 2019).

3.2 Reservoir Identification, Correlation and Well-to-Seismic Ties

Well correlation was the first stage of the pre-interpretation process. The process of well correlation involves lithologic description, picking top and base of sand-bodies, fluid discrimination and then linking these properties from one well to another based on similarity in trends. In between these two lithologies in the subsurface, the gamma ray log is often used. Correlation of reservoir sands was achieved using the top and base of reservoir sands picked. The correlation process was possible based on similarity in the behaviour of the gamma ray log the Niger Delta; the predominant lithologies are sands and shales. In order to discriminate shapes. Also, the thickness of the shale bodies overlying and underlying the sand body is considered during correlation. There are six basic steps involved in seismic interpretation relevant to this study and they include: seismic-to-well tie, fault mapping, horizon mapping, time surface generation, velocity modelling, and depth conversion analysis.

Seismic-to-well tie is a process that enables the visualization of well information on seismic data. For this process to be achieved, the following are basic requirements; checkshot, sonic log, density log and a wavelet. The sonic log, which is the reciprocal of velocity, was calibrated using the checkshot data. The calibration process is necessary in order to improve the quality of the sonic log because the sonic log is prone to washouts and other wellbore related issues. The results of calibrating the sonic log with the checkshot gives a new log called the calibrated sonic log. The calibrated sonic log is used along with the density log to generate an acoustic impedance (AI) log. The acoustic impedance log is calculated for each layer of rock. The next step involves generating the reflectivity coefficient (RC) log. The RC is calculated and generated using the AI log. The RC log generated is then convolved with a wavelet to generate a synthetic seismogram which is comparable with the seismic data. The statistical wavelet utilized for convolution is extracted from the seismic data. The synthetic seismogram was generated for every well that had checkshot, density and sonic log. The reflections on the synthetic seismogram were matched with the reflections on seismic data. The mathematical expressions that govern the entire well-to-seismic tie workflow are presented below:

$$AI = \rho v \tag{1}$$

$$RC = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \tag{2}$$

$$Synthetic\ Seismogram = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} * wavelet \tag{3}$$

where ρ = density, v = velocity, AI = acoustic impedance, RC = reflection coefficient.

Faults were identified as discontinuities or breaks in the seismic reflections. Faults were mapped on both inline and cross-line directions. Horizons are continuous lateral reflection events that are truncated by fault lines. The horizon interpretation process was conducted along both inline and Crossline direction. At the end of the horizon mapping, a seed grid is generated which serves as an input for time surface generation. Time surfaces were generated using the seed grids gotten from the horizon mapping process.

3.3 Faults and Horizons Interpretation

A fault is a discontinuity of layers of rocks resulting from the movement of the earth. Its evidence occurs on a seismic section, which has two dimensions. In a highly faulted area, a number of these faulted traces can be observed across the lines in the seismic sections and are identified on the seismic section by a break in the horizons. Faults were mapped on both inline and cross-line directions depending on which direction reveals them better. To validate the faults mapped, discontinuity attributes (variance cube) was generated and used. Fault were identified as breaks in the horizon loop being interpreted. In this study, Semblance cubes were generated and these helped to clearly delineate the field structural styles. The first semblance cube was obtained from variance volume attribute, while the second was obtained from a process that involves combining amplitude contrast volume attribute with edge evidence volume attribute, generated first along horizontal orientation and then along vertical orientation to capture every discontinuity (major and minor). With the fault trends (strike) established through the time slice of the semblance cubes, the faults as seen on the dip section of the seismic, which in this case were identify, is the Inline. In few cases, where the fault trend is oblique to the general dip section, an arbitrary section perpendicular to the strike of the fault was taken to enable an accurate interpretation of the fault.

A seismic horizon on seismic section is an interface between two different rock types. This interface is normally identified by a seismic peak or a seismic trough depending on the nature of acoustic contrast on the top or the bottom layer. Horizons are defined as surfaces that separate layers of different rock types in depositional environments characterized by different reflection properties and these horizons are usually interrupted by faults (Farakliotі and Petrou, 2004). The main purpose for picking horizons in seismic is for structural analysis whereby significant features can be identified and, in this project, horizons of interest (main reservoir) are selected due to prospectively significance. After the well to seismic tie was carried out and the establishment of the seismic response of the top of resolvable reservoirs, the reservoir tops were displayed on arbitrary seismic sections which were taken throughout the wells and loop tied the same reservoir top in different wells on seismic. The horizon to be mapped was then identified on one vertical section (inline section) and interpreted within the first block.

