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Research Article

Lithostratigraphic interpretation and the analysis of the depositional environment of Nigeria Chad basin using well log data and seismic data

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Abstract

This work aims at lithostratigraphic interpretation and the analysis of the depositional environment of Nigeria Chad Basin using well log data and seismic data. Well log data such as Gamma ray, resistivity, bulk density and sonic logs were used to identify lithology and stratigraphic boundaries of the subsurface formations while the 3-D seismic data was used to interpret the seismic facies, structures, and the nature of the environment of deposition. Seismic to well tie was used to validate the formation horizons identified. Lithological descriptions ascertained five formations with alternate sandstone and shale units, five lithofacies LF1, LF2, LF3, LF4, and LF5 were encountered, three lithofacies associations such as continental environment facies, transition environment facies, and marine environment facies were identified. Seismic attribute analysis was achieved using structural smoothing and media filter. Seismic facies analysis was obtained with low amplitude discontinuous facies (Bl facies), high and low amplitude convergent facies (Cbhl facies), high amplitude convergent (Cbh facies), and continuous and low amplitude facies (D facies) across the seismic volume. Structural mapping and surface seismic attribute maps were generated from the study. It was discovered that the Cretaceous Basement structural features controlled the deposition of the overlying formations in the basin.

Keywords: Seismic facies, Seismic attributes, Surface attribute, Formation, Lithofacies.

INTRODUCTION

Chad Basin is an intra-continental rift basin, which extends from Northeastern Nigeria to Chad Republic, Niger Republic and the Cameroon (Okpikoro and Olorunniwo, 2010). The basin is bounded by latitudes 10^0 N and 14^0N, and longitudes 12^0E and15^0E (Figure 1). It is believed to be genetically related to the Benue Trough, which resulted from a failed arm of a triple junction when South American continent separated from the African continent in the Early Cretaceous. These two basins are however separated by the Zambuk Ridge (Burke,1969; Genik, 1992). Since the late seventies, the Nigerian sector of the basin has been an area of interest in terms of hydrocarbon exploration mainly by the Nigerian National Petroleum Corporation (NNPC). Early exploration works were done by Shell-D Arcy in 1938, and later Mobil Exploration Nigeria Limited in 1955. At about 1965, all the oil prospecting companies limited their activities to the Southern Nigeria sedimentary basins, especially the Niger Delta Basin which has become the most prolific sedimentary basin for hydrocarbon exploration in Nigeria (Okpikoro and Olorunniwo, 2010).

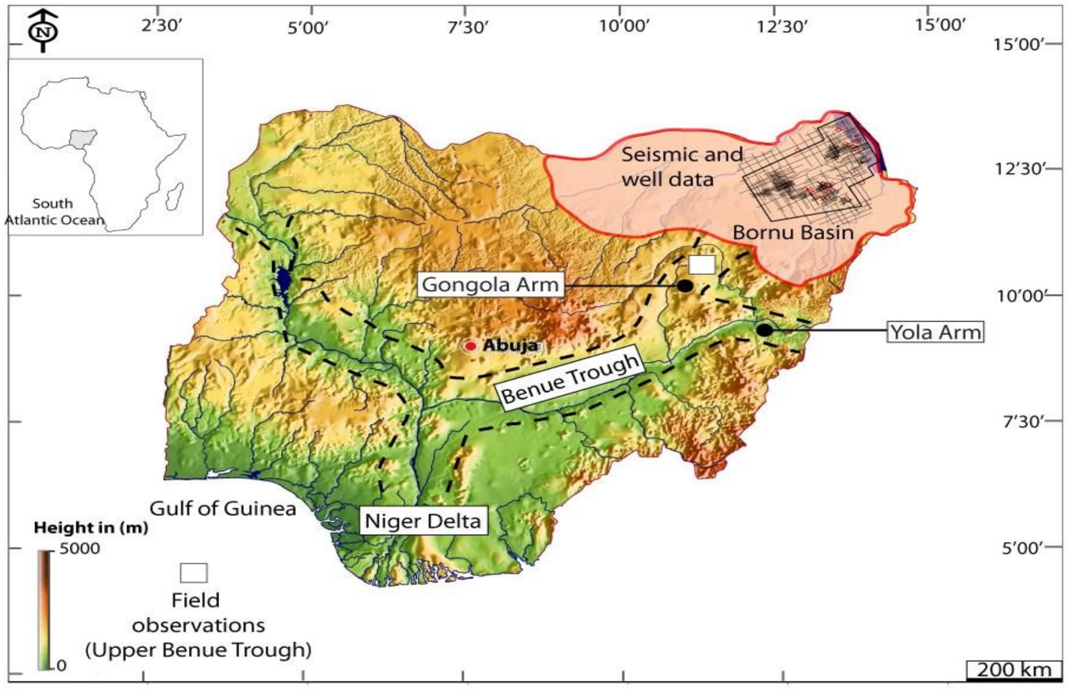


Figure 1. Map of Nigeria showing the location of Nigeria Chad Basin, inset is a map of Africa showing the location of Nigeria (After Adamu, 2016).

The Nigeria Chad Basin is characterised by semi-arid climatic conditions typical of the Sudan, Northern and Central Africa and the extent of the location is within regional Cretaceous West and Central African Rift System (Miller *et al*., 1968; Isiorho and Matisoff, 1990; Isiorho, and Nkereuwem, 1996) (Figure.2). Generally, bedrock outcrops in the basin are scarce, mainly covered by thick Quaternary sediments forming broad flat terrain in the north towards the southwestern boundary of Republic of Chad and the Lake Chad (Isiorho, and Nkereuwem, 1996). Nigeria Chad Basin is an inland sub- basin within the southwestern boundary of the Chad Basin and it forms part of the regional Cretaceous West and Central African Rift System (WCARS) basins (Binks and Fairhead, 1992; Genik, 1992). However, few outcrops were found in the southern part of the basin towards its boundary with the Upper Benue Trough (Obaje, 2009; Boboye and Akaeogbobi, 2012; Chinwuko *et al*., 2012; Hamza and Hamidu, 2012). These limited outcrops mapped using traditional field methods were used to generalise the stratigraphy of the entire basin. The stratigraphic investigations carried out in localised parts of the basin using the geological field mapping were therefore inadequate since the greater part of the basin in the northern part remained constrained by flat topography and inadequate bedrock outcrops. Previous subsurface stratigraphic studies in the northeastern part of the basin which involved few core samples or segregated ditch cuttings were obtained from few wells (e.g., Moumouni *et al*., 2007; Boboye and Abimbola, 2009; Alalade and Tyson, 2012; Hamza and Hamidu, 2012; Boboye and Akaegbobi, 2012; Adeigbe *et al*., 2013; Adegoke *et al*., 2014). Similar previous studies including Gamma ray log analysis (Adepelumi *et al*., 2012) and 2D seismic data analysis (Avbovbo *et al*., 1986; Okpikoro and Oluronniwo, 2010) were insufficient in identifying detailed subsurface stratigraphy of the northeastern part of the basin. Consequently, in the absence of bedrock outcrops and intact core samples, this study presents an alternative effective subsurface stratigraphic study using multi-well log data including Gamma ray, resistivity, bulk density and sonic logs obtained from the complete wells drilled in the basin and intersecting 3D seismic data. This work gears towards the re-evaluation of the stratigraphy, the structures, and the depositional environments of these rocks using combined 3D seismic data and well log suits. Several discrepancies exist in the literature for the lithostratigraphic classification of the Nigeria Chad Basin. The subsurface stratigraphy in the northeastern part of the basin towards the southwestern shores of the Lake Chad remain unclear since specific data were commonly used and not a combination of different datasets, which allows correlation and validation of the subsurface geology of the study area. The stratigraphy of the Nigeria Chad Basin was thus routinely associated with the stratigraphy of its south adjoining Gongola Basin in the Upper Benue Trough. There is possibility of hydrocarbon accumulation in the Nigerian sector of the basin because commercial volumes of hydrocarbons have been discovered in Chad and Sudan within the Central African Rift Subsystem. In Southwestern Chad, exploitation of the Doba discovery (with estimated reserves of about 1 billion barrels) by Exxon-Mobil has led to the construction of a 1,070 km long pipeline through Cameroun to the Atlantic coast.

Recent researchers on the Nigeria Chad Basin have integrated several geophysical methods of investigation to study the hydrocarbon potential of the basin. From the studies, exploration efforts in the Nigeria Chad Basin have had negligible success. For this reason, many aspects of the exploration programme have been temporarily suspended and the vast amount of data generated over the years is being evaluated to assist in designing a future exploration programme.

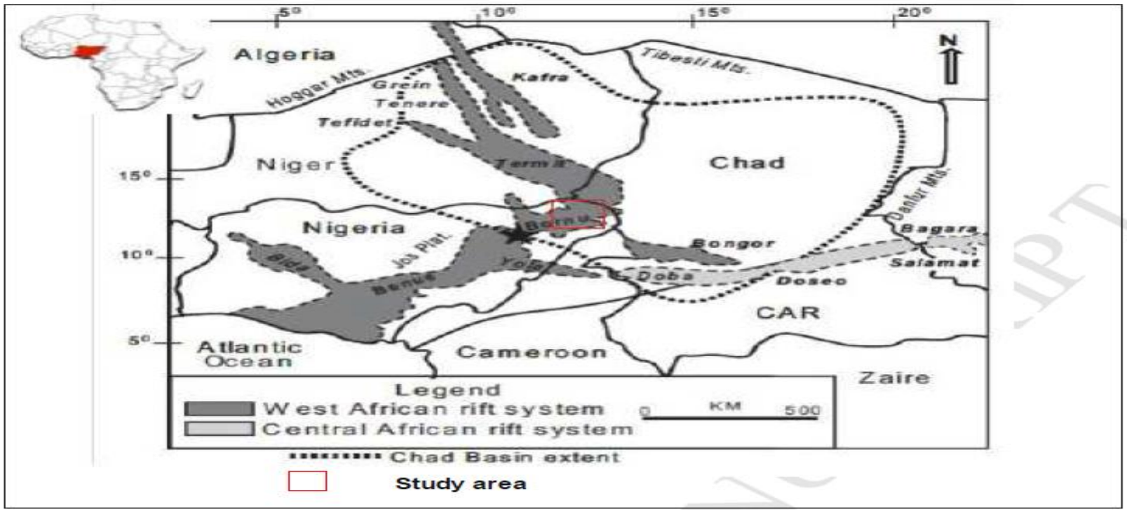


Figure 2. Map showing location and extent of Nigeria Chad Basin (modified from Alalade and Tyson, 2010)

Geology of the Nigeria Chad Basin

Sedimentary sequences were deposited from the Paleozoic to Recent, accompanied by a number of stratigraphic gaps. The sediments transport is from fluvial to shallow marine as indicated in Figure 3. The first sedimentary deposits are mainly continental, sparsely fossiliferous, poorly sorted, and medium-to coarse-grained, feldspathic sandstones called the Bima Sandstone. A transitional calcareous deposit Gongila Formation that accompanied the onset of marine incursions into the Basin, overlies the Bima Sandstones. These are overlain by graptolitics hale(Okosun,1995). The oldest rocks in the Chad Basin belong to Bima Sandstone and the youngest to the Chad Formation as shown in the stratigraphic column of the study area (Table 1). The lithology of the area is made up of six major formations as explained below:

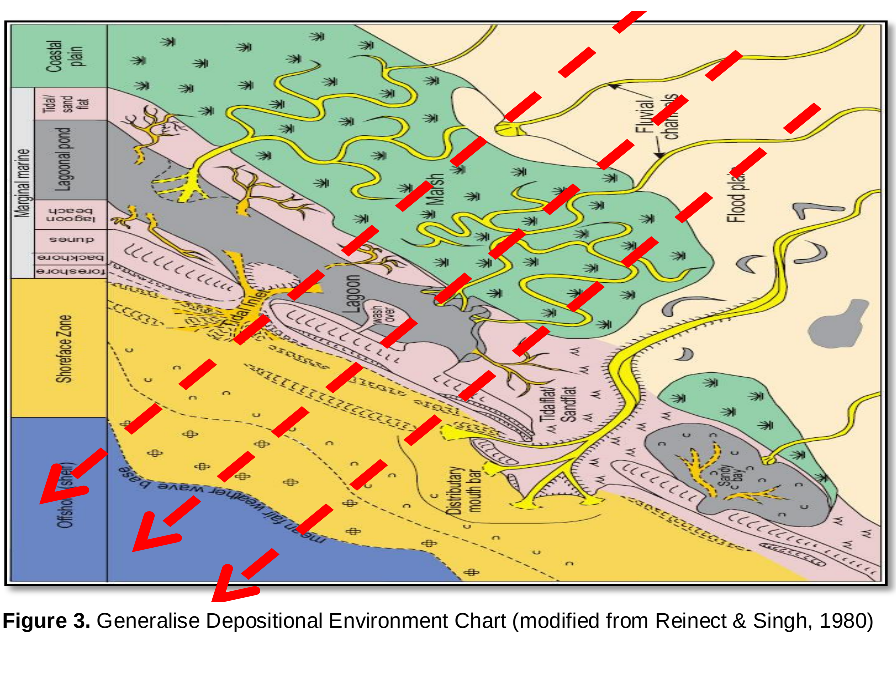


Figure 3. Generalise Depositional Environment Chart (modified from Reinect & Singh, 1980)

Table 1. Lithostratigraphic succession for the Nigeria Chad Basin proposed herein and compared with that of Carter et al. (1963) and Zaborski *et al.* (1997) of the neighbouring Gongola Basin.

ADAPTED HEREIN FROM ZABORSKI *et al.* 1997		CARTER *et al* (1963)		ZABORSKI *et al.* (1997)	
BORNU BASIN		CHAD BASIN (BORNU BASIN)	ZAMBUK RIDGE	GONGOLA BASIN	
Chad Formation	PLEISTOCENE - PLIOCENE	CHAD FORMATION			PLEISTOCENE
Kerri-Kerri Formation	PALAEOCENE-EOCENE	Kerri-Kerri Formation		Kerri-Kerri Formation	PALAEOCENE (at least in part)
Gombe Sandstones	MAASTRICHTIAN	Gombe Sandstones		Gombe Sandstone	MAASTRICHTIAN
FIKA SHALE: "FORMATION 5"	CAMPANIAN	Fika Shale	Gulani Sandstone	PINDIGA FORMATION: Fika ? Unconformity Member	CAMPANIAN
"FORMATION 4"	SANTONIAN				SANTONIAN
"FORMATION 3"	CONIACIAN				CONIACIAN
"FORMATION 2"	UPPER (TURONIAN)		Pindiga Formation	Dumbulwa/Gulani/ Deba Fulani Members	U (TURONIAN)
	MIDDLE (TURONIAN)	Gongila Formation	Yolde Formation	Kanawa Member	M (TURONIAN)
	LOWER (TURONIAN)				L (TURONIAN)
"FORMATION 1"	CENOMANIAN	Bima Sandstones		Yolde Formation	CENOMANIAN
BIMA GROUP: "Upper Bima Formation"	ALBIAN	Unconformity		BIMA GROUP: "Upper Bima Formation"	ALBIAN
"Middle Bima Formation"	APTIAN			"Middle Bima Formation"	APTIAN
"Lower Bima Formation"	Pre-APTIAN			"Lower Bima Formation"	Pre-APTIAN
++ ++ ++ Crystaline basement ++	PRECAMBRIAN	++ + + Crystaline basement ++		++ Crystaline ++ ++ basement +++	PRECAMBRIAN

Bima Sandstone

This formation has essentially the same lithology as in the upper Benue Basin. It is largely comprised of coarse feldspathic and cross-bedded sandstones. It is, however, thinner in the Nigeria Chad Basin. It has been dated Albian.

Formation

This unit consists of sequence of sandstones, clays, shales and limestone layers. It varies laterally into massive grey limestone overlain by sandstone, siltstones, limestone and shales with shaly limestone. To the south at Kupto, however, a thick limestone is overlain by sandstones, mudstones and shales with limestones (Carter *et al*., 1963). The limestone horizons are richly fossiliferous with abundant ammonites, pelecypods and echinoid remains and on the basis of these, Carter *etal*.(1963) assigned an Early Turonian age to the formation.

Fika Shale

This formation consists of blue-grey shale, at times gypsiferous; with one or two non-persistent limestones horizons. A maximum thickness of 430m has been penetrated in by boreholes near Maiduguri. Fossils of the Fika Shale consist mainly of fish remains and fragments of reptiles suggesting a Cenomanian to Maastrichtian age (Dessauvagie, 1975). However, Dessauvagie (1975) suggests a pre-Santonian upper age limit for the formation based on stratigraphic evidence.

Gombe Sandstone

This unit is a sequence of estuarine and deltaics and stone, siltstone and subordinate shale. Thin coal seams are locally present. In outcrop many of the sandstones and siltstones are ferruginised forming low-grade ironstones. The macro fauna is limited and consists of a few indeterminate lamelli branchs (Carter *et al*., 1963). Shell- BP palynologists dated the coallate Senonian - Maastrichtian.

Kerri-Kerri Formation

This consists of loosely cemented, coarse to fine-grained sandstone, massive claystone and siltstone; bands of ironstone and conglomerate occur locally. The sandstone is often cross bedded. The sediments are lacustrine and deltaic in origin and have a maximum thickness of over 200m (DuPreezandBarber,1965). The coal in the formation has yielded palynomorphs on the basis of which Shell-BP palynologists dated it Paleocene and later by Adegoke *et al*. (1986).

