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Research Paper

Lithological Description of Bornu Basin, Northeastern Nigeria Using Gamma Ray Log and Relative Acoustic Impedance Attribute

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Abstract— The Bornu Basin, which spans across Chad Republic, Cameroon, and Niger Republic, is an extensional basin that originated from the mechanical separation of the African crustal plate during the Cretaceous period. The geographical boundaries of the study area are defined by latitude 11.750 N to 13.000 N and longitude 12.000 E to 14.000 E. To better understand the distribution of rocks within the basin suitable for hydrocarbon accumulation, a lithological analysis was conducted using gamma ray logs and relative acoustic impedance attributes. By examining changes in gamma ray signatures across multiple wells, the formation tops of Chad, Kierri-kierri, Fika, and Gongila were identified, marked, and correlated across the wells. The well sections were aligned with the Chad formation, encountered at depths ranging from 0 to 220 meters across the wells. Further analysis of lithostratigraphy and seismic attributes, utilizing specialized seismic interpretation software, allowed for the interpretation of the basin's characteristics and the identification of potential prospects. The gamma ray log analysis revealed that the study area is characterized by interbedded layers of sand and shale. Additionally, lithologic correlation confirmed the presence of both basin and intra-reservoir seals. The relative acoustic impedance survey provided stratigraphic information, further supporting the presence of reservoir and seal rocks within the study area.

Keywords— Gamma Ray, Lithology, Stratigraphy, Acoustic Impedance, Shale, Well Correlation, Synthetic Seismogram, Density.

1. Introduction

The Chad Basin, spanning across Niger, Chad, the Central African Republic, and Cameroon, is a sedimentary basin [1]. In Nigeria, it is referred to as the Bornu Basin and has garnered renewed attention from the government in its pursuit of expanding the country's oil and gas reserves under the Nigeria's Decade of Gas (NDG) initiative. The NDG initiative, in effect from 2020 to 2030, focuses on exploring and developing Nigeria's hydrocarbon resources to drive economic growth [2]. Notably, the Nigerian sector of the Chad Basin has become the primary focus of recent exploratory endeavors due to the presence of commercial hydrocarbon deposits in the Chadian and Nigerien sectors [2]. The Termit Basin, situated in Niger and Chad, where commercial hydrocarbon discoveries have been made, shares geological continuity with the Nigerian sector of the Bornu Basin [3]. The dominant source and reservoir rocks in the Termit Basin consist of continental Aptian to Cenomanian deposits known as the Abu Gabra and Bentiu formations, respectively, which are correlated with the Bima Sandstone in the Bornu Basin [4]. Additionally, in the eastern Niger Graben of Niger Republic, oil and gas shows have been encountered in Mesozoic to Cenozoic sediments [5]. This study aims to provide a lithological description of the Nigerian sector of the Chad Basin to assess its potential for hydrocarbon accumulation. The methodology employed leverages variations in gamma ray activity among rock units and lateral changes in relative acoustic impedance to comprehend the subsurface geological features present in the study area.

1.1 The Study Area

The Bornu Basin, comprising one-tenth of the total area of the Chad Basin, stretches across Chad Republic, Cameroun, and Niger. It is an integral part of the Western Central African Rift System (WCARS), which originated from the mechanical separation of the African crustal block during the Cretaceous period [6]. This basin is situated within a larger active tectonic setting, characterized by geological structures that trend southwest towards the Benue trough and northwest towards the Air Mountains [7]. The specific study area under consideration lies between latitudes 11.750 N and 13.000 N, and longitudes 12.000 E and 14.000 E, encompassing an approximate area of 27,225 km2 (refer to Figure 1). The boundaries of the Bornu Basin are defined by the Yola basin and the Benue trough to the south (Nigeria), the Termit Basin to the north (Niger Republic), the Gongola basin to the west (Nigeria), and the Bongor and Doba basins to the east (Chad Republic).