The Cross line direction cutting the interpreted inline direction is then interpreted. Horizon interpretation is carried over to subsequent fault blocks by correlation; cutting a segment from one fault block with interpreted horizon and matching it with another fault block to establish the position of the horizon in that fault block. Several iterations through the sections covering the structural relief of the horizon in the first block was necessary before the interpretation was satisfactory. Selected vertical sections are revisited to establish the correlation into the next fault block and the procedure then repeats in that fault block. The interpretation was done from fault block to fault block until the prospect is covered. When problems in understanding the data at a particular location were encountered, reference to vertical sections through that point in in-line, crossline, and other directions is made. Arbitrary lines were specially extracted from the data volume for this purpose. The interpretation is done in the inline and cross line directions until the area of interest is covered.

After the interpretation of the horizon to cover the area of interest, the Fault Boundaries are then drawn. Mapping of horizons is the gridding and contouring of the interpreted horizon to form maps. A contour map for the horizon drawn on the seismic lines was obtained by gridding and contouring the interpreted seismic data. The horizon grid and contour are in time. After the contouring of the Horizon grid, a Time Map was produced. Depth Map is produced from the conversion of time grid to depth grid by the use of checkshot or velocity data. From the depth maps, areas of closure can be seen. Structural closures in maps are indications of anticline structures and form good hydrocarbon traps. Closures always terminate at faults.

3.4 Time, Depth and Reservoir Structural Interpretation

The mapped horizons and the generated fault polygons were used to generate time structural maps. The time structure maps. The time structure maps were then converted into depth and reservoir maps using the checkshot data obtained from the area. The purpose of checkshot data is to create a velocity model to convert seismic data, horizons and faults from time to depth domain. Check shot data from three (3) wells, namely; Wabi-10, Wabi-11 and Wabi-12 were available for this study (Figure 3). From the provided Check shots, depth values were generated and their corresponding two-way-traveltime (TWT) values along the Time-Depth curve. These were loaded into Petrel using appropriate format and used to build synthetic seismograms, producing an updated check shot data which were used to carry out well to seismic ties and build velocity models for time-depth conversion. Using the velocity model of the checkshot surveys of the three wells, each finalized two-way-travel (TWT) zapped horizons were re-sampled at 5x5 Inline and 10x10 Crossline grids and used as input for conversion to the depth domain. Similarly, all assigned faults and seismic data were depth converted.

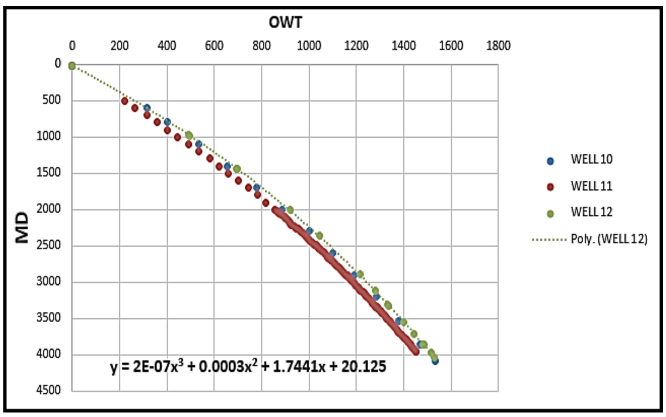


Figure 3: Polynomial time-depth (TZ) plot of Checkshot data

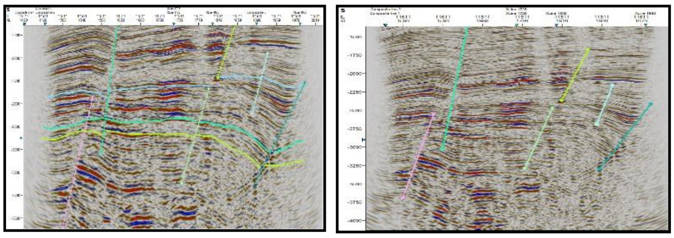
4. Results and Discussion

4.1 Results

The results as presented in Figures 4 - 10.

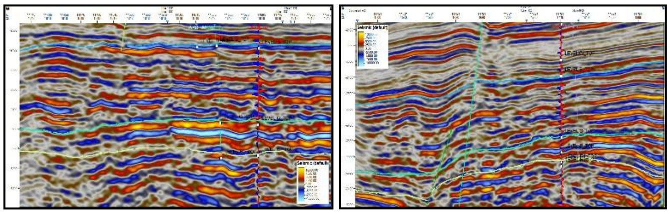
4.1.1 Interpretation of Faults and Horizons

Figures 4 and 5 show both synthetic and antithetic faults, and depths interpreted along seismic Inlines and Crosslines. All interpreted faults are normal synthetic and antithetic faults which are common in the Niger Delta basin. The interpreted sections show horizons, crestal collapsed synthetic, antithetic and regional growth faults along Dip, Strike and Regional Seismic Sections. These are evident in Figures 4 and 5. All interpreted faults are normal synthetic and antithetic faults which are common in the Niger Delta basin.