Chad Formation

This formation is a succession of yellow and grey clay, fine-to coarse-grained sand with intercalations of sandy clay and diatomites. Its thickness considerably varies. It is estimated to be about 800m thick on the western shore of Lake Chad. Vertebrate remains (*Hippopotamus imaguncula*) and diatoms collected from it indicate an Early Pleistocene (Villa franchian) age. However, its age is considered to range from Pliocene to Pleistocene. The Chad basin is capped by Tertiary volcanic rocks. The Biu plateau basalts underlie the Pleistocene diatomite deposits near Bulbaba but overly Cretaceous rocks (Carter *et al*.,1963). They are thus most probably of Tertiary age. The basalts consist of fine-grained, dense olivine-bearing varieties. Formations discussed are shown in Figure 4.

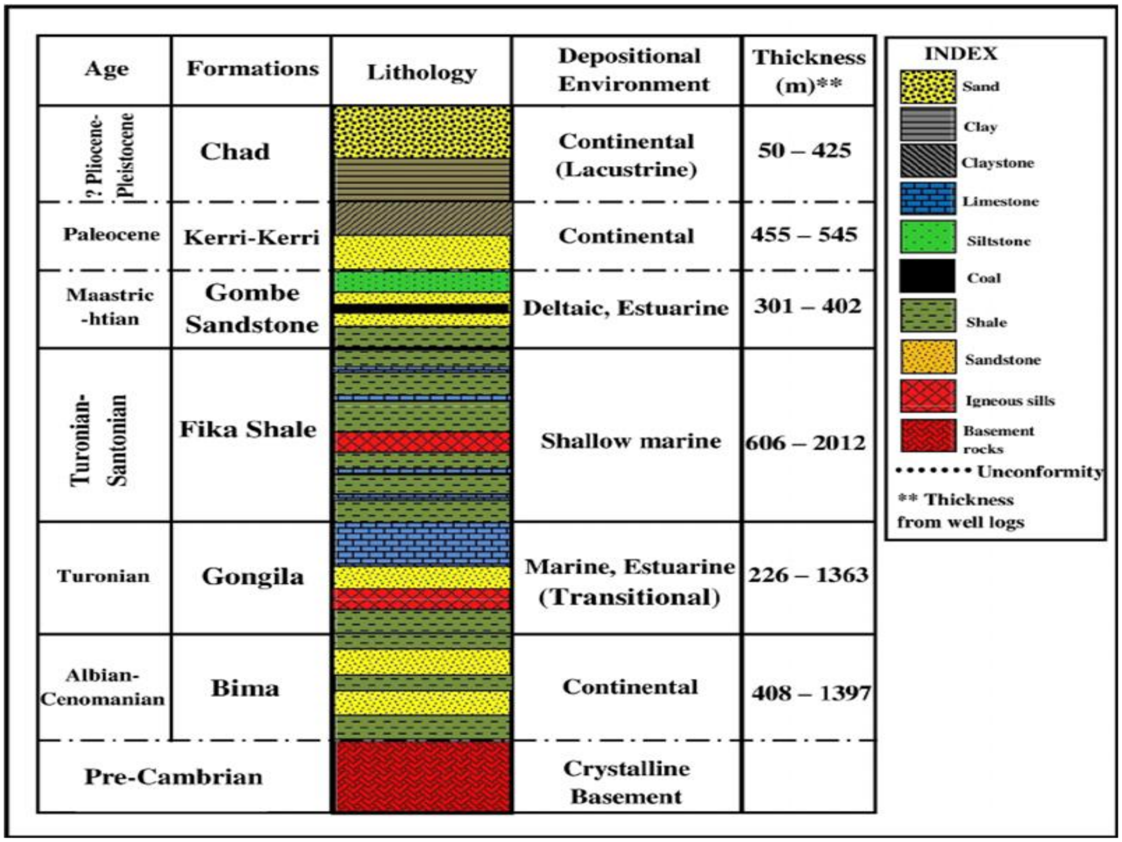


Figure 4. Stratigraphic data sheet of the Nigeria Chad Basin (after Okosun 1995; Avbovbo *et al.,* 1986; Carter *et al.,* 1963)

Stratigraphic Setting of the Nigeria Chad Basin

Sedimentary sequences began from the Paleozoic to Recent, accompanied by a number of unconformity surfaces. Sediments are mainly continental, sparsely fossiliferous, poorly sorted, and medium- to coarse-grained, feldspathic sandstones called the Bima Sandstone. A transitional calcareous deposit – Gongila Formation - that accompanied the onset of marine incursions into the basin, overlies the Bima Sandstones. These are overlain by graptolitic shale (Okosun, 1995). The oldest rocks in the Nigeria Chad Basin belong to Bima Sandstone and the youngest is the Chad Formation as shown in the stratigraphic column of the study area (Table 1). The Cretaceous sediments in the Nigeria Chad Basin are almost entirely concealed below the continental Pleistocene Chad Formation. Cretaceous outcrops are confined to its Southern periphery. Carter *et al*. (1963) ascribed the outcropping sediments in the Southwest of the Nigeria Chad Basin previously described by Jones (1932) and Raeburn and Jones (1934) to the Gongila Formation, Fika Shale and Gombe Sandstone. At Damagum and Maiduguri, 100m and 450m respectively of beds belonging to the Fika Shale were identified in boreholes which bottomed within the unit. In the Dumbulwa-Bage High area, Zaborski *et al*. (1997) subdivided the Cretaceous outcrops into the Kanawa, Dumbulwa and Fika Members of the Pindiga Formation above the “Lower Bima Sandstone”. Avbovbo *et al*. (1986) identified seven “seismic sequences” in the Maiduguri depression. Okosun (1995) and Olugbemiro (1997) provided direct lithological data from boreholes located to the north of Maiduguri. Three Cretaceous units were identified by Okosun (1995). Umar (1999) proposed the stratigraphic succession recognizing the Gombe and Kerri-Kerri Formations and proposing different ages for most of the formations as compared with Carter *et al*. (1963) and Okosun (1995). Correlation of the Cretaceous succession in the basin remains controversial. Okosun (1995) and Olugbemiro (1997) respectively suggested Albian to Turonian and Albian to Cenomanian ages for sedimentary unit of the Bima Group; Lower Turonian and Turonian ages for the Gongila Formation; and Turonian to Mastrichtian and Turonian to Santonian ages for the Fika Shale. Although Okosun (1995) indicated that Kanadi-1 well bottomed in the basement rocks, Olugbemiro (1997) reported arenaceous foraminifers were recovered from “Bima” deposits in the Kanadi-1. Inspite of all these observations, it is unlikely that the Bima Group was penetrated by the above mentioned wells. The wells actually bottomed within the Fika Shale or the equivalent of what is referred to herein as “Formation 1”. Microfossils were only recovered in the present study from the Fika Shale. The earliest Cretaceous marine beds in the Upper Benue Trough South of the Nigeria Chad Basin and the Mega Chad Basin to the North are Cenomanian (Bellion *et al*, 1989; Genik, 1993).

It is unlikely that the Albian “pre-Bima” shales of Avbovbo *et al*. (1986) are marine deposits or that the “pre-Bima” shales of Olugbemiro (1997) are pre-Albian marine deposits. Olugbemiro (1997) suggested that sedimentation in the Nigeria Chad Basin began only in the Albian to Cenomanian. Based on field evidence in the southwestern section of the Nigeria Chad Basin (Dumbulwa-Bage High), together with subsurface borehole lithostratigraphic studies Northeast of Maiduguri, a newly proposed lithostratigraphic succession (Hamza, 2007) has been set up. This is in agreement with the new proposed lithostratigraphic succession of the Gongola Basin in the Upper Benue Trough by Zaborski *et al*., (1997). Carter *et al*. (1963) and Avbovbo *et al*. (1968) presented the generalised stratigraphic scheme for the Nigeria Chad Basin (Table 1). The scheme indicated Cenomanian Bima Sandstone as the oldest formation which overlies an unnamed ‘Pre Bima’ Formation on the Basement. Bima Sandstone was a product of weathering of the Basement rocks and represents the Continental deposit in Nigeria (Adepelumi *et al*., 2012). Bima Sandstone is overlain by Gongila Formation deposited from the Turonian transgression and comprised of alternating sand and shale layers with limestone interbeds. Santonian marine Fika Shale overlies the Gongila Formation and marked the end of Cretaceous deposition in the basin. Subsequent regression deposited Gombe Sandstone which was overlain by Tertiary Kerri-Kerri Formation made up of iron rich sandstone and clay with lateritic cover. Quaternary Chad Formation is the topmost layer consisting of alternating sequence of clay with sand interbeds.

MATERIALS AND METHOD

Materials

To carry out this research effectively and successfully, the following materials were used;

1. Well log suites (Gamma ray log, Resistivity log, Density log, and Sonic log)
2. Formation tops
3. 3-D Seismic data
4. Workstation/laptop (core i3)
5. Petrel 2015 software
6. Base maps

Dataset

The dataset that was used for this analysis consists of 3-D seismic volume, and four well log suites. The dataset was made available by a reputable anonymous oil company in Nigeria.

3-D Seismic data

The 3-D seismic volume used for this work is in SEG-Y format. It is a time migrated zero phase data, with SEG normal polarity convention where a peak (coloured red) represents a positive amplitude/reflectivity or an increase in acoustic impedance. The seismic volume covers an area extent of 2190.4km^2 (Figure 5a), and the bin spacing of the data is 25.00m (inline) by 25.00 (cross line). The inline (dip section) ranges from 5047 to 6047, while the cross line (strike section) ranges from 4885 to 6985 (Table 2). The seismic reflection quality is good. The reflection events are continuous except for where they are truncated by faults. However, below 3000ms the reflections tend to be chaotic (Figure 5b), and this could be largely attributed to edge effects and poor imaging, as well as a function of depth of probe.

Table 2. Seismic data acquisition parameters

Annotation	Start	End	Step
Inline:	5047	6047	1
Xline:	4885	6985	1
Lateral geometry	**Origin**	**End first inline**	**End first crossline**
X:	328376.44	379088.64	321905.72
Y:	1421602.78	1435191.67	1445750.79
Intervals:		25.000	25.001
Rotation [degrees]:		74.999	-15.001

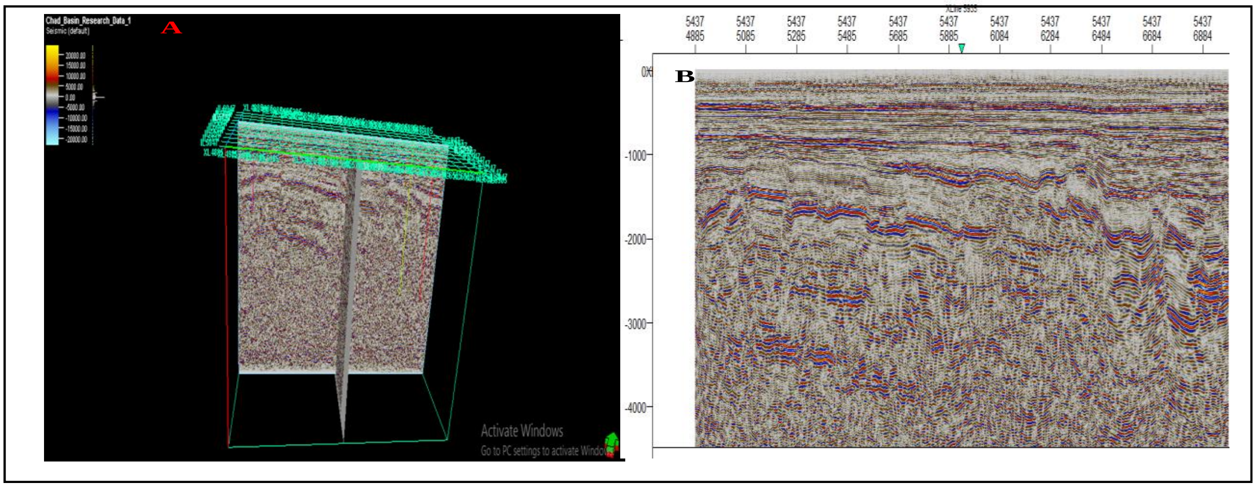


Figure 5a. 3-D visualization of the seismic volume, (5b) Seismic dip line 5437

Well data

Four (4) wells, namely: Bab-1, Bab-2, Bab-3 and Bab-4 were acquired for the purpose of this study but due to the problem associated with Bab-3 well log data such as the lack of Gamma ray log, resistivity log, density log and sonic log at interval within the well, it was not used. Formation tops was given but check shot data and the deviation data were not given. The logs used were acquired mainly within the zones of interest. The quality of the well log data was examined for the acquired depth range before being imported into the petrel software used in the interpretation of the data. Table 3 shows the available well log data with good sign "✓" and unavailable well log data with cross sign "**X** "

Table 3. Available well and well log data

INFORMATION	BAB 1	BAB2	BAB3	BAB4
TOTAL DEPTH (M)	1467.00	4714.95	5013.05	1897.98
GAMMA RAY	✓	✓	X	✓
RESISTIVITY LOG DATA	✓	✓	X	✓
DENSITY LOG DATA	✓	✓	X	✓
NEUTRON LOG DATA	✓	✓	X	✓
SPONTANEOUS POTENTIAL LOG DATA	✓	✓	X	✓
CALIPER LOG DATA	✓	✓	✓	✓
FORMATION TOP	✓	✓	✓	✓
CHECKSHOT DATA	X	X	X	X
DEVIATION DATA	X	X	X	X

'✓' – Available 'X' – Unavailable

Software Used

Schlumberger's Petrel 2015 interpretation software was adopted for this study. Petrel is known for its strong visualization capabilities and ability to quality-check all data in 3D. The choice of software was primarily based on availability. The packages used include all available tools for seismic and well data interpretation.

Methods

The dataset was loaded into the Petrel software and quality checked (QC) to make optimum use of the information provided. The well log data was used for facies description, log correlation, and determination of environment of deposition. The log data was used to generate a synthetic seismogram with which seismic-to-well tie was done.
The seismic attributes were used to enhance signal-to-noise ratio, enhance visibility of the faults, and characterize the seismic section into seismic facies based on information on their amplitude, geometry, and continuity.
Structural interpretations (fault and horizon mapping) were carried out on the seismic data. The cross-section of the map in depth was generated and as well as the Isochore maps. The summary of the workflow that was employed in this research is given in Figure 6. This approach was effective enough to carry out the studies.

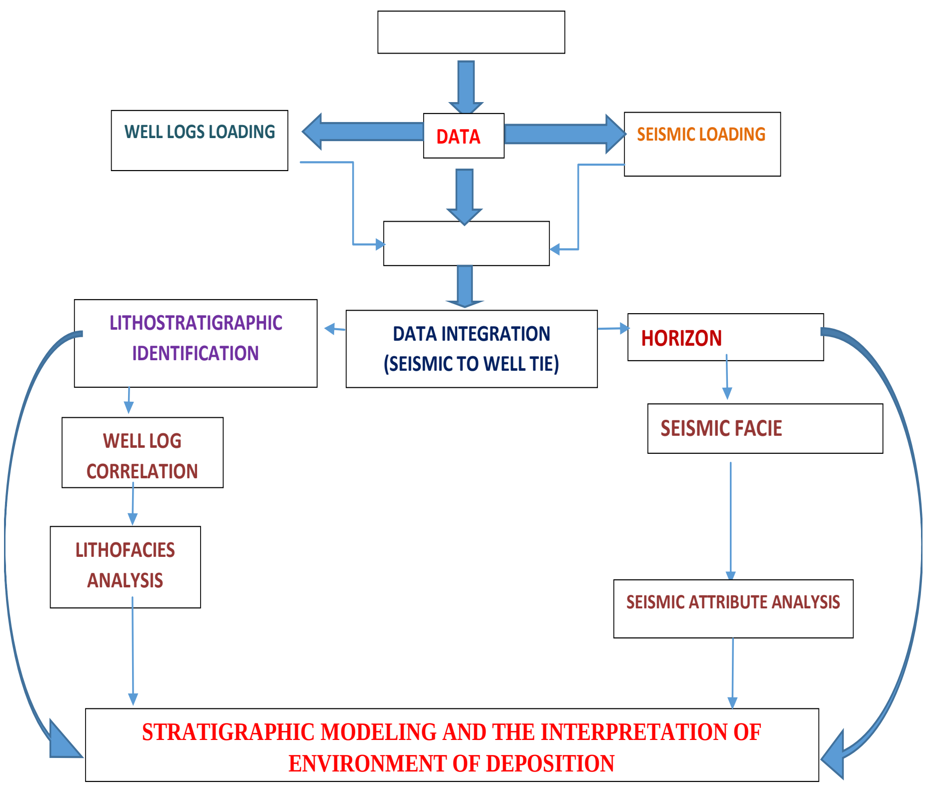


Figure 6. Workflow Chat

Lithostratigraphic Interpretation

The lithologic interpretation was carried out using the Gamma ray log. The Gamma ray log has approximated counts measured on the horizontal scale from 0 to 150, calibrated in American Petroleum Institute (API) units. The lithologies was classified based on the Gamma ray reading by choosing a baseline of 65 API. Gamma ray log measures the amount of radioactive minerals present within a rock such as uranium and thorium. Of the constituent lithologies, clays contain the greatest amount of radioactive minerals, making the Gamma ray log a proficient tool for identifying clay and clay rich minerals. Sand facies also have distinctive Gamma ray signatures. The sand bodies were identified by the decrease in Gamma ray deflections to the left, while the shales were delineated by increase Gamma ray deflections to the right (Figure 7).

Interpretation of the lithologies penetrated by the studied wells was done using the petrel calculator to set the cut-offs on the gamma ray logs as follows; <65API = sand, 65-75 API = silt, >75 API = shale.