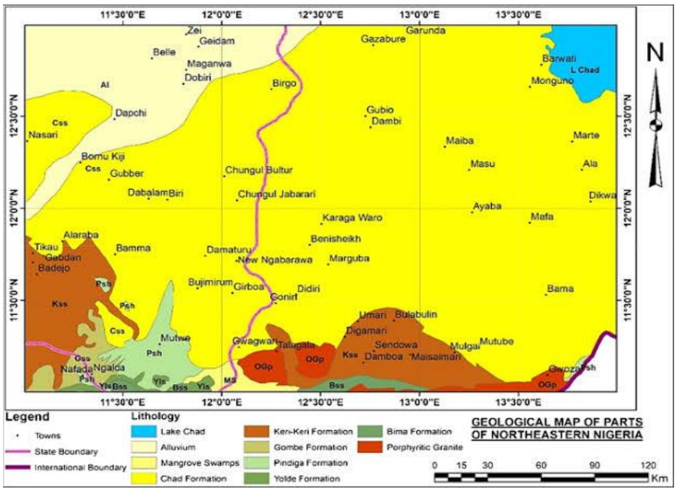

Figure 1. Geological Map of the Study Area [8]

Based on the nature of deposits in the Bornu basin, the basin is divided into six formations namely; Chad formation, Kierri-Kierri, Gombe formation, Fika formation, Gongila formation and Bima Formation [9].

2. Related Work

[6], introduced a comprehensive model to describe the regional framework and tectonic evolution of the rift basins in Niger, Chad, and the Central African Republic during the Cretaceous-Paleogene period. The model incorporates geophysical and geological interpretations of available data, revealing a complex network of Cretaceous grabens that extend from the southwest of the Benue Trough. The collected data strongly suggest a common tectonic origin for these grabens, involving the thinning of the Earth's crust both within and beneath the grabens. Additionally, the presence of igneous intrusions within the horst/graben structures near the surface has been observed, along with a relatively thick sequence of sedimentary materials overlying them. To summarize, the model proposed in [6] provides valuable Insights into the tectonic processes that shaped the Cretaceous-Paleogene rift basins in Niger, Chad, and the Central African Republic. It highlights the complex nature of these basins, characterized by grabens with thinning crust and intrusions of igneous material within horst/graben structures, all of which are covered by a substantial layer of sedimentary deposits.

In their study, [10] provided a detailed account of the Chad Basin's stratigraphy, highlighting the predominant characteristics of its sediments. The sediments within the basin primarily consist of continental deposits, which are sparsely fossiliferous and exhibit poor sorting. They predominantly comprise medium to coarse-grained, feldspathic sandstones, collectively known as the Bima Sandstone. Furthermore, the researchers observed the occurrence of a transitional calcareous deposit called the Gongila Formation. This formation marked the onset of marine incursions into the basin, appearing above the Bima Sandstones. Overlying the Gongila Formation in an unconformable manner are the Keri-Keri Shales, characterized by the presence of graptolites. These shales are stratigraphically positioned above the transitional calcareous deposit. Finally, the Chad Formation rests atop the Keri-Keri Shales and extends to the Earth's surface. The Chad Formation represents the uppermost layer within the basin's stratigraphy.

In a study conducted by [11], the hydrocarbon potential of the Chad Basin was thoroughly investigated through the utilization of wireline logging techniques. The researchers employed various types of logs, including gamma ray, caliper, neutron, density, sonic, and resistivity logs, to accurately identify crucial aspects such as reservoir zones, lithology, fractured rock formations, porosity, and estimated hydrocarbon saturation. The analysis of the acquired data through petrophysical calculations yielded significant findings, suggesting that the Chad Basin exhibits promising attributes as a potential gas province. These results indicate favorable conditions for the accumulation of natural gas resources within the basin.