(a) (b)

Figure 4: (a) Inline 11511 Seismic Section; (b)Crossline 11511 Faults Interpreted Seismic Section Faults Interpreted



(a) (b)

Figure 5: (a) Horizons on XLine (W-E) S) Well through Wabi-10; (b) Horizon on Inline (N-through Well Wabi-10

4.1.2 Reservoir Identification, Correlation and Well-to-Seismic Ties

The results for lithology and reservoir identification are presented in (Figure 6). A total of nine (9) sand bodies were identified and correlated across all six wells in the field. Three (3) reservoir sands were selected for the purpose of this study (B, O and R1). Reservoir B is 50ft thick (9560-9610ft), Reservoir O is 320ft thick (11690-12010ft), while Reservoir R1 is 110ft thick (12640-12750ft). The resistivity logs which reveals the presence of hydrocarbons were used to identify the hydrocarbon bearing sands. The results for well-to-seismic tie conducted on WABI field using density log, sonic log and checkshot of Wells Wabi-10, Wabi-11 and Wabi-12 is presented in Figure 7.

4.1.3 Reservoir Identification, Time and Depth Structural Interpretation

The results for lithology and reservoir identification are presented in (Figure 6). A total of nine (9) sand bodies were identified and correlated across all 6 wells in the field. The three (3) reservoir sands were B, O and R1. In level B, the separation between the top and the base (50ft) is very thin although it can still be seen. This is an indication that the reservoir is very small. Level O has very thick separation (320ft), while level R1 is thin (110ft). The reservoir time and depth surfaces (Figures 8 - 10) reveal that the reservoir structure is a collapsed crest, bounded by two regional faults. Figures 8 - 10 show the fault models of the field is dominated by synthetic fault with minor antithetic ones present in the field, with a general N-W to S-E trends. The preponderance of the accumulated hydrocarbons is trapped in structures with three-way fault dependent closures.

Depth structural maps of the reservoirs is shown in Figures 8c, 9c and 10c. Structural highs are observed at the N-W and central part of the field. This area forms a good trapping system, thereby increasing retentive capacity for hydrocarbons. The hydrocarbon trapping system in the central part of the field where the wells are located is a faulted rollover anticline. The low faults throw in the area is responsible for outstanding retentive volume of hydrocarbons. Accumulations are within the fault blocks and trapped by a combination of fault and dip closures. Structural lows are seen in the north and south-eastern region and the area obviously has no prospect. Structural highs observed in the N-W part and the central part serves as good traps for the hydrocarbon accumulation. The hydrocarbon trapping system is still faulted rollover anticlines. In the N-W and central region of the field, structural lows are observed.

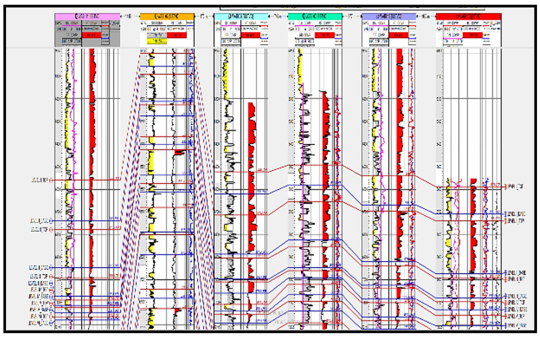


Figure 6: Well Section showing Reservoir generation Identification and correlated for Wabi Field across Wabi Field

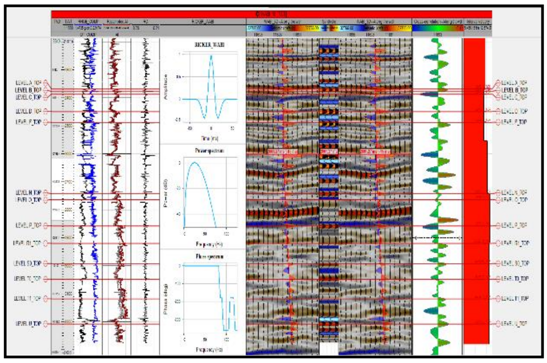


Figure 7: Synthetic Seismogram and Well-to-Seismic Tie Using Well Wabi-10, example