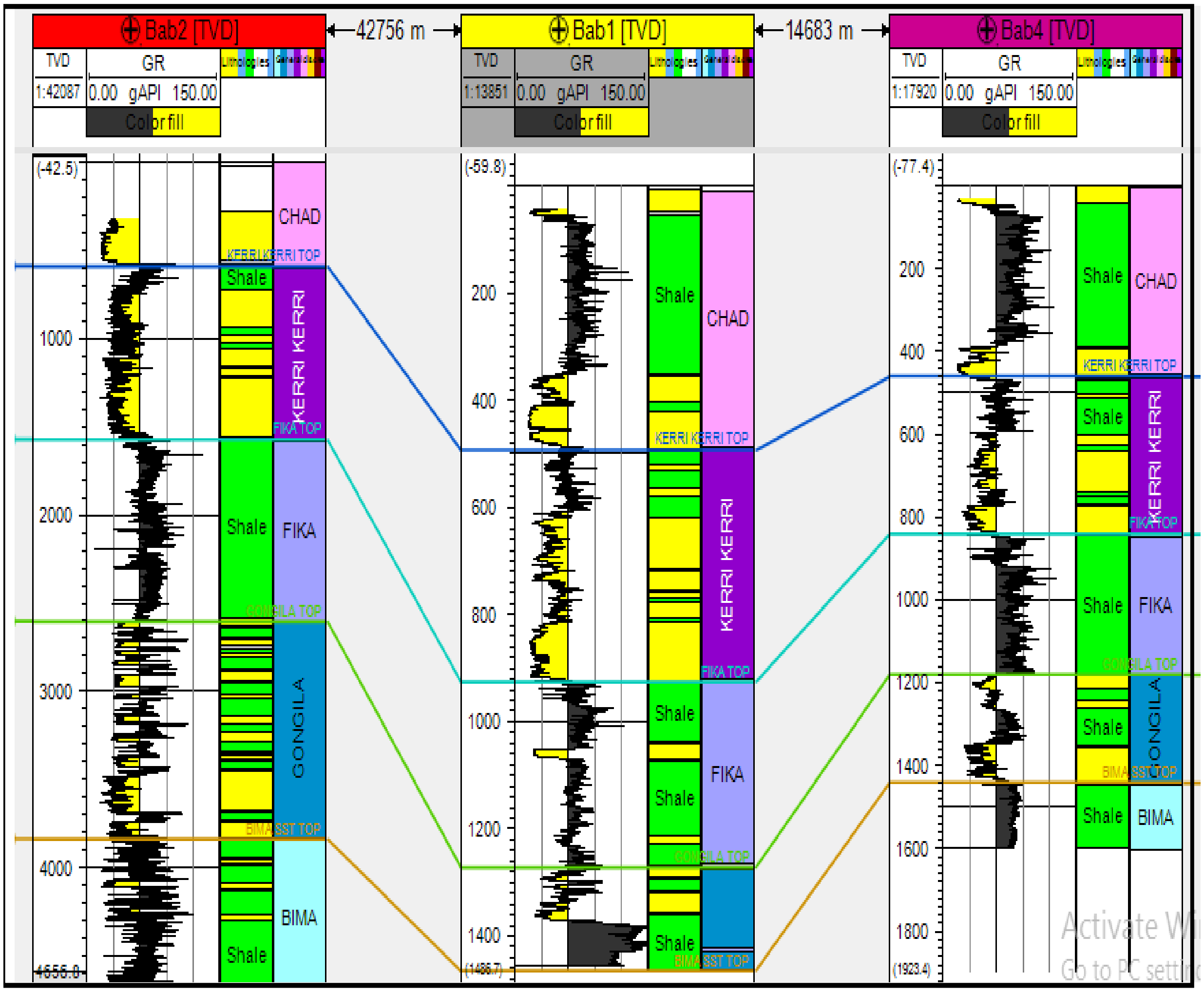


Figure 7. Lithological description using Gamma ray log

Well log correlation

Well log correlation can be defined as the act of locating equivalent geological units in time and stratigraphic position with specific tools. The importance of well log correlation is to reveal lateral continuity and/or variations. The aim is to look for log signals that are similar from well to well in order to establish the lateral lithofacies character or changes, and predict geology in gaps between wells. However, correlation or equivalency is a basic pan of subsurface geology and it includes many techniques and uses. Well log correlation could also be considered the identification and connection of equivalent patterns and/or values between log curves and adjacent wells. After the well importation into the petrel software used for the interpretation, well log visualization and settings were done to the standard before well correlation. From the formation tops given, the identified formations were correlated across the wells.

Well log Facies and Associated Depositional Setting

The well log facies analysis and associated depositional environments was interpreted using the gamma ray log responses to shaliness according to Rider (1990) and Cant (2002), and the Gamma ray responses and different depositional environments according to Kendall (2003), as modified from Rider (1990) (Figure 8). Five different Gamma ray log responses to shaliness as described by Rider (1990) that was used for the interpretation include;

1. Cylindrical with abrupt top and base
2. Coarsening upward with abrupt top (funnel)
3. Finning upward with abrupt base (bell)
4. Symmetrical
5. Serrated Gamma ray response

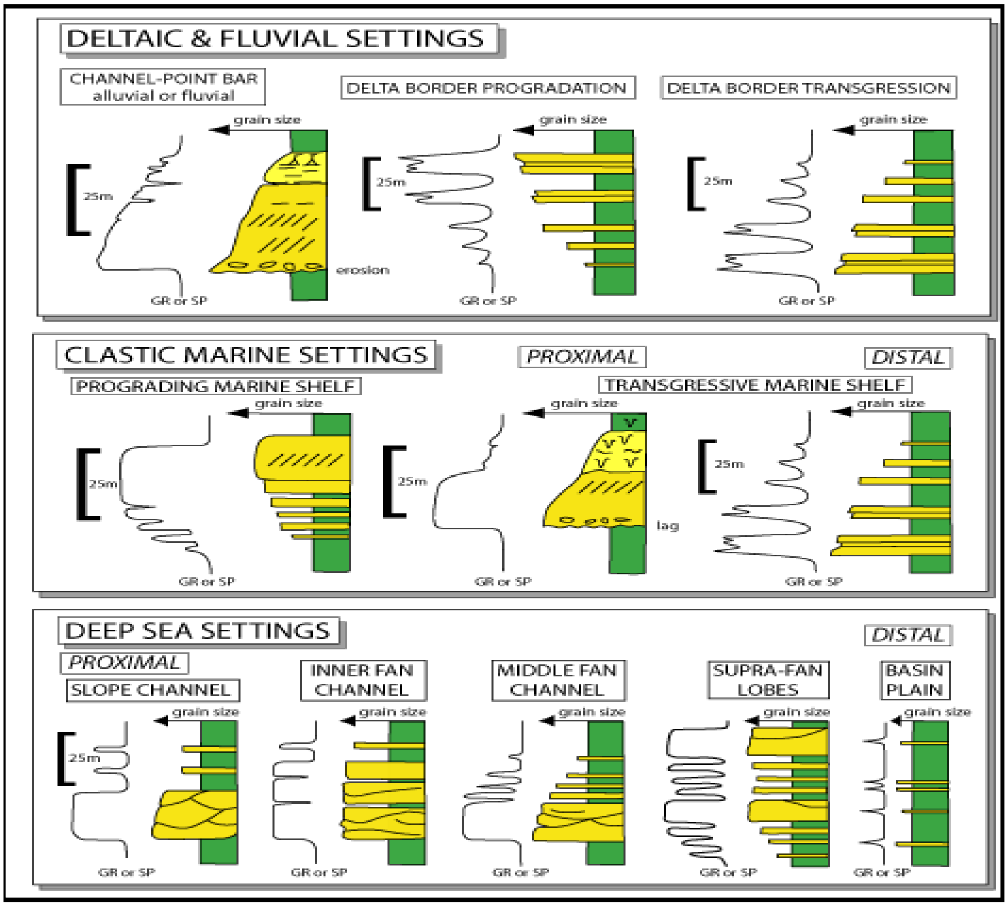


Figure 8. Gamma Ray log responses and different depositional settings. (After Kendall (2003) and Modified from Rider (1999)

The cylindrical (blocky) log motif generally represent thick uniformly graded sandstone unit, probably Aeolian deposits, braided/distributary channel fills, submarine canyon fill, carbonate shelf margin or evaporate fill of a basin. The funnel shaped log patterns implies decreasing clay content up section and normally marks crevasse splays, river mouth bars, delta front, shoreface, submarine fan lobes and change from clastic to carbonate deposits. Bell shaped log patterns imply increasing clay content up section. It normally depicts fluvial point bars, tidal point bars, deep channel fills, tidal flats and transgressive shelf. The symmetrical log motif represents reworked offshore bars and transgressive and regressive shoreface delta, typically due to fluvio-marine and tidal processes. Serrated log motif represents fluvial floodplain, storm dominated shelf and distal deep marine slope deposits.

Similarly, deltaic and fluvial settings, clastic marine settings and deep sea settings as described by Kendall (2003), will be of help for this very study. However, the serrated coarsening upward and fining upward log motifs respectively, represent delta border progradation and retrogradation. Prograding marine shelf exhibit coarsening upward log motif which becomes erratic at the base. The proximal part show non-serrated upward fining, while the distal part is serrated and fine upwards. The well log correlation that was carried out in this study was based on pattern recognition and marker beds on Gamma ray logs as control for well to well correlation.

3-D Seismic Interpretation

The seismic reflection data was used in this study to map the subsurface features, infer geological information and identify depositional environment from well logs at well point. This method is known to provide a structural model of the subsurface which is comparable to what could be obtained from a number of boreholes in close proximity. The method involves both horizon and fault mapping. The seismic data was loaded in SEG-Y format into the petrel software before seismic overview was overtaken for possible identification of structures and seismic facies. The wells were displayed on the seismic volume in order to observe the position of the wells within the seismic volume when the time-depth data generated from the sonic logs have been imported into the software since well data give actual point information of the study area in depth while seismic data give a regional information about the study area in time.

Structural interpretation

The 3-D seismic structural interpretation within the study area was based primarily on the seismic reflectors, their terminations against fault and chaotic reflections. Tectonic and non-tectonic structures were identified based mainly on break in reflection events or abrupt termination of reflection events. The structures were represented on the seismic section as discontinuous lines along a preferred orientation of reflectors. For example, the faults were picked on the seismic dip section, and names were assigned to each mapped faults. The faults were interpreted on every 10 x10 inline spacing, with closer grids of 5 x 5 inline spacing at some more complex areas.

The fault interpretation was analyzed using variance time slice as a seismic volume attribute. The variance edge attribute (Semblance volume) extraction was generated on the seismic cube for better visualization of the faults (Figure 9). Variance is an attribute that indicates lateral variations. This attribute is calculated in 3-dimension, and represent the trace-to-trace variability over a particular sample interval, and therefore produces interpretable lateral changes in acoustic impedance. Furthermore, fault model was generated for easy visualization of the faults geometry and trends.

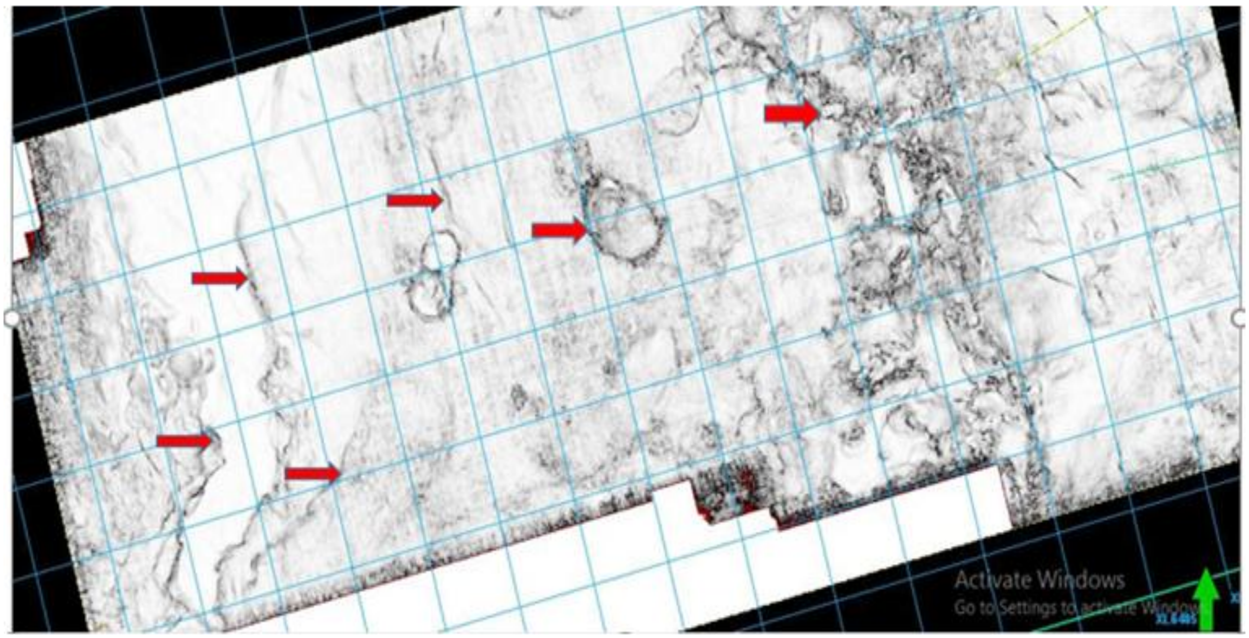


Figure 9. Display of Variance slice at 1476ms highlighting most of the faults. Red arrows indicate the faults

Synthetic Seismogram

The synthetic seismogram relates the well data recorded in depth and seismic data recorded in time. A synthetic seismogram was generated for the well that has sonic and density logs and was correlated across the well.

One of the wells was used to generate the acoustic impedance and reflection coefficient. The polarity and the phase of the data were determined, and the reflection coefficients generated was convolved with the wavelet to generate the synthetics. The synthetics was tied to the original seismic data in order to determine which stratigraphic top defined in the wells is responsible for a particular seismic event. This helped in horizonal identification and mapping across the entire seismic volume for stratigraphic surface map generation in time and depth.

Horizon mapping

Horizons are the reflectors (or seismic events) picked on individual profiles. These reflectors represent a change in rock properties across a boundary between two layers of rock, particularly seismic velocity and density. The objective of seismic horizon mapping is to produce grid surfaces that will be used to generate time and depth structural maps of the stratigraphic tops in order to enhance the integration of the stratigraphic surfaces and the identified structures such as non-tectonic structures like stratigraphic pinch out and unconformity surfaces in the seismic volume. Horizons were mapped across both in line and cross-line as much as they could be observed throughout the entire seismic volume. The horizons were mapped to follow a particular seismic reflector which represents the lateral continuity of the stratigraphic top. The horizon interpretation grids that was used is 5 x 5line spacing, and 2 x 2line spacing in structurally more complex areas.

Time to depth Conversion

The domain conversion was done using a single well velocity function method. This involves using a single check shot to generate a lookup function by plotting Two-way-time (ms) against depth (m) (Figure 10). The generated function was applied to the time surface maps to generate the depth structure maps.
The equation is as thus:

$$Y = - 264.333 + 1.01672 * X - 0.00019902 * X^2 \quad \text{.......................................3.1}$$

R = 0.993691

Where, Y= Measured Depth (Z) (m), and X =Two-way time (TWT) (ms), R= Coefficient of correlation

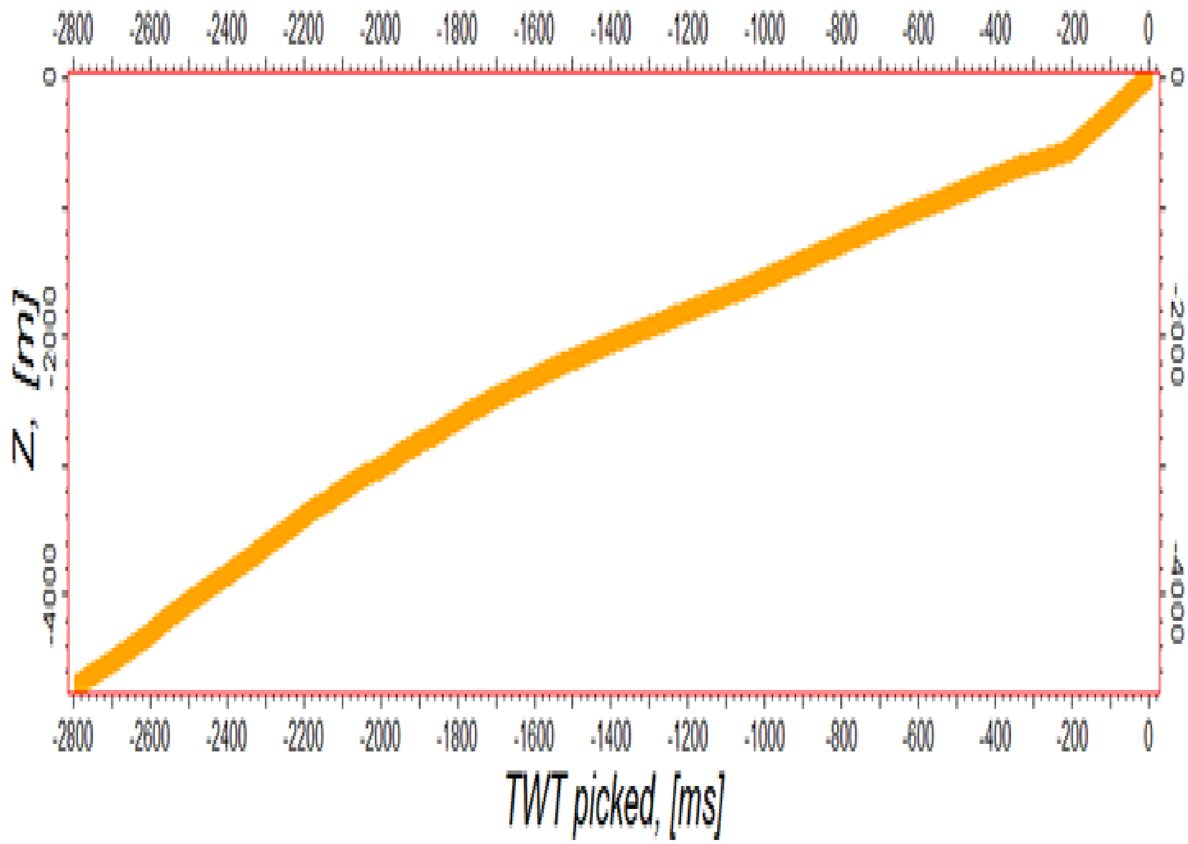


Figure 10. Lookup function plot of Z (m) vs TWT (ms) used for time-depth conversion

Seismic Attribute Analysis

Seismic attribute analysis was applied to aid proper interpretation of the seismic horizons for the purpose of modeling the structure and stratigraphy of the depositional environment. Signal processing attributes (structural smoothing and median filter) was applied to the original seismic as volume attributes to help in the visualization of structures such as faults (Figure 11). The attribute provided an objective translation of the seismic data into a geologically meaningful image.