In their comprehensive investigation, [12] conducted an integrated study of the Chad Basin in Nigeria, utilizing multiple geological data sets including heat flow, Bouguer gravity anomaly, depth to basement maps, and interpreted seismic reflection data. Through their analysis, they identified significant structural elements such as faults and folds, which exhibit a prevailing orientation in the northeast-southwest direction. Furthermore, they also observed the presence of additional features like grabens and horsts, which form as a consequence of tensional stress, as well as magnetic intrusions within the examined sections. The authors' findings indicate that the combination of heat flow, Bouguer gravity values, and seismically determined structural characteristics suggest favorable conditions for hydrocarbon exploration in the Cretaceous rocks of the Chad Basin in Nigeria. They propose that the basin exhibits high potential for both structural and stratigraphic traps. Based on their study results, they recommend focusing further drilling efforts to deeper depths along the southwestern and northeastern axes of the basin. Overall, the integrated analysis conducted by [12] provides valuable insights into the geological attributes of the Chad Basin in Nigeria, highlighting its promising prospects for hydrocarbon exploration and suggesting specific areas for future exploration activities.

In their study, researchers [13] confirmed the existence of the three fundamental components necessary for the accumulation of hydrocarbons in the Bornu basin, namely Source rock, Reservoir, and Seal. Their findings demonstrated that the shale formations of Bima, Gongila, and Fika contain significant amounts of organic matter suitable for hydrocarbon generation. Through their calculations, they determined that the Total Organic Carbon (TOC) in most of the samples ranged from 0.54 wt% to 1.25 wt%. The

Hydrocarbon Index (HI) values varied from 11 to 173.8 mg/g within a temperature range of 365 to 519°C, indicating the potential for hydrocarbon generation. The researchers identified the kerogen content as primarily type III with a minor presence of type II kerogen, suggesting the possible presence of gas in the basin. Furthermore, they identified potential reservoir rocks within the Bima, Gombe, and Kierri-Kierri formations, which consist of sandstone beds. In terms of trapping systems, both stratigraphic and structural mechanisms were observed in the basin, indicating the presence of favorable conditions for hydrocarbon accumulation. These findings provide valuable insights into the hydrocarbon potential of the Bornu basin and contribute to our understanding of the geological factors involved in the formation and trapping of hydrocarbons in this region.

[14] carried out integrated well log and 2-D seismic data interpretation to image the subsurface stratigraphy and structures in North – eastern Bornu basin. They deployed well log suits gamma ray, resistivity, bulk density and sonic log to identify lithology and stratigraphic boundary of the subsurface formation. Four well log facies and environment of deposition were determined in their study. They showed that the main subsurface structural lineament in the area includes NW – SE, NE – SW and NNW – SSE trending faults which formed horst and graben features.

[15] studied the petroleum system elements and migration pattern of Chad basin, employing the method of coupled structural analysis and petroleum system modelling to investigate the structural and hydrocarbon evolution of the basin in order to reassess the hydrocarbon potential and migration trends. The modelling result showed no significant accumulation of commercial hydrocarbon in the Bornu basin.
[16] worked on the lithostratigraphic interpretation and analysis of depositional environment of the chad basin. Their seismic analysis showcased region of low amplitude discontinuous facies, high amplitude convergent facies, and continuous low amplitude facies across the seismic volume. Their study indicate that cretaceous basement features controlled the deposition of overlying formations in the basin.
[9] worked on the reservoir identification in the Nigerian sector of the chad basin using seismic attributes analysis. The Relative Acoustic Impedance (RAI) also confirmed the presence of seal and reservoir rock layers in the study area. Their work showed chad basin as crisscrossed by network of faults which could serve as structural trap. Network of faults and some structural features observed from the seismic interpretation, together with RMS amplitude and sweetness survey identified distinctive high amplitude reflections (Bright Spots) which are usually correlated to the presence of hydrocarbon.

[2] worked on reservoir identification in chad basin based on well log Analysis, Using the available well log data, three reservoirs were identified with the aid of Gamma log (GR), Resistivity log (ILD), Density (RHOB) and Neutron Porosity log (NPHI). Petrophysical calculations were done employing the Archie's equation which revealed that some reservoir across Kanadi and Kinasar well have up to 72% hydrocarbon saturation, while some other identified reservoirs are water saturated. Porosity-Resistivity cross plot confirmed the presence of hydrocarbon in the Kinasar well.