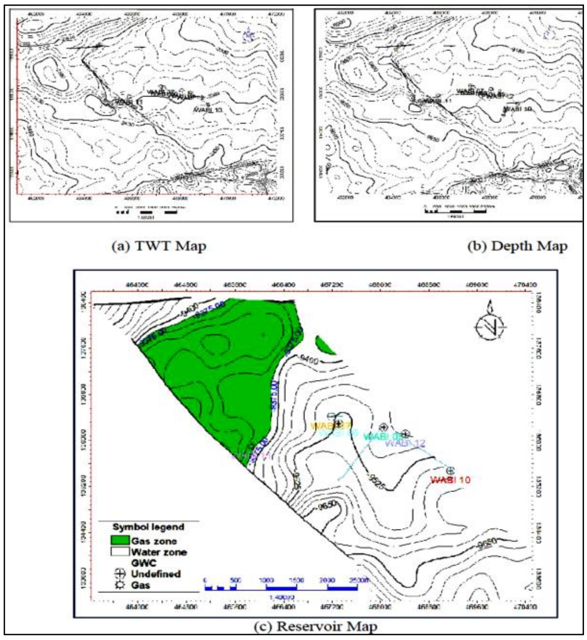


Figure 8: B Reservoir Depth Structure Map

5. Conclusion

The findings in this research are summarized in the follow sections:

5.1 Seismic Interpretation

(i) Several faults, horizons and continuities are within the field.

(ii) The seismic interpretation reveals that the geologic events of faults, horizons correlated on Wabi wells tied perfectly to reflections on the seismic.

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(iii) The faulting pattern shows that the structural geometry over the Wabi field consist of an elongated N-W to S-E trending, collapsed crest, roll-over structure with two crests separated by a central saddle.

5.2 Structural Interpretation

Based on their lateral extent and throws Faults in Wabi Field can be classified into:

(i) Boundary faults that confined the Wabi structure;

(ii) Synthetic and antithetic faults are within the crestal roll-over structure;

(iii) The interplay of these faults, combined with the structural dip, provides the closure for the hydrocarbon accumulation within the field.

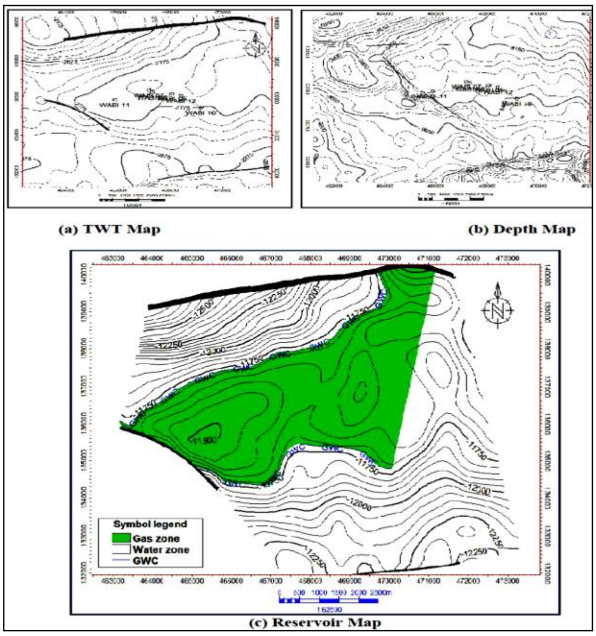

Figure 9: O Reservoir Depth Structure Map

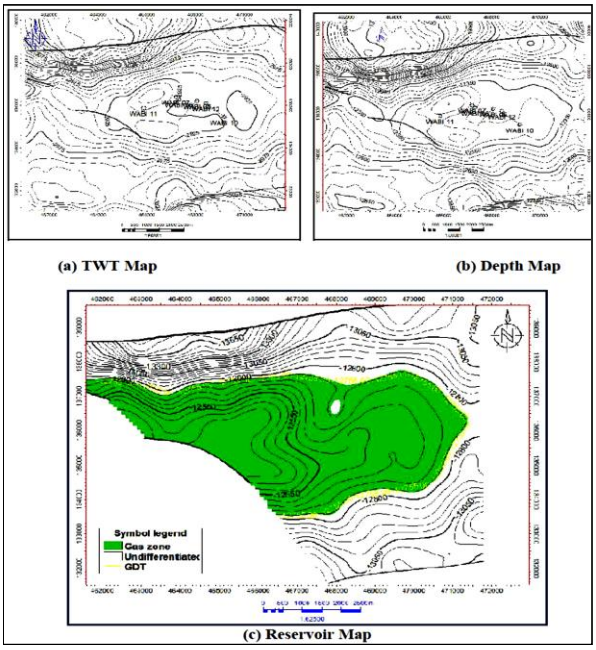

Figure 10: R1 Reservoir Depth Structure Map

5.3 Reservoir Framework

(i) Hydrocarbons in the field are encountered between 9,560 and 12,750ftss, contained within 3 stacked reservoirs in crestally collapsed rollover anticline. These reservoirs are mostly in B, O, and R1 reservoirs.

(ii) The reservoirs are predominantly shore face and are creatable throughout the Field.

(iii) Well correlation and sand analysis showed that sand R1 was the thickest sand unit by 320ft.

(iv) Sand B was the thinnest sand unit in Wabi Field, it was 50ft. The thinning of the sand sequences at greater depths id indicative of bulk density being increased as the sediment compacted.

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