The signal processing attributes (structural smoothing and median filter) significantly improved the signal-to-noise ratio, thereby increasing the signal content of the seismic data, and enhanced seismic reflectors' continuity. Furthermore, the 3-D seismic volume of the structural smoothing attribute was used as input data to generate other attributes of interest.

Surface attributes were run on the generated maps to aid in the qualitative interpretations of the environment. These attributes include; the Root Mean Square (RMS) attribute, and the Sum of Negative Amplitude (SNA).

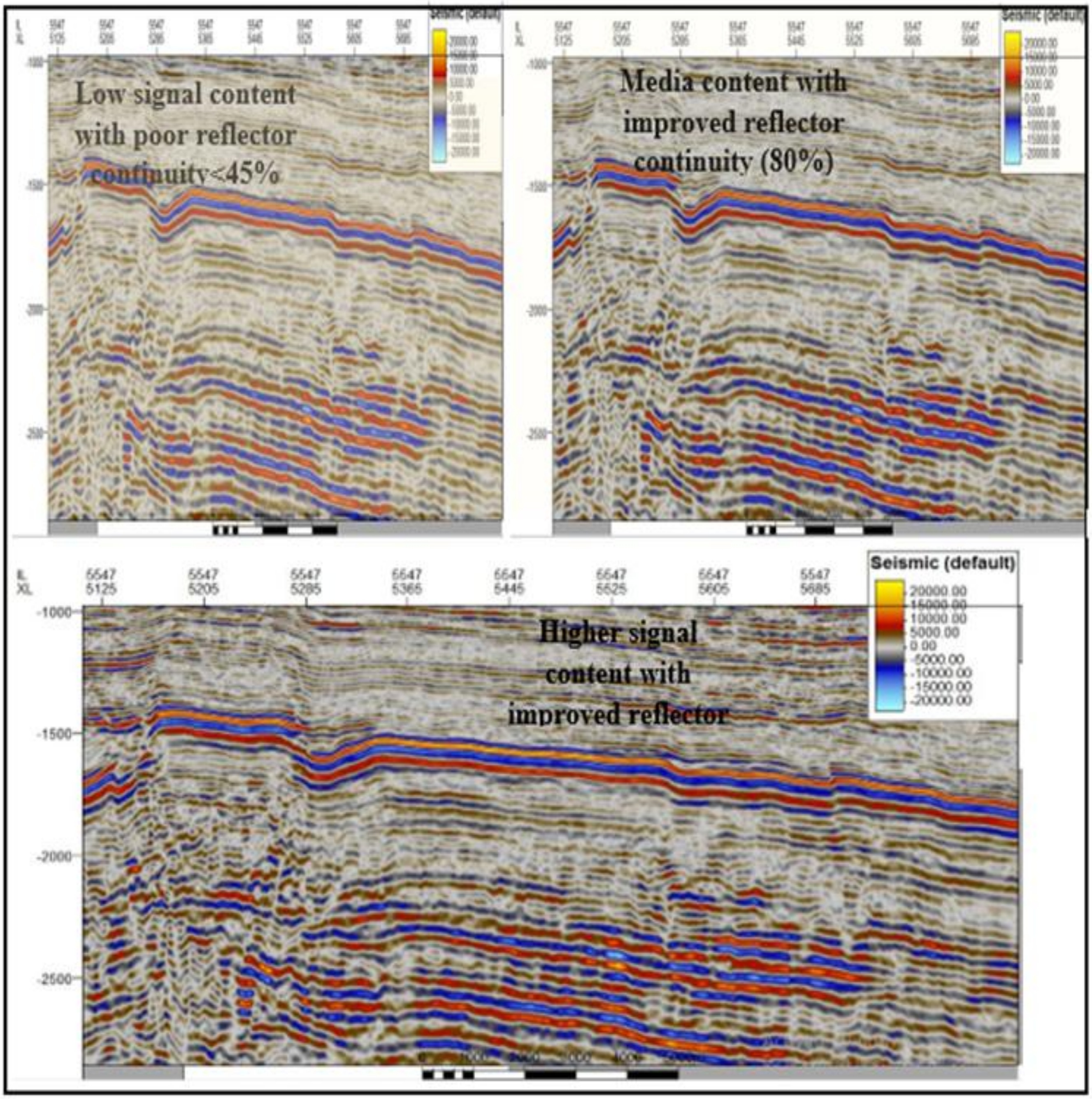


Figure 11. Display of seismic dip line 5547 showing (a) Original Seismic, (b) Media filter attributes (c) Structural smoothing

Seismic Facies Analysis

Seismic facies analysis of the study area was done in order to identify the lithological facies within the seismic volume. The method adopted for the analysis was as describes by Prather *et al* (1998). The interpretation was based on seismic reflection amplitudes, configuration, as well as the continuity of the reflections as seen on vertical transects (Figure 12). For an effective interpretation, the conventional seismic amplitude displays were not only used, rather, signal processing attribute display sections were used. The identified seismic facies were aligned with the Gamma ray log in order to observe the log responses within the different facies intervals. Calibration of facies with well control increases confidence in the interpretation because seismic facies are unique, and the continuity and configuration of seismic reflectors changes in a predictable manner from one seismic facies to another (Anomneze *et al.,* 2015).

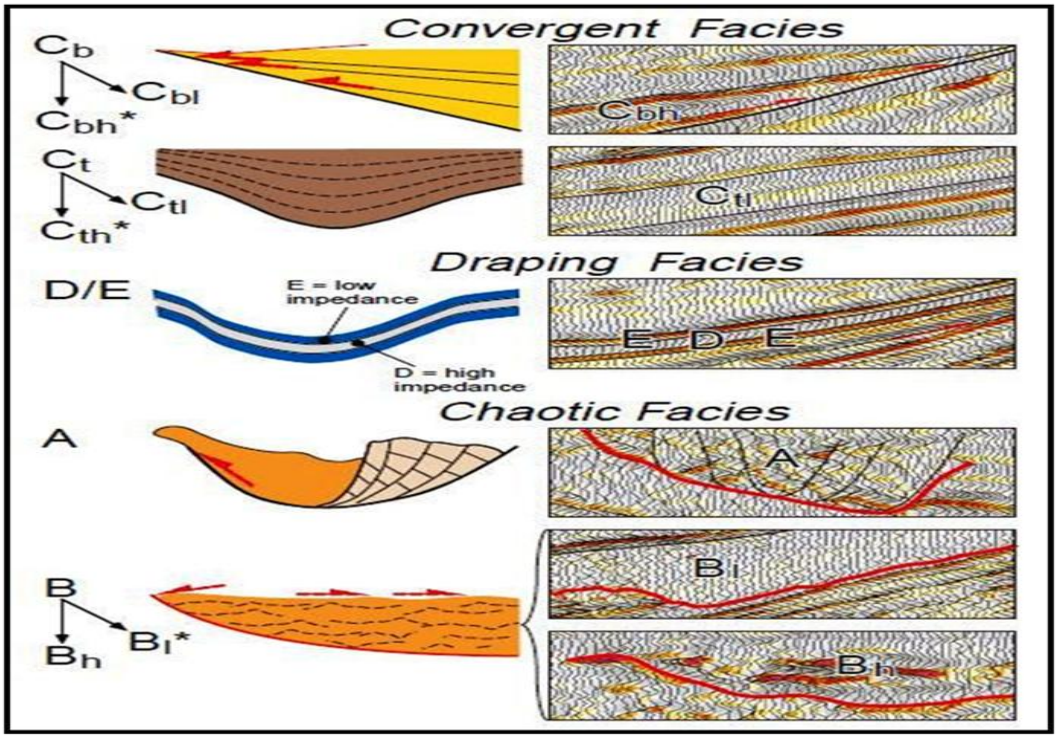


Figure 12: Seismic facies type convention. Cbl - Low amplitude convergent, Cbh - High amplitude convergent, Ct - Convergent by thinning at Paleobasin margin, D&E continuous high and low amplitude, A - Chaotic with rotated blocks, Bl - Low amplitude discontinuous, shingled to chaotic, Bh - High amplitude discontinuous, shingled to chaotic (Prather *et al.,* 1998)

RESULTS AND DISCUSSION

Lithologic Description

The lithologic description of the study area was done using the Gamma ray log motifs. The distinct lithologies was identified as sand lithology and shale lithology. The sands are associated with the lower Gamma ray readings, while the shale are associated with the higher Gamma ray reading. The description of the lithology was done within the five formations across the three wells. The correlation of the formation tops was done in the northeastern and southwestern direction. The distance between Bab 2 well and Bab 1 well is 4256m while the distance between Bab1 and Bab 4 well is 14683m. (Figure 13)

Bab 2 well

The deepest well is Bab 2 well with the total depth of 4714.95m. It penetrated all the formations which are Bima Sandstone, Gongila Formation, Fika Shale, Kerri Kerri Formation and Chad Formation. Bima Sandstone (3837.90 - 4708.47m) contains shale (4300.07 - 4556.19m), sandstone (4236.04 - 4300.07m), shale (4117.12 - 4236.04m), sandstone (4071.38 - 4117.12m), and shale (3837.90-4071.38m). Gongila Formation (2598.67-3837.90m) contains sandstone (3742.08-3837.90), shale (3705.49 - 3742.08m), sandstone (3467.66-3705.49m), shale (3440.22 - 3467.66m), sandstone (3376.19 - 3440.22m), shale (3303.81 - 3376.19m), sandstone (3238.98 - 3303.81m), shale (3202.39 - 3238.98m), sandstone (3147.15 - 3202.39m), shale (3065.18 - 3147.15m), sandstone (3019.44 - 3065.18m), shale (2973.71 - 3019.44m), sandstone (2918.82 -2973.71m), shale (2809.06 - 2918.82m), sandstone (2781.61 - 2809.06m), shale (2726.73 - 2781.61m), sandstone (2699.29 - 2726.73m), shale (2662.70-2699.29m), and sandstone (2598.67 - 2662.70m). Fika Shale (1566.02 - 2598.67m) contains very thick shale deposit (1566.02 - 2598.67m). Kerri Kerri Formation (583.21 - 1566.02m) contains sandstone (1243.44 - 1566.02m), shale (1205.50 - 1243.44m), sandstone (1182.73 - 1205.50m), shale (1152.38 - 1182.73m), sandstone (1061.31-1152.38m), shale (1023.37 - 1061.31m), sandstone (970.24 - 1023.37m), shale (924.71 - 970.24m), sandstone (727.40-924.71m), and shale (583.21 - 727.40m). Chad Formation (302.42-583.21m) being the youngest formation, contains sandstone (302.42 - 583.21m).(Figure 13).

Bab 1 well

This well penetrated only four formations since Bima Sandstone is absent here. The total depth of this well is 1467.00 meters. It is the shallowest well and the lithological description began from the Gongila Formation (1272.42-1447.25m) which encompasses shale (1374.82 - 1447.25m), sandstone (1322.37 - 1374.82m), shale (1299.90 - 1322.37m), and sandstone (1272.42 - 1299.90). The second formation is Fika Shale (930.28-1272.42m) which encompasses shale (1232.47 - 1272.42m), thin sandstone (1217.48 - 1232.47m), shale (1075.13 - 1217.48), sandstone (1050.15 - 1075.13m), and shale (930.28 - 1050.15m). The third formation is Kerri Kerri Formation (493.22-930.28m) which contains thick deposit of sandstone (817.88 - 930.28m), shale (803.40 - 817.88m), sandstone (782.99 - 803.40m), shale (772.94 - 782.99m), sandstone (762.95 - 772.94m), shale (752.98-762.95m), sandstone (722.99-752.98m), shale (713.00-722.95m), sandstone (618.10-713.00m), shale (578.14 - 618.10m), sandstone (563.15 - 578.14m), shale (533.18 - 563.15m), sandstone (518.20 - 533.18m), and shale (493.22 - 518.20m). The youngest formation penetrated by the well is Chad Formation (36.19 - 533.18m). It contains sandstone (420.80 - 533.18m), shale (403.81 - 420.80m), sandstone (368.66 - 403.81m), shale (61.17 - 368.66m), and sandstone (0.72 -61.17m). (Figure 13)

Bab 4 well

This is shallower than Bab 2 and deeper than Bab 1 with a total thickness of 1897. 99m. It penetrated the five formations which are Bima Sandstone (1442.68-1601.01m), and it contains shale (1442.68-1601.01m). Gongila Formation (1184.19-1442.68m) which contains sandstone (1352.21-1442.68m), shale (1268.20-1352.21m), sandstone (1245.58-1268.20), shale (1216.50-1245.58m), sandstone (1184.19 - 1216.50m) Fika Shale (844.92-1184.19m) contains shale (844.92-1216.50m). Kerri Kerri Formation (411.90-844.92m) contains sandstone (773.83-844.92m), shale (738.29-773.83m), sandstone (638.13-738.29m), shale (621.97-638.13m), sandstone (599.35-621.97m), shale(518.57-599.35m) sandstone (502.42-518.57m), and shale (470.11-502.42m). Chad Formation (1.57-470.11m) contains sandstone (392.58-470.11m), shale (50.06-392.58m), and sandstone (0-50.06m) (Figure 13)

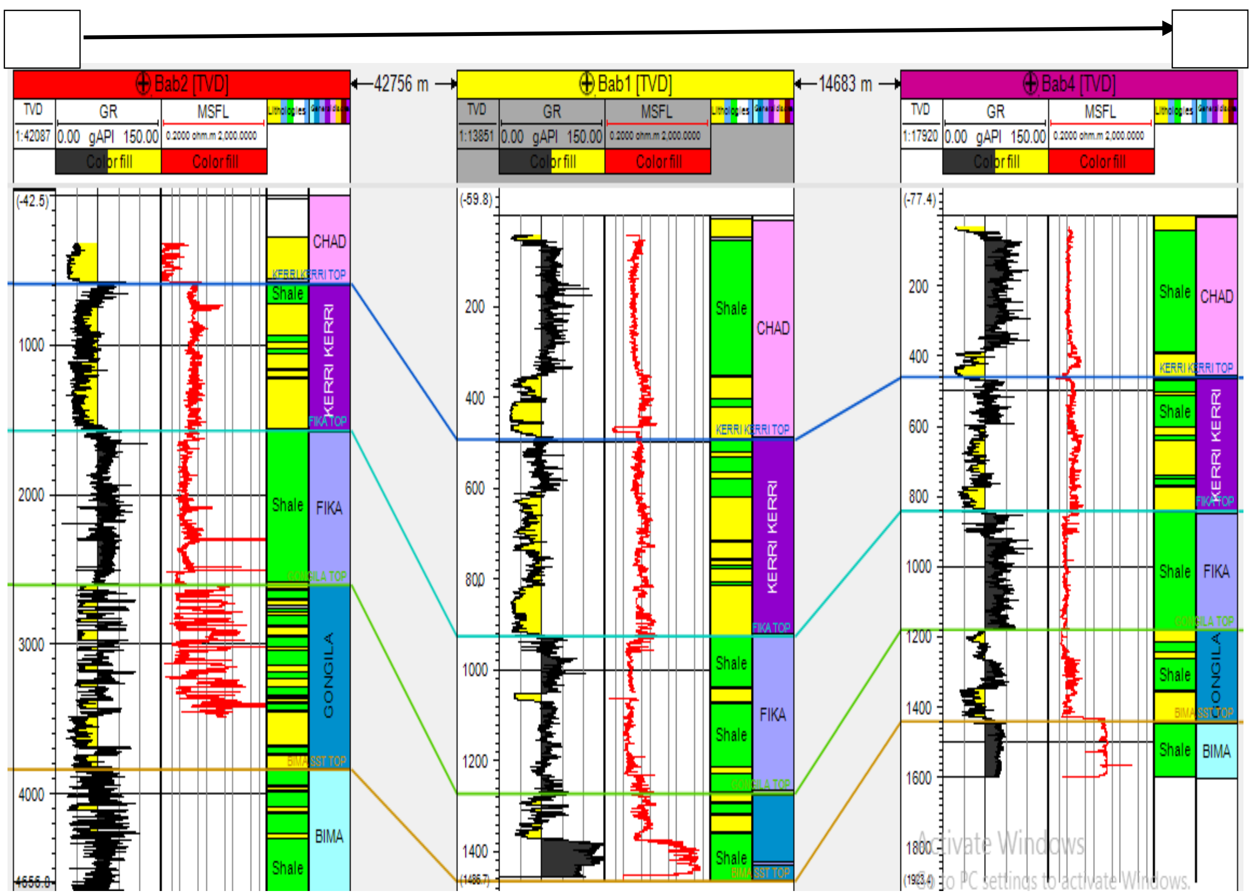


Figure 13. Lithologic description of the study area showing the different lithologies distributed vertically and laterally across the four wells

Lithofacies Analysis

The lithofacies analysis was generated using the most suitable well (Bab 2), which is the deepest well drilled within the study area. The facies units were identified using this well, and the interpreted facies were correlated across the other wells in order to identify if there is a lateral change in the facies between the well points. The five lithofacies LFI, LF2, LF3, LF4, and LF5 representing Bima, Gongila, Kerri Kerri, Fika and Chad Formations respectively were identified from the combined well log analysis of the Gamma ray log curve characteristics. Delineation of corresponding boundary intervals across the different types of well logs for each well allows for the stratigraphic subdivision of the lithofacies into different genetic groups with lateral relationships. The lithofacies displayed consistent distinct pattern behaviour in the GR logs corresponding to individual sedimentary cycles. Each lithofacies is separated from the other by an observable sudden change in log pattern with associated changes in the multi-log physical properties and log values due to the distinctive change in lithology. In this study, due to the absence of core log samples, which would have provided detailed petrographic and biogenic components in the subsurface rocks, the lithofacies analysis relied on the generic lithostratigraphic descriptions of the formations in Chad Basin by Avbovbo *et al.* (1986) to deduce and assign the corresponding lithostratigraphic unit. Lithofacies identified were designated into strata and characterised into stratigraphic intervals to interpret the various depositional and stratigraphic framework for the study area from the basal to the upper units. Individual facies characteristics are classified based on their differences in lithological composition, thickness, shale and sand contents and stratigraphic position.