3. Theory

Lithological analysis is accomplished through the use of seismic attributes analysis, which are measurements, calculations, or derived properties obtained from seismic data. Seismic attributes are the different elements of seismic data that are obtained through various measurement techniques, computations, and other methods of seismic interpretation. They were first introduced in the early 1970s as a means of enhancing seismic interpretation. Over the years, numerous new attributes have been developed and computed, many of which have commercial value. However, the full potential and application of these attributes are still not completely understood by many interpreters and users.
The analysis and interpretation of seismic data in conjunction with attribute analysis can aid in the assessment of fault patterns, fault locations, as well as the continuity and discontinuity of seismic traces [17]. Various researchers, including [18], have introduced different types of attributes such as Relative Acoustic Impedance (RAI), Coherence, Variance, and Curvature, along with their respective applications. The introduction of seismic attributes such as coherence, curvature, relative acoustic impedance in the mid-1990s, and spectral decomposition in the late 1990s has revolutionized the possibilities offered by seismic data analysis. These attributes provide robust tools that were previously unavailable to geoscientists. One such attribute, Relative Acoustic Impedance, is particularly useful for discriminating lithology, identifying thickness variations, and indicating sequence boundaries associated with changes in elastic constants. It can also reveal unconformity surfaces, discontinuities, porosity, sequence boundaries, and the presence of hydrocarbons in a reservoir. The seismic trace, which is a band-limited reflective series, can be mathematically represented by equation (1) [19].

$$f(t) = \frac{1}{2}\left[\frac{\Delta\rho V}{\rho V}\right] \qquad (1)$$

Where f (t) = seismic trace, $\boldsymbol{\rho}$ is density while V is seismic wave velocity.
Relative acoustic impedance is a simplified inversion that is generated as an asynchronous attribute in the seismic interpretation software [20]. It is derived from a zero phase trace by two methods; integrating the zero-phase trace (a running sum) or rotating the phase of the zero-phase trace by ± 90°

Relative impedance is more of an interval attribute (Schroeder, 2018). According to [18], the relative acoustic impedance (RAI) can be computed by integrating the real part of the seismic trace as in equation (2).

$$\ln(\rho V) = 2\int_{t=0}^{t=T} f(T)\,dt \qquad (2)$$

Where f (T) = real part of seismic trace, ρV is acoustic impedance while ρ and V are density and seismic wave velocity respectively. A filter in the form of equation (3) is applied to suppress long-wavelength trends that originated from the integration process [19].

$$BL(f) = \frac{1}{1+F/F_n} 2n \quad (3)$$

Where BL (f) = band –limited signal in frequency; f_n = frequency cutoff value of 10 Hz, (N = filter of order three. It is used for delineating sequence boundaries, unconformity surfaces, and discontinuities.

4. Procedure

The data utilized for this study comprised a 3D-seismic volume in SEG-Y format, four well log suits in LAS file format, check shot data, formation tops, and a field map indicating the location of each well. The well log suite consisted of several logs, including Gamma ray (GR) log (ranging from 0 to 160 API), Resistivity Log (LLD) (ranging from 0.2 to 2000 Ωm), Neutron Porosity (ΦN) (ranging from 1.83 to 2.67), Sonic log (DT) (ranging from 40 to 240 µs/ft), and density (RHOB) (ranging from 1.9 to 2.9 g/cm3). These data were obtained from the Nigerian National Petroleum Corporation (NNPC) in accordance with the Department of Petroleum Resources (DPR) and the Federal government's policy on education.