Lithofacies analysis 1 (LF1)

Bima Sandstone in Bab2 well, is characterized by a retrograding shale facies (4314.52 - 4689.25m) which fines upwards before an aggrading sequence sets of sandstone and shale facies (4314.52 - 3842.84m). This formation is absent in Bab 1 well but present in Bab 4 well which has a retrograding facies (1596.27-1439.81m) that contain thick shale unit. (Figure 14).

Lithofacies analysis 2 (LF2)

In Gongila Formation across Bab2 well, there is a prograding facies (1340.24 - 1439.81m) of sandstone and a retrograding facies (1278.86 - 1340.74m) of shale before aggrading sequence (179.04 - 1278.86m) of sandstone and shale. Across Bab2 well, there is a prograding sequence (1378.48 - 1458.90m) with thick shale unit and aggrading sand and shale facies (1271.62 -1378.48m). Across Bab4 well, there is prograding facies (1340.24 - 1439.81) of sandstone, retrograding facies (1278.86-1340.74) of shale, and aggrading shale and sandstone facies (179.04 - 1278.86m). (Figure 14)

Lithofacies analysis 3 (LF3)

In Fika Shale across Bab2 well, there is transgressive sequence (1574.86 - 2602.25m) of shale facies. At Bab1 well, the same shale appeared with little sand at depth 922.31 to 1271.62 m and across Bab4 well, the Fika Shale outcropped at depth 844.92 - 1184.19m. (Figure 14)

Lithofacies analysis 4 (LF4)

In Kerri Formation across Bab2 well, there is a prograding sand facies (1103.21 - 1574.86m), retrograding facies of shale (961.50 - 1103.21m), prograding sandstone facies (748.52 - 961.50m), and transgressive shale facies (588.77 - 748.52m). Across Bab1 well, there is a prograding sequence of sand facies (897.81 - 922.31m), retrograding sandstone facies (885.32 - 897.81m), prograding sandstone facies (862.85 - 885.32m), retrograding sandstone facies to shale facies(752.96-862.85m), prograding sand facies (727.98 - 752.96m), and transgressive shale facies with thin sandstone (473.34 - 727. 98m). Across Bab4 well, there is a prograding sand facies (778.4-842.41m), retrograding shale facies (738.10 - 778.34m), prograding sand facies (638.52 -738.10m), retrograding facies from sand to sandy shale (458.37 - 638.52m). (Figure 14)

Lithofacies analysis 5 (LF5)

In Chad Formation across Bab2 well, there is a prograding sandstone facies (408.66 - 590.80m) and retrograding sandstone facies (325.19-408.66m). Across Bab1 well, there is a retrograding sandstone unit (413.31-490.73m), prograding sandstone facies (353.37-413.31m), and transgressive thick shale facies (61.13-353.37m). Across Bab4 well, there is a prograding sandstone facies (428.10 - 463.64m), and retrograding facies from sandstone to thick shale facies (59.75-463.64m). (Figure 14)

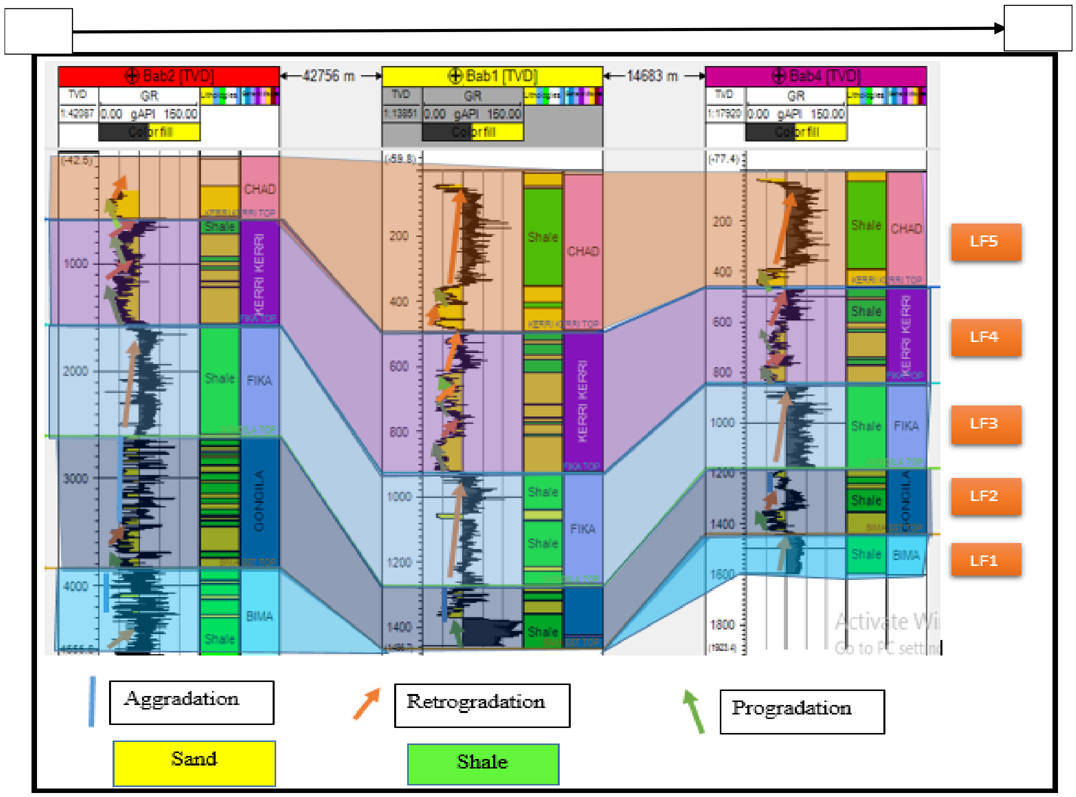


Figure 14. correlation of well log facies across Bab1 well, Bab2 well, and Bab3 well

Facies Associations

The identified facies were grouped into facies association which allow proper interpretation of the depositional environment. The facies were grouped into three facies associations namely; Continental environment (Fluvial and Lacustrine) facies, Transitional environment (Deltaic and Estuarine) facies, and Shallow Marine environment (Shore) facies following the methods of Selley (1985, 1998), Cant (2002), and Rider (1990). Bab2 well was used as a reference since it has greatest depth. (Figure 15).

Bima Sandstone facies association (3837.90 - 4708.47m interval)

Bima Sandstone presented a retrograding well-log facies (bell shaped Gamma ray log signature) in Bab2 well suggesting fluvial point bar facies as indicated by thick deposit of shale; and aggrading facies (serrated shaped Gamma ray log signature) of sandstone and shale which indicate fluvial floodplain facies. This formation is absent in Bab1 well but present is Bab4 well which has a thick transgressive shale deposit. The facies association indicate continental environment facies. (Figure 15)

Gongila Formation facies association (2598.67 - 3837.90m interval)

In Bab2 well this started with prograding facies (funnel shaped Gamma ray log) which indicates river mouth bar. Before the upper aggrading facies, there is a retrograding facies (bell shaped Gamma ray log) which indicates tidal point bar deposits. In the upper part, there is aggrading sandstone and shale facies within the formation, and it indicates storm dominated shelf deposits. Across Bab1 well, the same type of the prograding and aggrading facies appeared with funnel shaped Gamma ray signature and serrated shaped Gamma ray signature respectively which suggested the same type of prograding facies and aggrading facies seen in Bab2 well. In Bab4 well, there is a prograding sandstone facies, retrograding shale facies, and aggrading sandstone and shale facies which confirmed the facies indicated in Bab2 well and Bab1 well. The facies association shows estuarine and shallow marine deposits. (Figure 15).

Fika Shale facies association (1566.02-2598.67m interval)

This shows transgressive shale deposit across all the wells with little sandstone intercalations in Bab2 well. The Gamma ray signature indicates transgressive shelf environment. (Figure 15)

Kerri Kerri Formation facies association (583.21-1566.02m interval)

The formation has about four para-sequence sets of prograding facies and retrograding facies across all the wells. The geometry of the Gamma ray signature indicates crevasse splay deposit for prograding facies and fluvial point bar for retrograding facies. The facies association indicates continental environment facies(Figure 15).

Chad Formation facies association (302.42-583.21m interval)

From the Gamma ray signature, there is a prograding sandstone facies and retrograding sandstone facies within the formation, that is, from coarse grain sandstone to fine grain sandstone deposits across Bab2 well. In Bab1 well and Bab 4 well, there is prograding sandstone facies, retrograding sandstone facies and transgressive thick shale facies. In Bab 4 well, there is a prograding sandstone facies and transgressive shale facies. The facies association indicates continental environment facies (Figure 15).

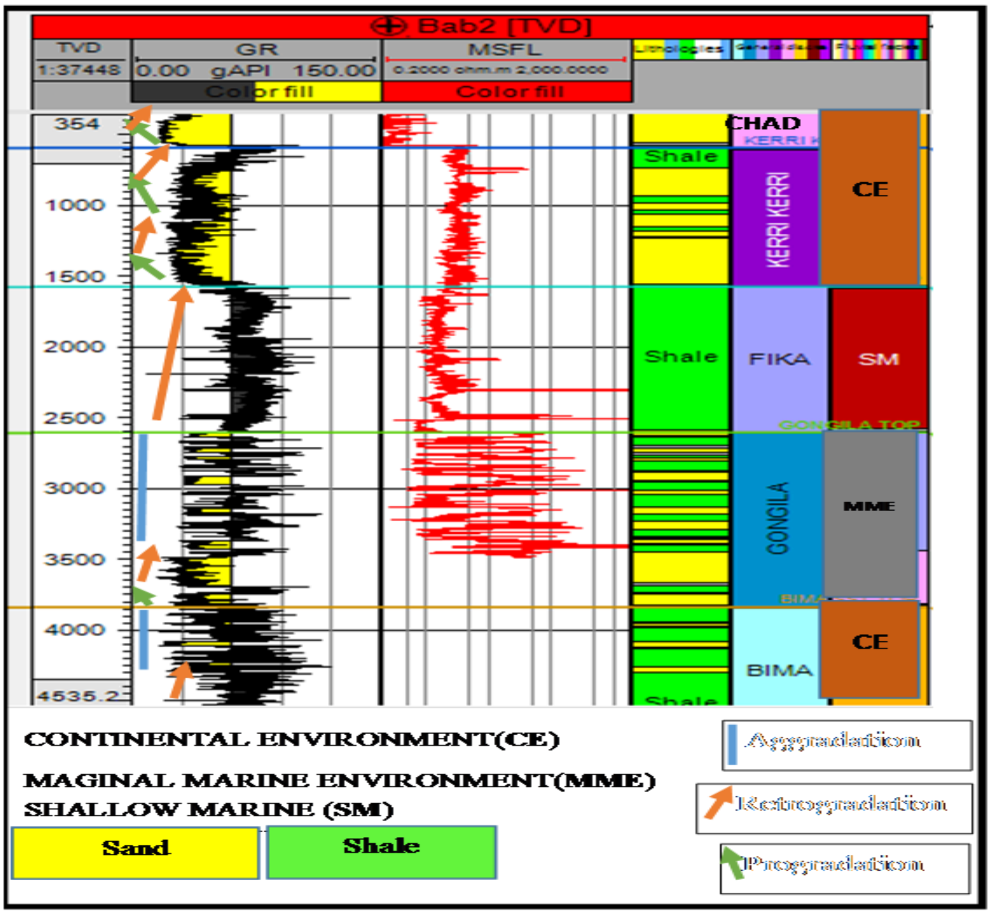


Figure 15. Identified deposition environment in Bab2 well

Depositional Environment

The interpretation of the depositional environments was from the electrofacies, as well as the facies associations as described from the wireline logs. Based on the identified facies association of the study area, the environment of depositions of the area which has been inferred to be continental to marine environments were validated (Figure 16, Table 4.1)

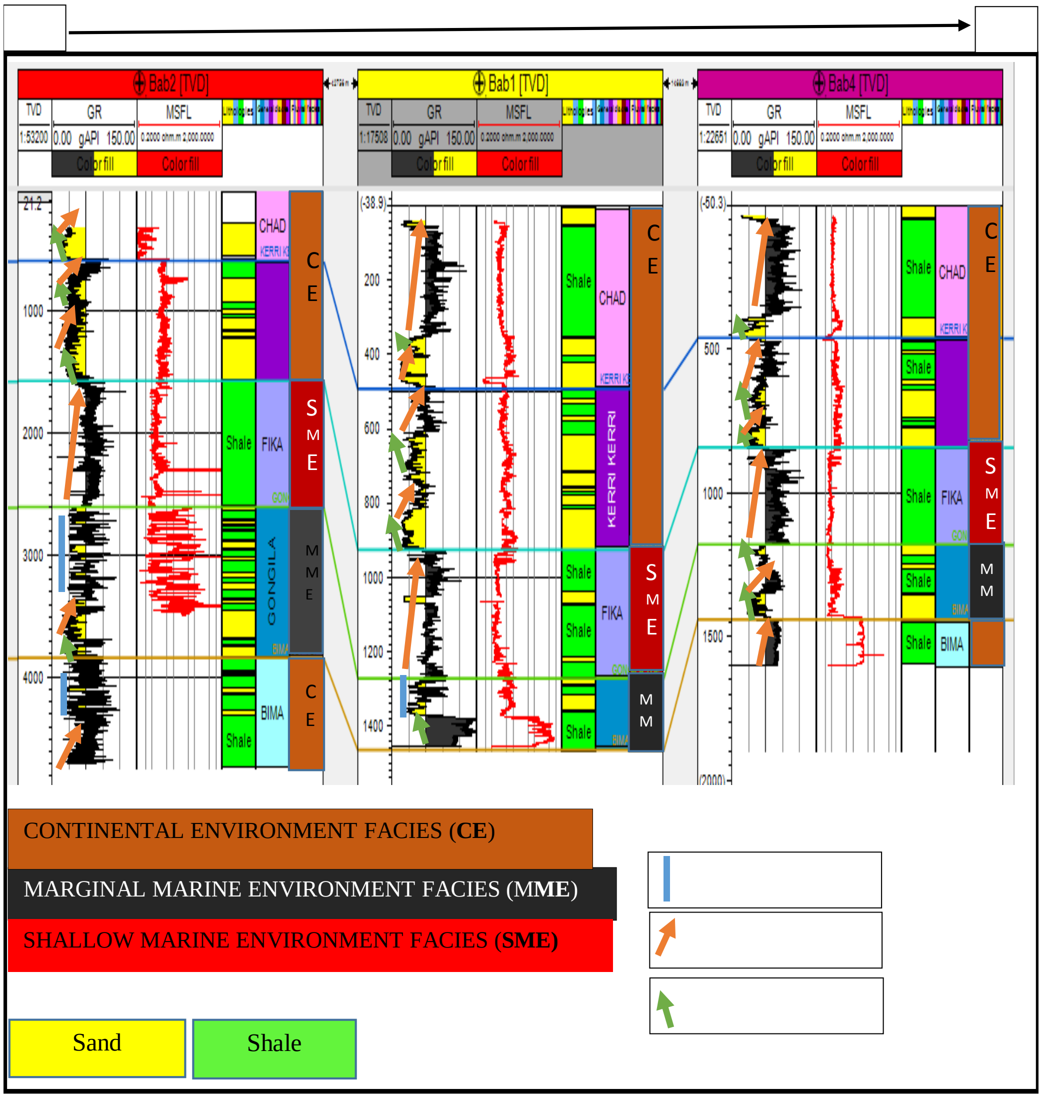


Figure 16. Identified depositional environment across Bab2 well, Bab1 well and Bab4 well.

Table 4. Lithostratigraphic unit of Chad Basin Nigeria recognised in Bab 2 well

Period	Formation	Maximum thickness from well log(m)	Maximum depth from well log(m)	Well log facies lithologies	Sediment stacking pattern	Environment of deposition
Quaternary	Chad Formation	280.73	583.21	Sand and Shale	Retrogradation Progradation	Continental
Paleocene	Kerri kerri Formation	982.81	1566.02	Shaly sand	Progradation Retrogradation	Continental
Santonian	Fika Shale	1032.65	2598.67	Shale	Retrogradation	Shallow marine
Turonian	Gongila Formation	1239.23	3837.90	Sandy shale	Aggradation Retrogradation Progradation	Marginal marine
Albian/Cenomanian	Bima Formation	870.57	408.47	Shaly sand	Aggradation Retrogradation	Continental

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 0 to 5100 ms on inline 5547 and observations were made (Table 5). (a) Parallel continuous reflections within the interval of 0 to 800 ms, (b) parallel to sub-parallel reflections, continuous to discontinuous reflections across faults within the interval of 800 to 5000 ms, and (c) chaotic reflections within the interval of 4000 ms to 5000 ms were observed (Figure 17). For further observations made with respect to some other significant geologic features prevalent within the study area, seismic attributes analysis was applied (Figure 18a-c). Seismic horizon mapping was carried out to map the formation tops on the seismic volume, identify unconformity and stratigraphic pinch out; while structural interpretation was carried out to identify faults, and fold. Time structural maps and depth structural maps were generated from the surfaces of each horizon along the formation tops interpreted across the seismic volume. Isochore depth structural maps generated identified the depocenters within the stratigraphic packages.

Table 5. Seismic facies interpretational model

Amplitude	Reflection pattern	Reflection continuity	Inferred depositional environment
High	Parallel	Continuous	Uniform depositional environment
Low –moderate	Parallel – subparallel	Discontinuous	Low energy depositional settings
Low	Chaotic	Chaotic	Soft sediment deformation or high energy depositional environment

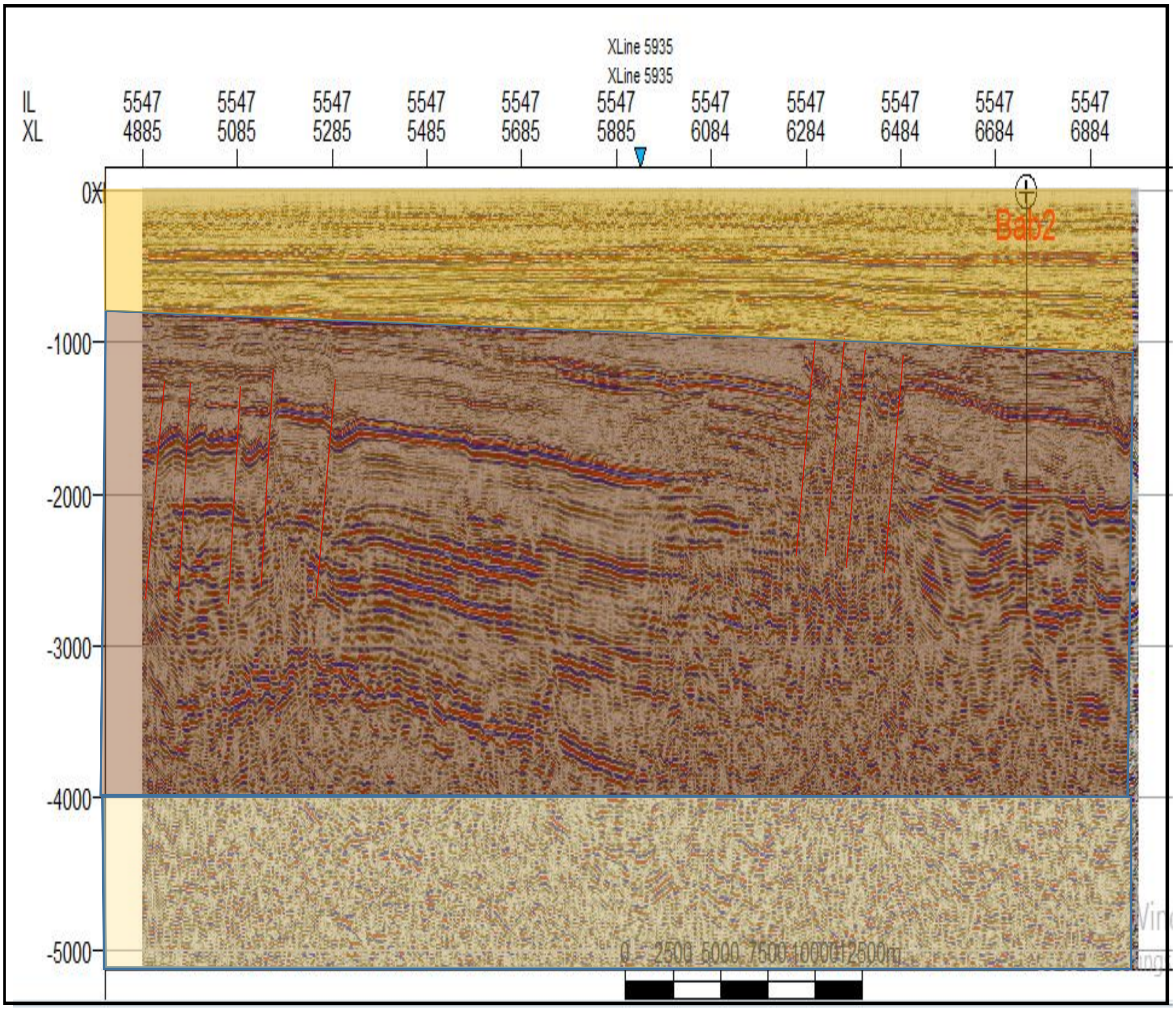
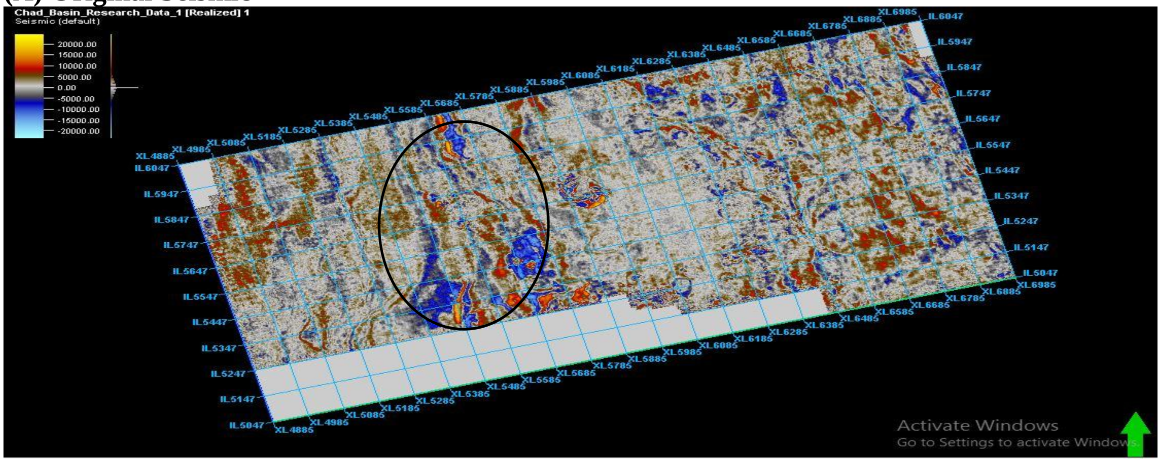


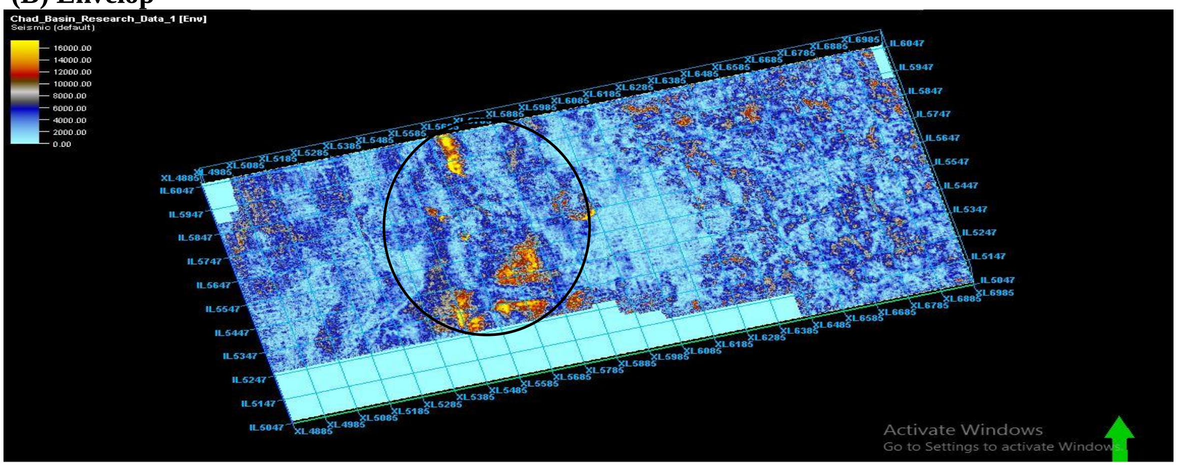
Figure 17. Seismic overview using Seismic dip line 5547 showing observations made on the seismic

The identification of the amplitude anomalies was based on their response to well-known seismic attributes which are indicative of the presence of porous and permeable lithologies with high values of original amplitudes (Figure 18a), localized high values of envelop attribute is an indication of porous lithologies and it suggest sandstone lithology (Figures 18b). The localized high values of RMS amplitude attribute (Figure 18c) within the high amplitude zones of the envelope attribute indicate fluid-filled sandstone.

(A) Original Seismic



(B) Envelop



(C) RMS Amplitude

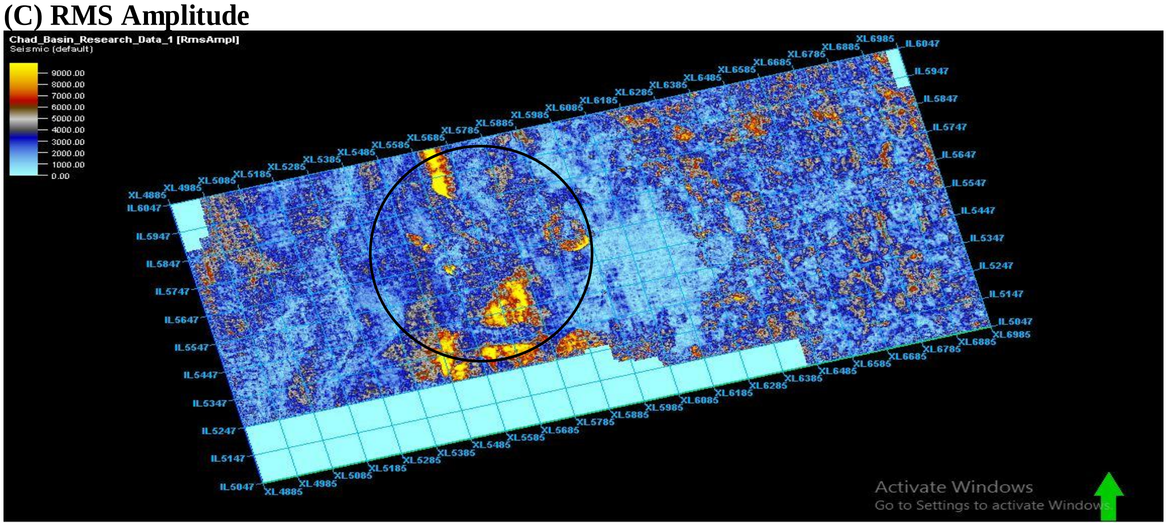


Figure 18a-c. Seismic attributes taken at time slice 1120 showing localized amplitudes

Seismic to well tie

The synthetic seismogram generated from the sonic and density log for the study area showed a near perfect tie with the seismic data, with very high percentage confidence level (Figure 19). The Fika Shale top used corresponded to positive amplitudes denoted by peak signature reading (red colour), which depicts high acoustic impedance and reflectivity, thus, the peak is shale while the trough (blue colour) is sandstone (Figure 20).

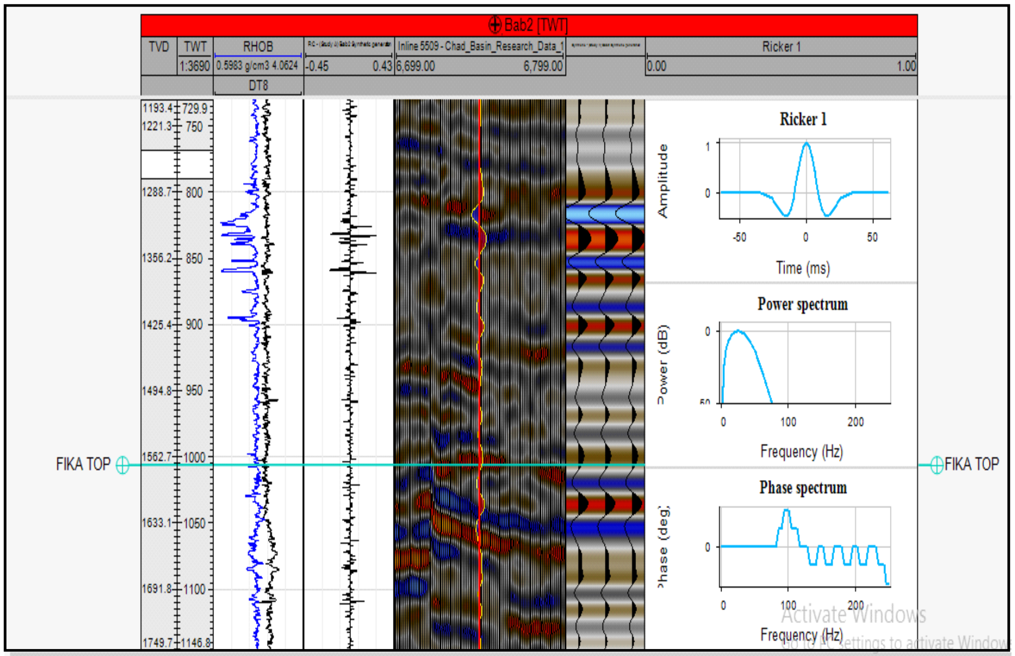


Figure 19. Well to seismic tie using Bab2 well and Fika Shale top

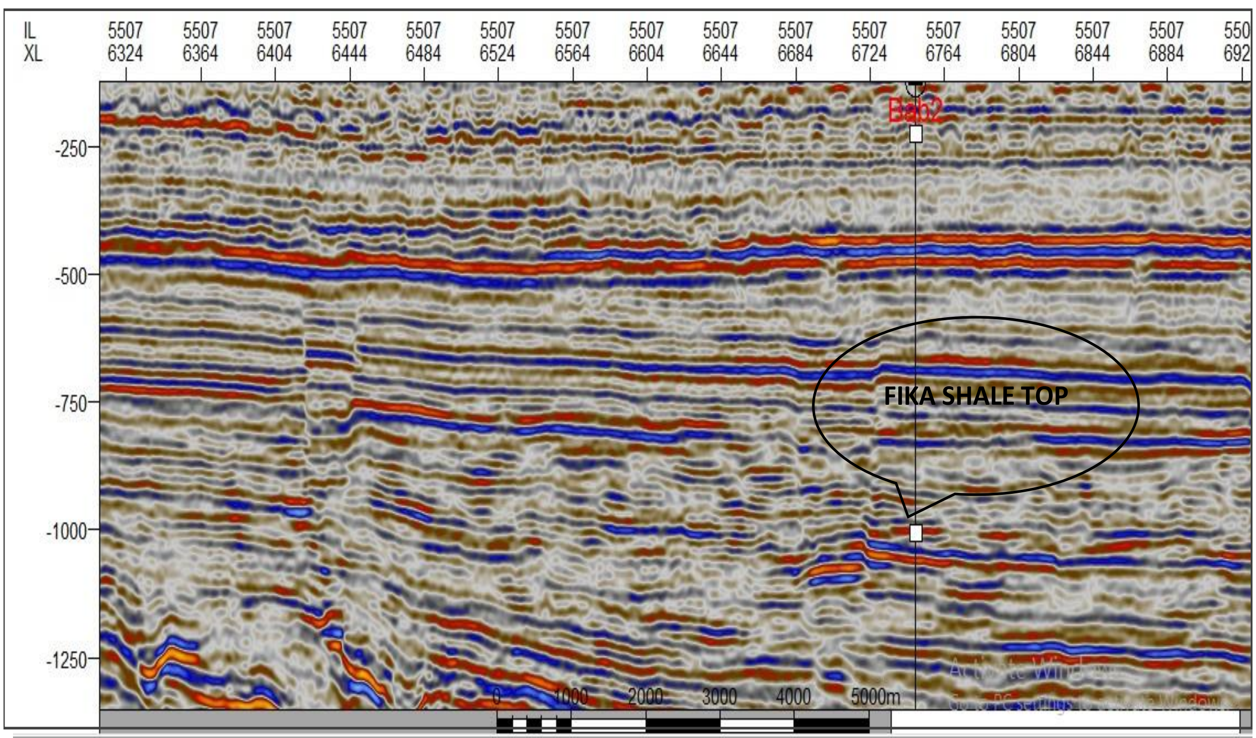


Figure 20: Display of the tied well on the seismic showing that the Fika Shale tops corresponded to the red peaks on inline 5507 of the seismic volume.