The Petrel® E&P software platform 2017 was employed for various tasks such as 3D seismic interpretation, attribute visualization, and displaying well logs data. Four wells, namely Kasade, Kinasar, Bulte, and Kanadi, were selected for this study. The coordinates of these wells are as follows: Kasade (14250000N, 3280000E), Kinasar (14500000N, 3640000N), Bulte (14450000N, 3280000N), and Kanadi (14400000N, 3600000E).To ensure data quality, the 3D seismic data and well logs were imported into the Petrel environment and examined in various windows such as the interpretation window, well section window, and 3D window. The data, along with their respective coordinate reference system, were loaded into the Petrel Software (as shown in Figure 3) following the flow chart. Prior to interpretation, a quality check (QC) was performed on the data. The well data played a crucial role in lithological interpretation and stratigraphic correlation. To integrate the log data with the seismic data, time-depth data (check shot data) were utilized to generate a synthetic seismogram and establish a relationship between the well log data and the seismic data (seismic-to-well tie). The seismic data aided in subsurface fault interpretation and horizon mapping. The Gamma ray log, with a scale of 0 to 160 API (American Petroleum Institute), was utilized for lithology determination and lithostratigraphic correlation. A shale baseline of 60 API was adopted, classifying zones with gamma ray readings below 60 API as sand zones and vice versa. The resistivity log, with a scale of 0.2 to 2000 Ohms meter, helped identify potential hydrocarbon zones. The sonic log also played a role in the seismic-to-well tie process. Faults were interpreted in both the seismic inline and cross-line sections. Finally, relative acoustic impedance attributes were employed to enhance the visualization of lithology and layer porosity.

Lithology Description: With the help of gamma and resistivity log, the lithology and potential reservoirs zones in Bornu Basin were identified and mapped across the wells. The well section window is populated with well logs. Well tops are displayed by toggling on the checkbox in front of the well top folder. The available gamma-ray and resistivity logs from the oil wells in the field were grouped and used for lithologies and reservoirs delineation. Logs were colour filled for better visualization and then followed by interactive facies interpretation using the discrete log class tool available in Petrel 2017 interpretation software. A shale baseline of 60 API was used, such that deflections of the gamma ray signature below 60 API indicate sand zone while the deflection of above 60 API signifies shaly zone. Marking of the observed lithology across wells is what is termed as lithostratigraphic correlation. After the lithostratigraphic interpretation, the rock units of the same properties in time and in space were correlated across the wells. This helped in revealing the lateral continuity and or variations of the rock units across the wells. The correlation was achieved by the identification of log signals that are of the same signatures from well to well in order to establish the lateral lithofacies changes as well as to classify the geology of the study area.

Synthetic Seismogram: Synthetic seismogram was generated using checkshot data, seismic volume and the density logs from Kanadi well. It showed changes in acoustic impedance (4) which is given by equation (3.16) [16], and expected variation of seismic signature across the basin.

$$I = \rho V \quad (4)$$

Where I is acoustic Impedance, V is seismic velocity and ρ is density

The synthetic seismogram relates the well data recorded in depth and seismic data recorded in time. Synthetic seismogram was generated for the well that has sonic and density logs and was correlated across the well. Kanadi well with density log (RHOB) and Check-shot data was used to generate the acoustic impedance and reflection coefficient series which under convolution with the Ricker wavelet produced the synthetic seismogram for the Bornu basin. The polarity and the phase of the data were determined, in order to determine which stratigraphic top defined in the wells is responsible for a particular seismic event; this is crucial for horizon identification and effective structural analysis.

5. Results and Discussion

Mapping Formation Tops: The formation tops were mapped using the gamma ray log, by observing remarkable changes in gamma ray signatures across the wells, the formation of tops (Chad, Kierri-kierri, Fika and Gongila) were identified, marked and correlated across wells, The well section was flattened on top of the Chad formation which is encountered at approximate depth of 0 – 220 m across the wells. Figure 2 shows the well top formations correlating in the study area while their depths, Table 1 shows to the marked formation tops in the study area. Bulte, Kasade and Kanadi wells.