Seismic Facies analysis

Seismic facies analysis was carried out in order to properly identify and characterize the facies of interest. Four different seismic facies were identified (Figure 21), they include; the D-Facies (Continuous high and low amplitudes), Cbh-Facies (High amplitude convergent), Cbhl-Facies (High and low amplitude convergent), and Bl-Facies (Low amplitude discontinuous, shingled and chaotic).

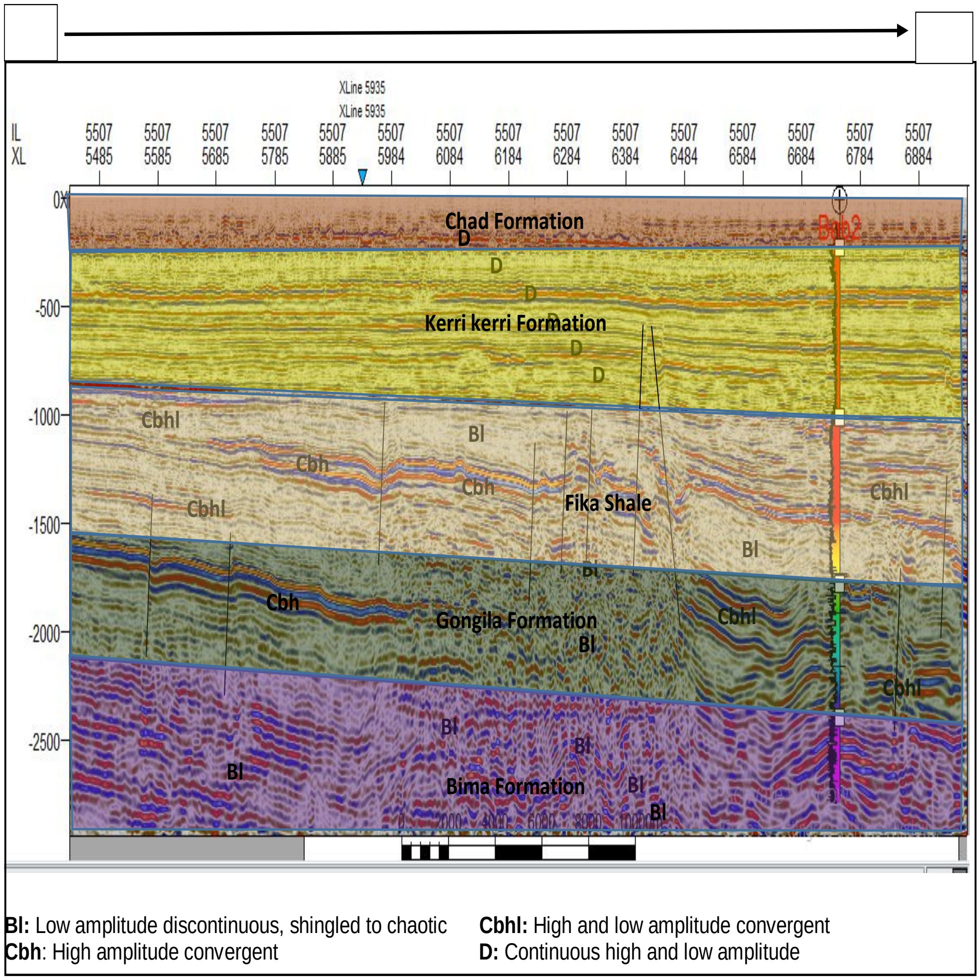


Figure 21. Seismic facies on inline 5507 showing the distribution of facies within the study area

Further analysis was done to classify the seismic facies in each of the formations in order to suggest the nature of the environment of deposition and constrain that interpreted from well log facies analysis. Bab2 well tied on seismic inline 5507 section was used for the analysis (Figure 21). From the seismic facies as illustrated in Table 6, Bima Sandstone and Gongila Formation have been affected by severe tectonic activities that gave rise to post tectonic structures such as fault and igneous intrusion that cut across all the formations except Chad Formation. The Bl facies seen in Bima Sandstone (2300-300ms) indicates highly disturbed environment, the Cbh, Cbhl, and Bl facies seen across Gongila Formation (1600-2300ms) and Fika Shale (800-1600ms) shows moderate to highly disturbed environment whereas Kerri-Kerri Formation and Chad Formation with D facies depicts low to moderately disturbed environment of deposition. These seismic facies analysis was adopted from Prather *et al.,* (1998).

Table 6. Seismic facies and the environment of deposition

Time (ms)	Formations	Seismic facies	Environment of Deposition
0-250	Chad Formation	D	Low to moderate disturbed environment
250-800	Kerri Kerri Formation	D	Low to moderate disturbed environment
800-1600	Fika Shale	Cbh, Cbhl, Bl	Moderate to high disturbed environment
1600-2300	Gongila Formation	Cbh, Cbhl, Bl	Moderate to high disturbed environment
2300-300	Bima Formation	Bl	High disturbed environment

Structural Interpretation

Structural interpretation was enhanced by the use of the variance edge attribute (Figure 22) which revealed that the field is characterized by structural styles such as reverse faults, as well as normal faults forming collapse crest structures (Figure 23).

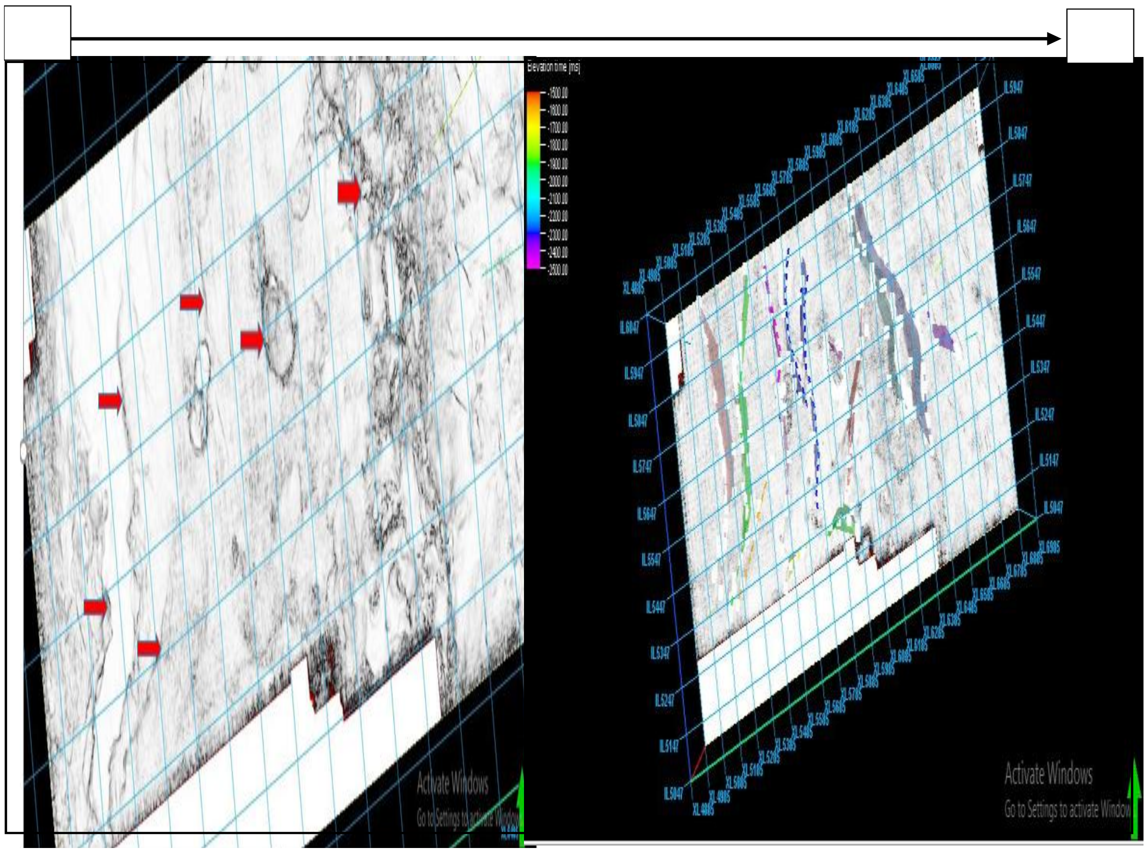


Figure 22. Time slice of variance edge attribute at 1476ms highlighting the faults (the red arrow indicates fault)

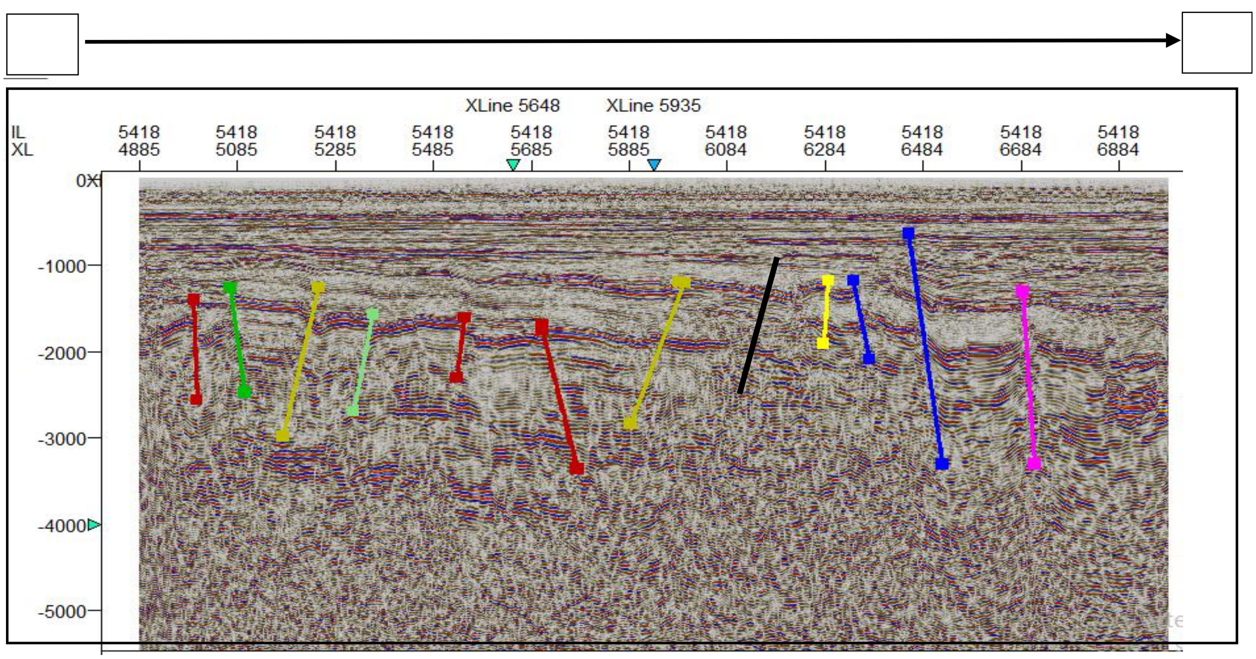


Figure 23. Seismic dip line 5418 showing normal faults dipping south, as well as reverse faults

The formation tops were mapped across the seismic volume using Bab2 well as shown in dip line 5418 (Figure 24). The Bima Sandstone and Gongila Formation have shown serious tectonic intrusions which gave it shingles to chaotic reflection geometry on the southern part of the inline 5418 section. Fika Shale and kerri kerri Formation have many faults cut across it with minor intrusion whereas the Chad Formation is free from faulting and intrusion.

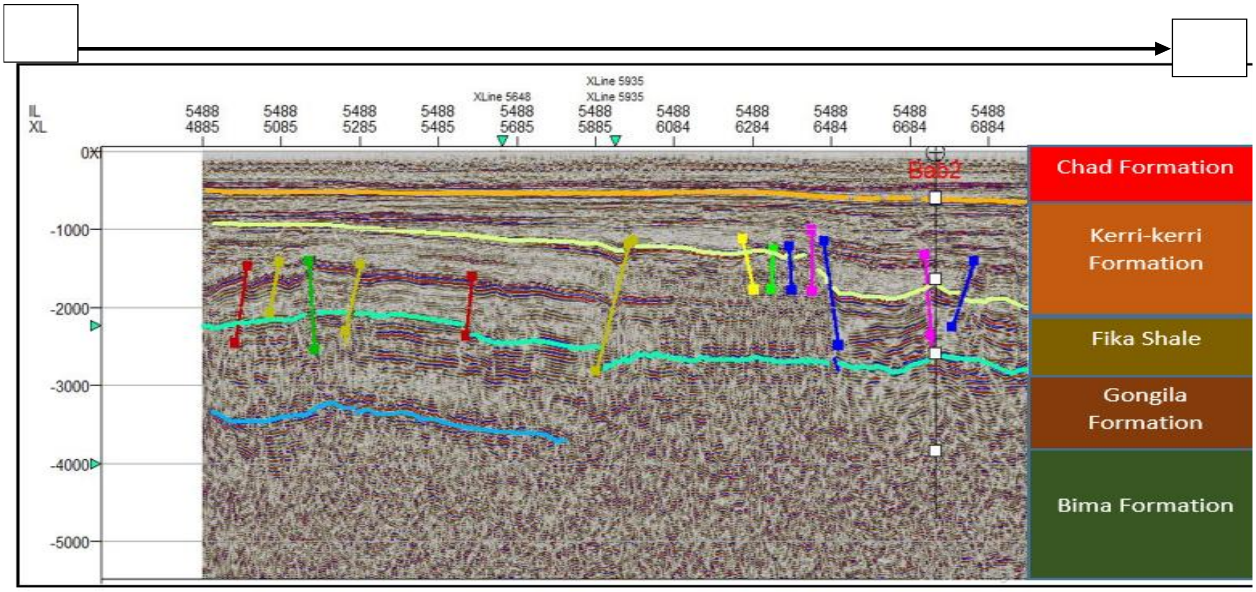


Figure 24. Seismic inline 5488 showing the four interpreted horizons

Geologic cross-sections

Geologic cross-sections for the interpreted structural surfaces were produced in order to show the present day geometry of the formations (Figures 25a – d). The cross sections show that the interpreted surfaces are dominated by faulted structural lows towards the east, and faulted structural highs towards the west. The cross-section was taken from line XY across all the maps and the geometry of each map is shown beneath the map with black colour line. The profile of the cross-section shows that Gongila Formation is highly faulted and the faults are pronounced in it than any other formation. The horst and graben in Gongila Formation shows evidence of extensional and compressional tectonics. There is normal fault across Gongila Formation and Fika Shale profile which did not appear in Kerri-Kerri Formation profile and Chad Formation profile.

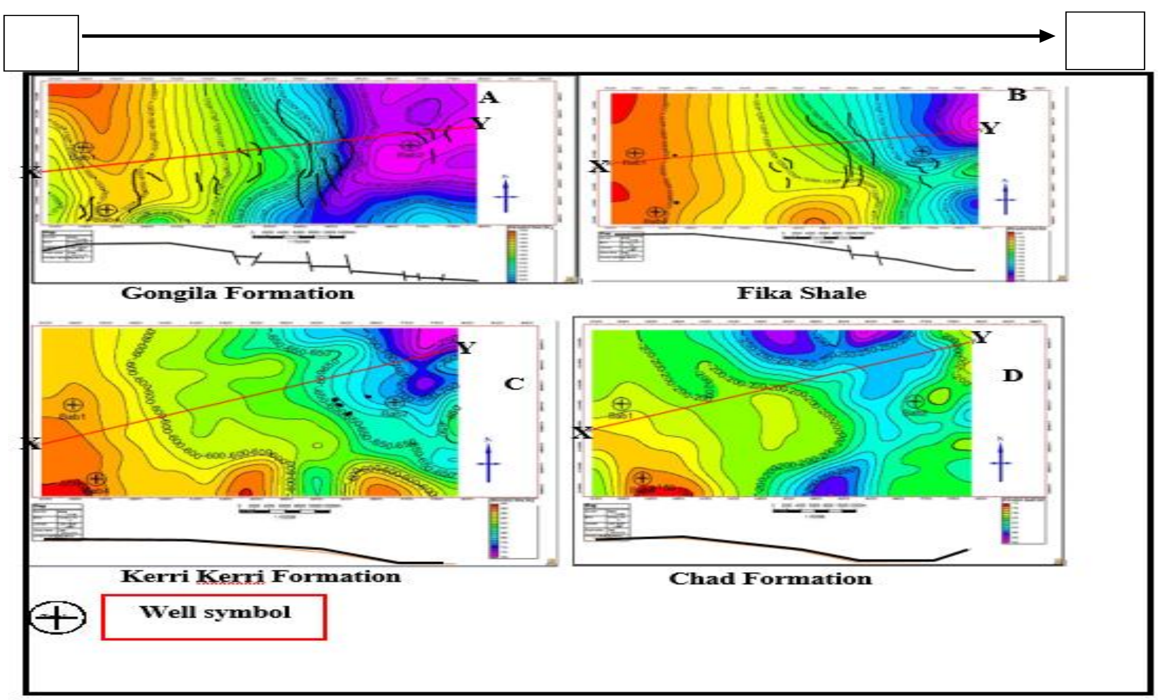


Figure 25. Cross section of the maps generated for the study area (a) Gongila Formation, (b) Fika Shale, (c) Kerri Kerri Formation, and (d) Chad Formation.