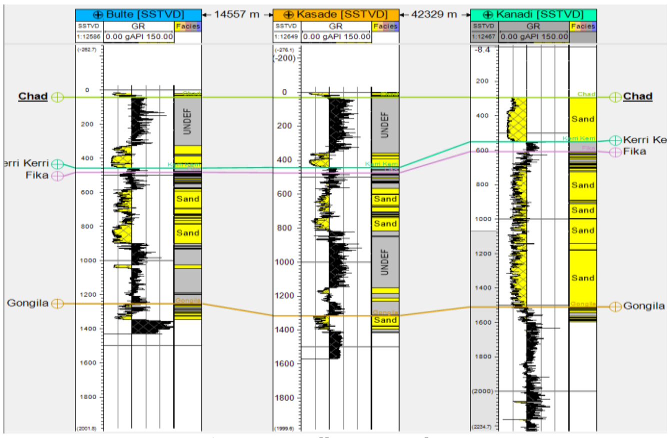

Figure 2. Well Top Correlation

Table 1. Depth to Marked Formation Tops in the Study Area

Formation Tops	Bulte Interval (m)	Kasade Interval (m)	Kanadi Interval (m)
Chad	0 – 50	0 - 50	0 – 200
Kierri-Kierri	480	430	570
Fika	500	490	600
Gongila	1250	1300	1480

Lithology Result: The lithological description of the study area was done using the Gamma ray log motifs. Two distinct lithology were identified they are; Sand lithology and Shale lithology. The sand lithology is associated with the lower Gamma ray readings, while the shale lithology are associated with the higher Gamma ray reading (Figure 3). The lithologic description shows an intercalation of sand and shale in sequence suitable for hydrocarbon production and storage, whereby the underlying shale serve as source rock, the embedded sand serve as reservoir rock overlain by another shale bed which serves as seal. This system of sand shale intercalation is observed across the four marked formations and extends up to the depth of 3500 m. The sand and shale facie were further marked using discrete log class tool available in the Petrel interpretation software.

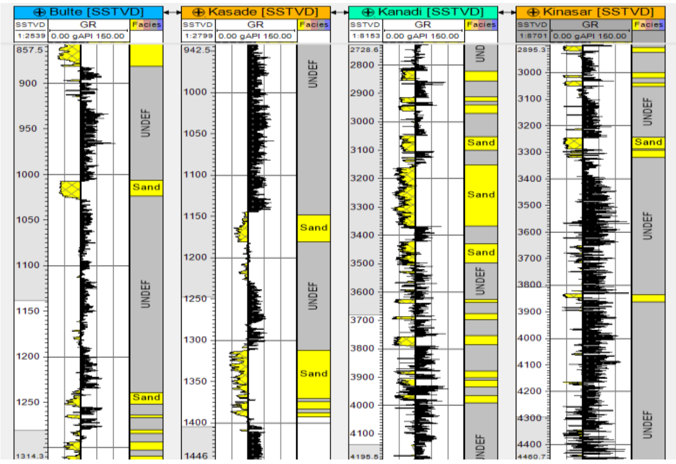

Figure 3. Well Top Correlation

Synthetic Seismogram: Synthetic seismogram was generated using checkshot data, seismic volume and the density logs from Kasade well. The seismogram showed changes in acoustic impedance (I) and expected variation of seismic signature across the basin.

The synthetic seismogram relates the well data recorded in depth and seismic data recorded in time. Synthetic seismogram was generated for the well that has sonic and density logs and was correlated across the wells. Bulte well which has density log (RHOB) and Check-shot data was used to generate the acoustic impedance and reflection coefficient series (figure 4) which under convolution with the Ricker wavelet of 25Hz produced the synthetic seismogram for the Bornu Basin (figure 5). Through the synthetic generation, the polarity of the seismic trace was determined to be normal polarity, thereby helping to define the lothologic class responsible for a particular seismic event in the seismic volume; this is crucial for effective structural analysis.