Isochore maps

The thickness maps of the study area were produced using the top and base of the formations, and is shown in Figures 26a-d. They show the areas with the thickest sediments, known as the depocenters. These maps as well show changes/migration of structurally controlled depocenters through time within the formations which is from Gongila Formation to Chad Formation. The depocenter of Gongila Formation is in the Northwest direction, that of Fika Shale is in the northwest–southwest direction, whereas that of Kerri-Kerri Formation and Chad Formation are in the southwest direction. Usually as expected, fluids in these regions if any will buoy up and migrate away from this depocenters to adjacent locations of structural highs, that is, from southwest to northwest direction within the study area. Bab 1 well and Bab 4 well were drilled on structural high while Bab2 well was drilled on structural low and it happens to be the deepest well within the study area. The positions of the depocenters indicate that the major sediment transport direction in this study area is from the northeast to southwest direction. Based on the red to yellow colouration of each of the formation's surfaces generated, the areal extent of the depocenter is largest in Fika Shale followed by Gongila Formation and Chad Formation before the smallest being kerri-Kerri Formation. This suggests that Fika Shale is more regional than any of the formations, and after it follows Gongila Formation, Chad Formation and Kerri-Kerri Formation.

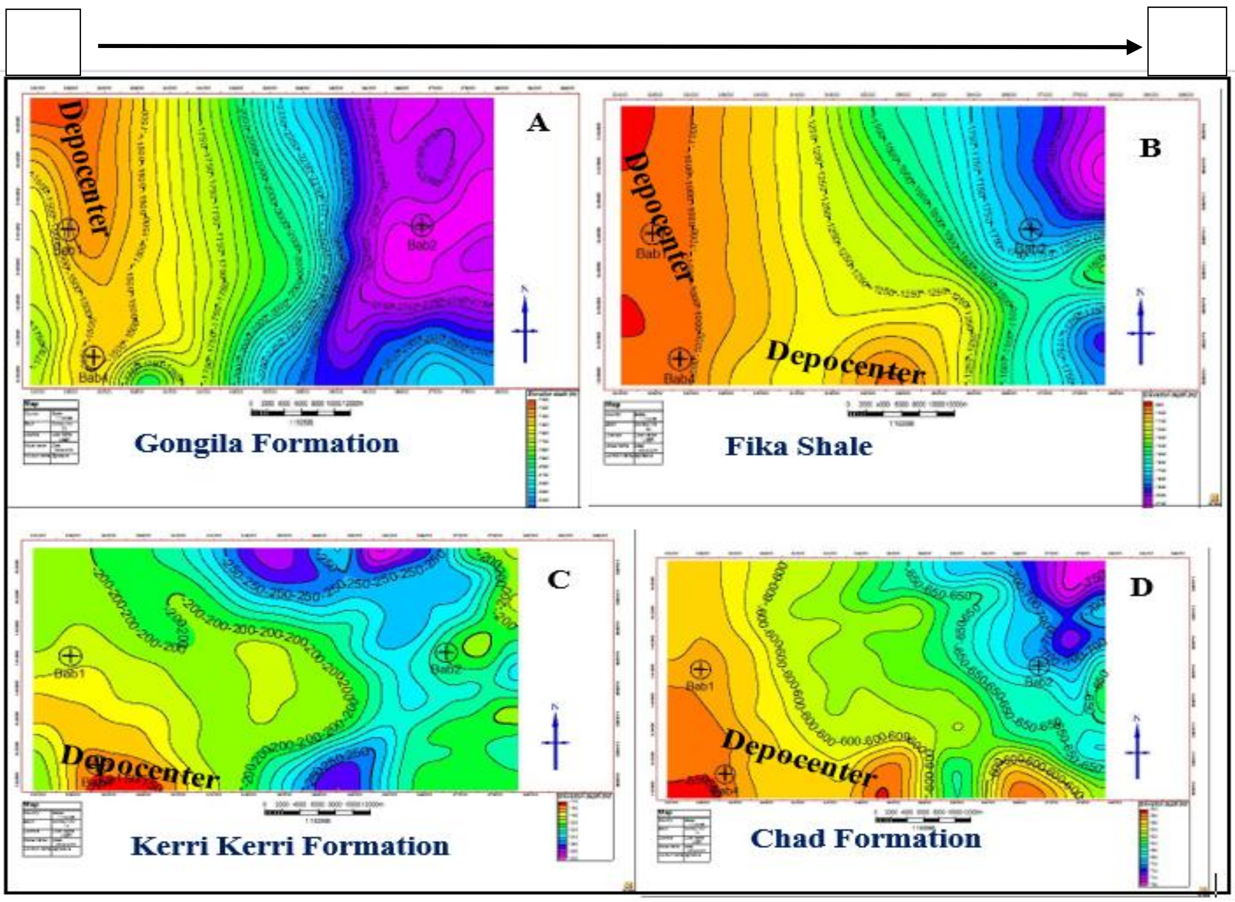


Figure 26. Isochores maps generated for the study area (a) Gongila Formation, (b) Fika Shale, (c) Kerri Kerri Formation, and (d) Chad Formation**.**

Surface seismic attribute analysis

Surface seismic attribute analysis was further carried out to characterize the amplitudes of the reflections. Usually, when amplitudes are correctly analysed, a host of additional features can be derived and used in interpretation. Fortunately, in most cases, the amplitude of reflections correspond directly to the porosity and/or the saturation of the underlying formations, because these rock properties have a strong effect on both velocity and density.

The Root mean square (RMS) and Sum of negative amplitude (SNA) attributes ran on the generated surfaces allowed for the identification of localized amplitude anomalies within the surfaces indicating areas with increased porosity and or increased fluid saturation.

The first seismic attribute map shows that the region with yellow colour has high Root mean square(RMS) amplitude which indicated the presence of sandstone while the region with dark blue colour has low root mean square amplitude(RMS) which indicated the presence of shale as shown in the map (Figure 27a-b). The second map is negative amplitude attribute map which shows that the region with green patches imply decrease in negative amplitude and it is interpreted as sandstone while the regions with increase in negative amplitude is covered with yellow patches which is attributed as shale (Figure 28a-d). However, this attribute maps confirmed the lithological classification which indicated that Gongila Formation has almost equal proportion of shale and sandstone, while other formations such as Fika Shale which contains more shale and little sandstone intercalations has as well been confirmed by the attribute maps. Obviously, kerri Kerri Formation has presented more sandstone than shale while Chad Formation indicated more Shale than Sandstone as compared to Figure 13 of lithological classification.

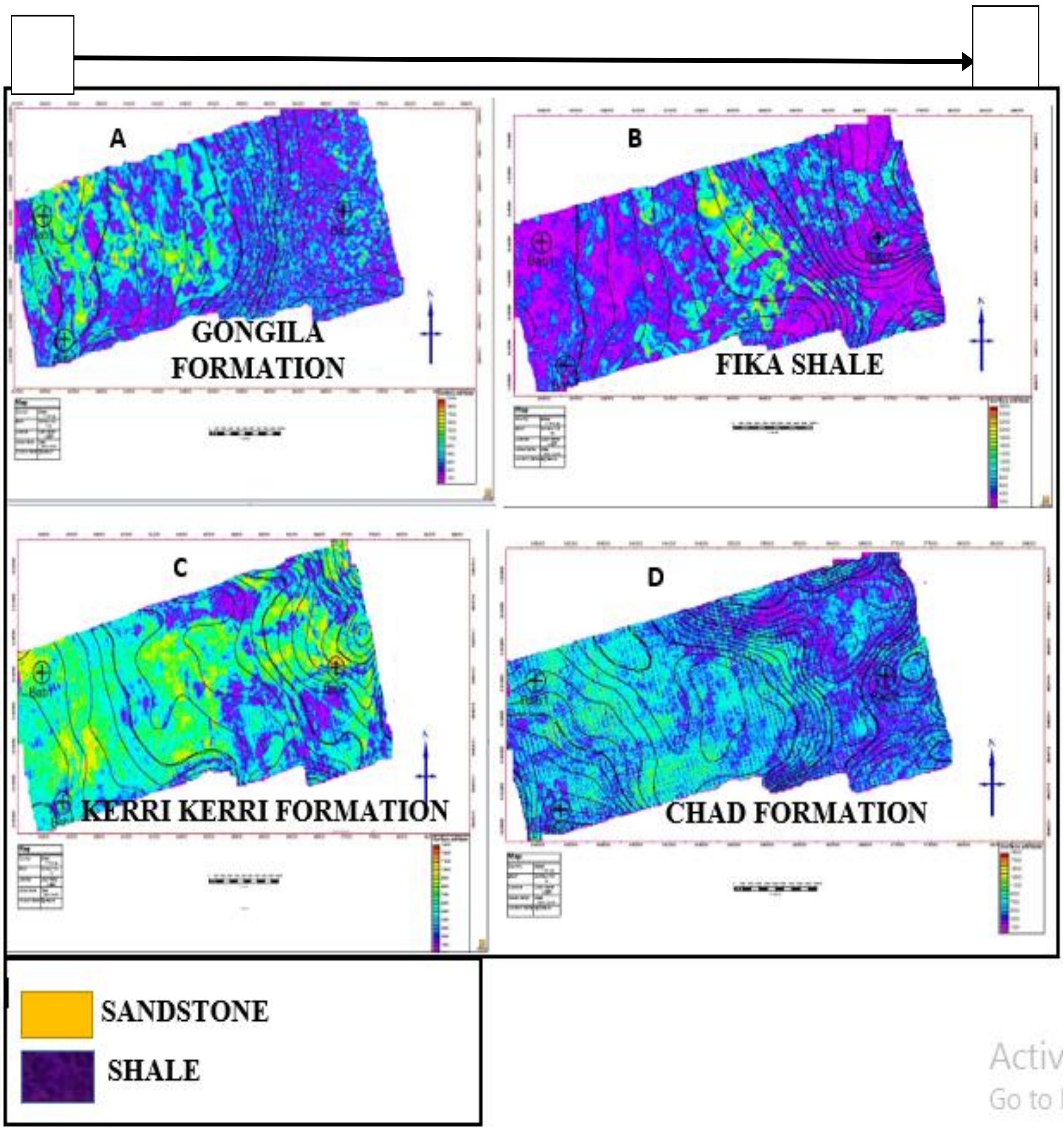


Figure 27. RMS amplitude attribute maps generated for the study area (a) Gongila Formation, (b) Fika Shale, (c) Kerri Kerri Formation, and (d) Chad Formation

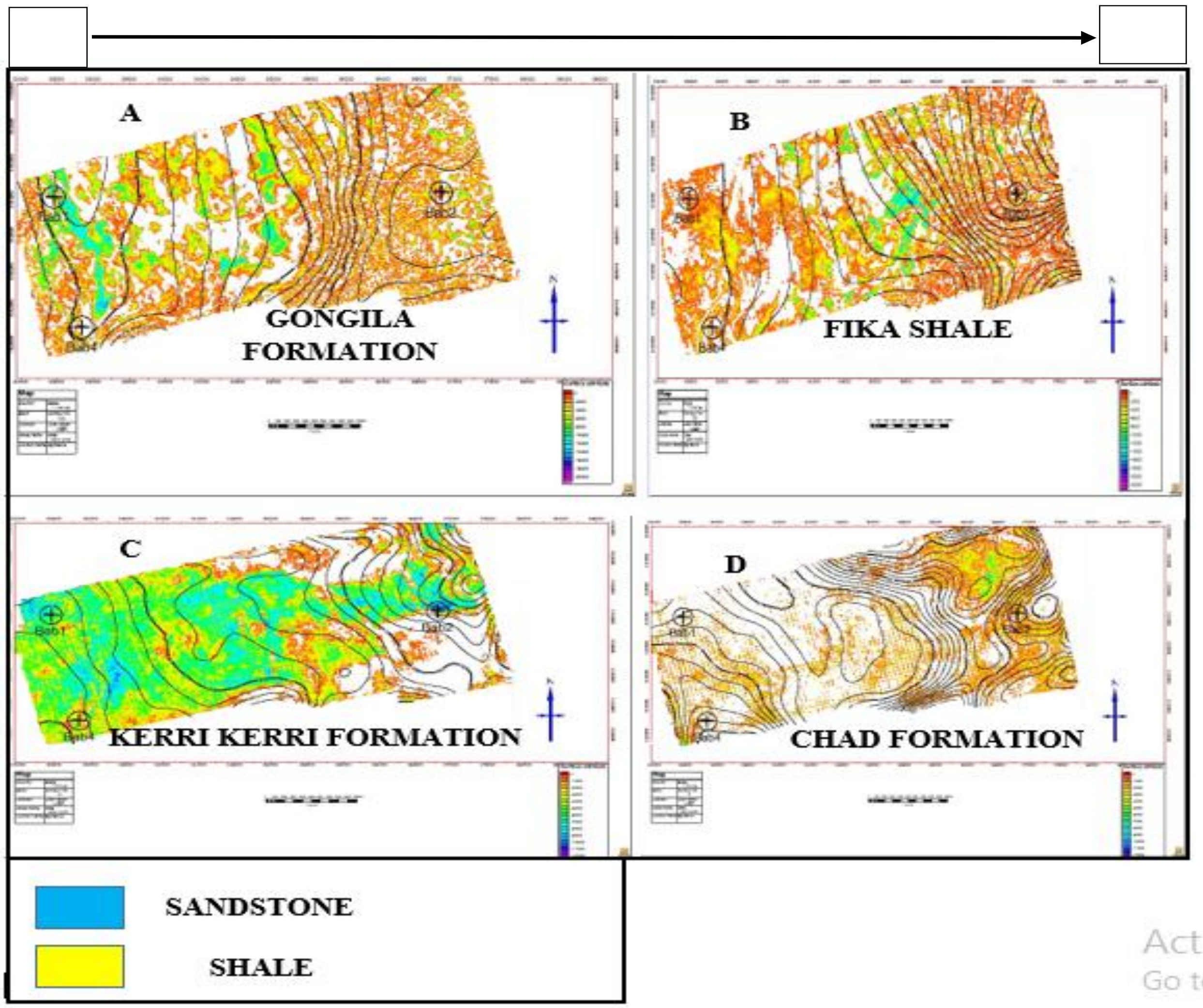


Figure 28. Negative amplitude attribute maps generated for the study area (a) Gongila Formation, (b) Fika Shale, (c) Kerri Kerri Formation, and (d) Chad Formation

SUMMARY, CONCLUSION AND RECOMMENDATION

Summary

The integration of multiple data sets has allowed the interpretation of the subsurface stratigraphy, structures and the depositional environments within the study area. It has also shown how the changes in the stratigraphy and structures affected the depositional environments. The lithological classifications were done across each of the wells ranging from the oldest formation, Bima Sandstone to the youngest formation, Chad Formation. It was observed that Bima Sandstone are found across Bab 2 well and Bab 4 well but absent in Bab1 well, and its lithological description shows that it contains more of shales than sandstone. Gongila Formation is observed across all the wells with almost approximately equal proportion of sandstone and shale. Fika Shale is as well found across all the wells, and it contains more of shale and little sandstone intercalations. Kerri Kerri Formation has more of sandstone than shale as found across all the wells whereas Chad Formation has more of sandstone at Bab 2 well but more of shales at Bab 1 well and Bab 4 well. Interestingly, about five lithofacies analysis were obtained, that is, LF1, LF2, LF3, LF4, and LF5 with respect to the formations, ranging from Bima Sandstone, Gongila Formation, Fika Shale, Kerri Kerri Formation to Chad Formation respectively. It was observed that, (1) Bima Sandstone has retrograding and aggrading sedimentary facies, (2) Gongila Formation has retrograding, prograding and aggrading facies, (3) Fika Shale has only retrograding facies, (4) Kerri Kerri Formation contains retrograding and prograding facies, and (5) Chad Formation contains prograding and retrograding facies too.

Obviously, the facies association suggests the environment of deposition of the sediments in the basin, which are; continental environment, transition environment and marine environment of deposition.

Seismic facies analysis presented low amplitude discontinuous facies (Bl facies), high and low amplitude convergent facies (Cbhl facies), high amplitude convergent (Cbh facies), and continuous and low amplitude facies (D facies) across the seismic volume among the formations which helped in identification of the nature of the environment of deposition. The cross-section of the depth structural maps of the said formations were generated which shows how the interpreted faults cut across the formations. Finally, Isochore maps and surface seismic attribute maps of the formations were generated so as to pinpoint the depocenters and the lithology respectively.

Conclusion

Nigeria Chad Basin has five sedimentary formations classified into different lithofacies that helped in the proper delineation of the subsurface stratigraphy and the environment of deposition. It has been confirmed through the structural interpretation and modelling that the basin has been tectonically disturbed such as basin invasion and igneous intrusion. Seismic facies analysis across the seismic volume among the formations helped in the validation of the nature of the environment of deposition. Overall detailed lithofacies analysis, seismic facies and surface attribute analysis have confirmed Gongila and Kerri kerri Formation as a focal point for hydrocarbon prospectivity. The Isochore map generation have shown the depocenters and a real extent of each formation across the study area.

Recommendation

Following the research work done, the following is recommended

(1) Close deeper wells like Bab 2 well penetrated all the formations should be drilled across the study area to provide more information about the subsurface stratigraphy of the area.

(2) Biodata and checkshot data should be provided for all the wells for accurate studies/interpretation of environment of deposition

(3) More log data, such as spontaneous potential log should be run to aid in lithological classification of the study area

(4)Gongila Formation and Kerri Kerri Formation should be targeted for petroleum system analysis because the lithological classification, well log facies analysis, seismic facies analysis, structural interpretation, and surface map attribute analysis have shown that they might have good petroleum elements such as source rock, seal rock, reservoir rock, trap, timing, and migration pathways.

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