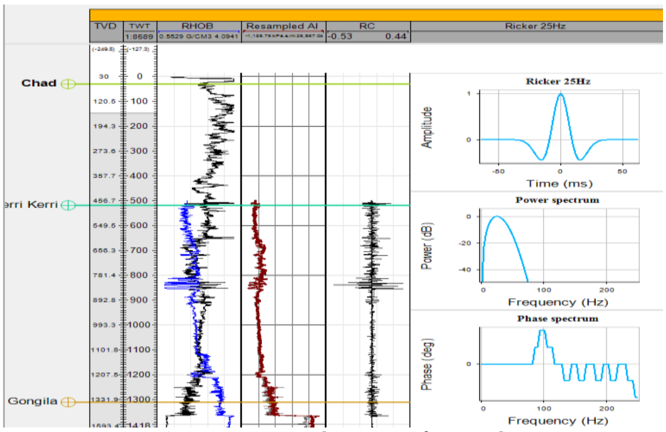

Figure 4. Generated RC series for Kasade

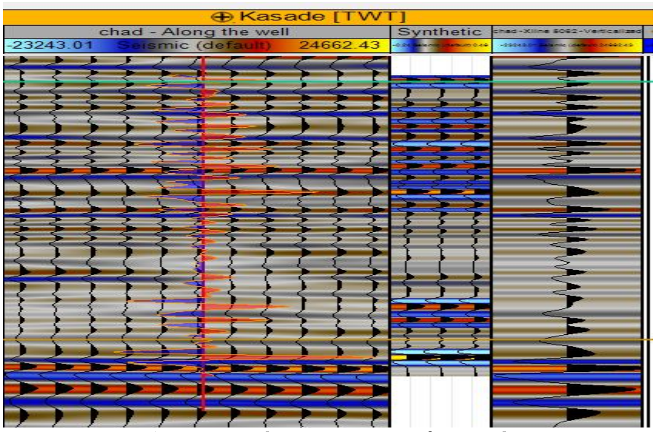

Figure 5. Synthetic Seismogram for Kasade

Seismic Interpretation: Seismic interpretation formed the second phase of the technical interpretation. Before the interpretation, a general overview of the seismic section was done. The seismic section used for this study was cropped from 1000ms to 2250ms which cuts across Kierri-Kierri Formation, Fika Formation, and Gongila Formation. It is characterized by continuous and discontinuous reflectors that terminate against faults, low – high amplitudes, parallel to subparallel and chaotic reflection patterns. (Figure 6)

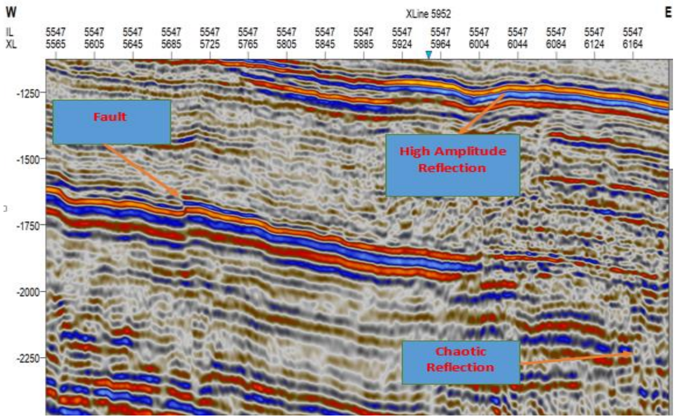

Figure 6. Seismic overview at inline 5547

Horizon Mapping: From the 3D seismic data, five key horizons representing Chad, Kierri-Kierri, Fika, Gongila and Bima formation were identified and shown in figure 7, mapped and interpreted using their seismic signatures at different unconformities. The continuities of the fault segments and their assignment were rigorously checked on the seismic sections. Some part of the horizons picked were observed to have fallen on chaotic zones at varying intervals on the seismic volume which required keen observation to determine continuity of the horizon at these intervals. Horizon 1 representing Chad formation is characterized by low amplitude reflections with moderate continuity, its chaotic nature related to lithologic heterogeneity and unconsolidated nature. Horizon 2 representing the Kierri - Kierri formation is characterized by low - moderate amplitude reflection with moderate to good continuity, Horizon 3 representing Fika formation and is marked by good continuity reflections, mostly appearing parallel-to-sub parallel and it is not disturbed by fault truncations. Horizon 4 representing Gongila formation is characterized by high amplitude reflections and truncated by series of faults and other structural features like anticline, folds, hoist and graben etc. Horizon 5 represents the Bima formation and is characterized with high amplitude poor continuity reflections, mostly disturbed by some truncations such as faults and folds.

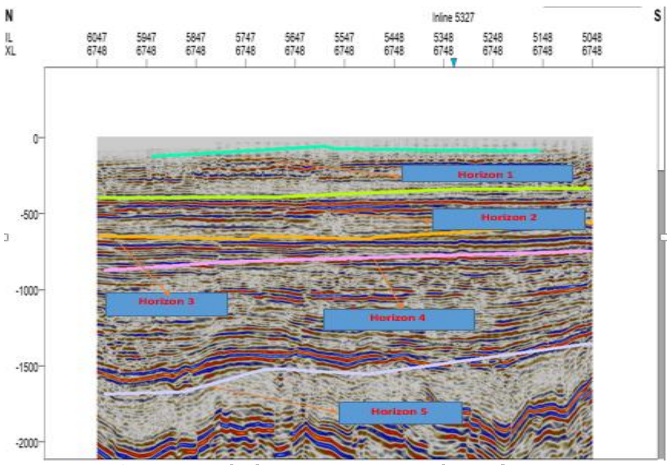

Figure 7. Marked Seismic Horizon in the Study Area

Relative Acoustic Impedance Time Slice: The relative impedance data shows the changes in acoustic impedance of the subsurface, offering a quality visuals of the various horizons, lithology changes and sequences boundaries across the study area. Most of the potential reservoirs are observed between two way travel time (TWT) of 100 – 2000 ms.

Panning through the data, multiple structural trends (synclines and Anticlines) and geo-bodies including various types of faults are observable from the seismic in the interpretation window. These structures are target for either gas or oil. Zone of structural highs are the anticline and are usually a target for drilling a wells. (Figure 8) is time slice at -700 m and – 900 ms with a display of relative acoustic impedance showing the stratigraphic trends in the study area.

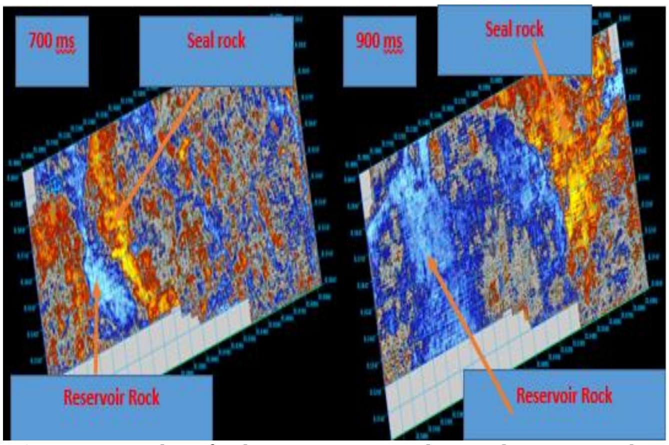

Figure 8. Time Slice of Relative Acoustic Impedance Volume at Time slice 700 and 900ms

6. Conclusion and Future Scope

The utilization of well log data and 3D seismic data integration has greatly facilitated the analysis of lithology in the Chad Basin. The lithological assessment identifies significant formations such as the Chad Formation, Kierri-Kierri Formation, Fika Formation, and Gongila Formation. Within the study area, a series of sand and shale lithologies are observed, aligning with other established hydrocarbon provinces. The sandy lithology functions as a reservoir, while the shale lithology acts as a seal. Drawing upon the interpreted results, it can be inferred that the relative acoustic impedance attribute proves to be an effective tool for visualizing lithological trends within sedimentary basins. The lithological analysis reveals that the Chad Basin encompasses two primary rock types capable of generating and storing hydrocarbons, namely shale and sand formations. To enhance further studies in the study area, the following recommendations are proposed:

1. Drilling additional wells accompanied by check shot data would provide valuable insights.
2. Conducting a seismic survey employing angle gather techniques in the study area would enable the utilization of amplitude variation with offset for predicting fluid types within the identified sand reservoirs.

By implementing these recommendations, a more comprehensive understanding of the study area's lithology and potential hydrocarbon reservoirs can be attained.

Data Availability
None

Conflict of Interest
Authors did not encounter any conflict of interest regarding this research paper

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None

Authors' Contributions
All the stages of this research were conducted by the authors in combined effort.

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