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Structural Architecture of Chad (Bornu) Basin Using 3-D Seismic Data

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Abstract: *Chad (Bornu) Basin is located within latitudes 9° 30`N and 13° 40`N, and longitudes 11° 45` E and 14° 45`E,Northeastern Nigeria, covering an area extent of about 23,000 square kilometres. And the aim of this study is to delineate the structural architecture of Chad (Bornu) Basin using 3D seismic data across the drilled well in the field. The method employed was basically on seismic attributes analysis based onthe reflection geometry, amplitudes, and continuity. The results generated shows that the basin has undergone different tectonic regimes which include rifting, subsidence, and basin inversion. These tectonic regimes controlled the deposition of the sedimentary formation within the basin, these formations are Bima Sandstone, Gongila Formation, Fika Shale, Kerri-Kerri Formation and Chad Formation. Extensional tectonic regime gave rise to the presence of normal faults, horst, graben and intrusives while the compressional tectonic regime let to formation of reverse faults, folds and igneous activities. Non-tectonic structures were mapped across the seismic volume such as pinchout, unconformity surface between Bima Sandstone and the Basement complex rock and the unconformity surface between Fika Shale and Kerri-Kerri Formation which are nonconformity and disconformity respectively. These interpreted structures could act as seal, reservoirs, trap and migration pathways for hydrocarbon. The Stereonet diagram depicted NW-SE trend, NE-SW trend and N-S trending faults. Down to basement faults (F8 and F9) and other faults mapped which could easily be identified in the generated structural framework, the fault models, time structural maps and depth structural maps.*

Keywords: *Rifting, subsidence, inversion, formation, fault, fold, seal, trap, reservoir, migration pathway, unconformity, nonconformity, and disconformity.*

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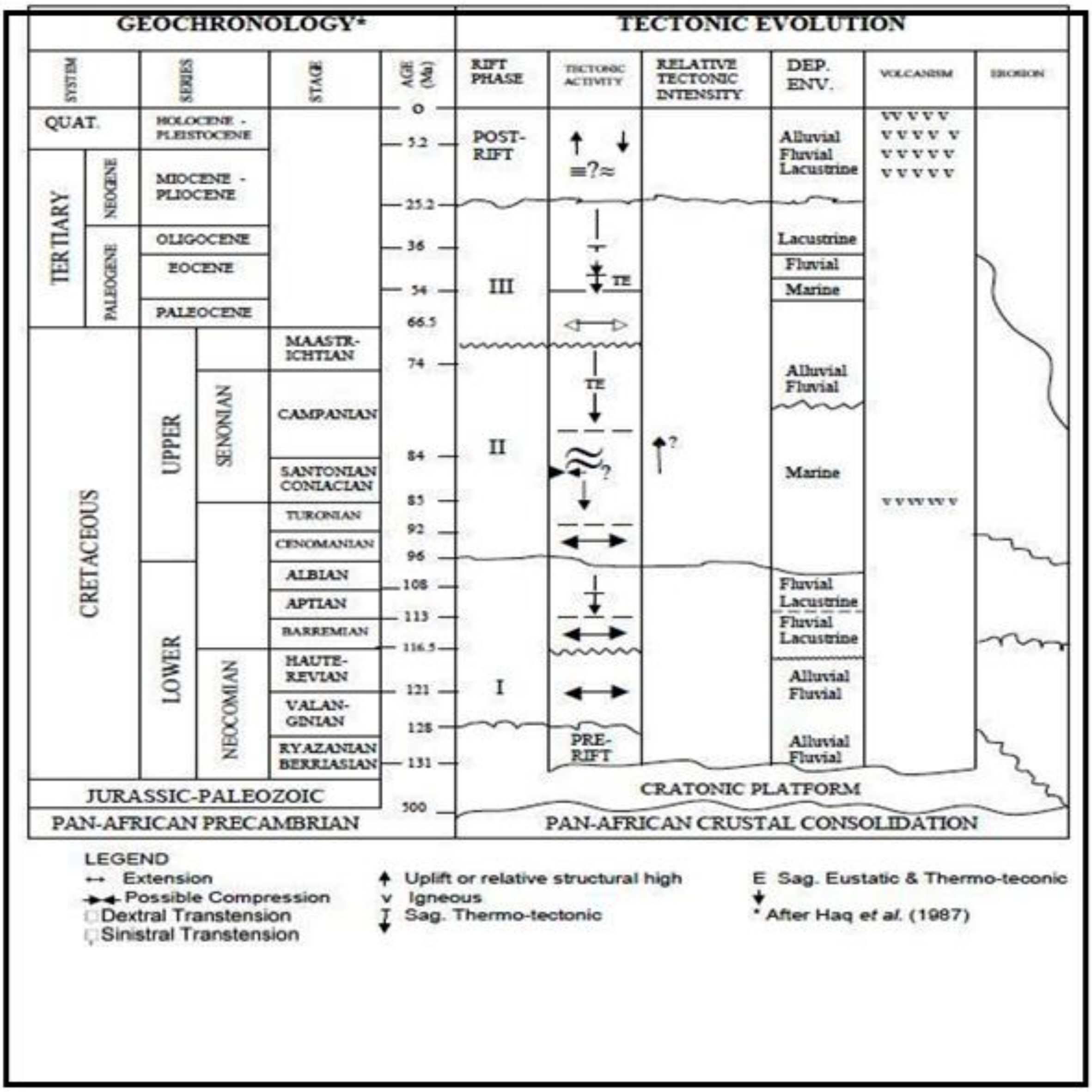
I. Introduction

Chad Basin is part of a regional active tectonic setting with geological structures trending southwest to the Benue Trough and northwest to the Air Mountains (Ajayi and Ajakaiye, 1981).The structural architecture of rift basins depends solely on the initial crustal structure, strain rate, basin geotherm, and total strain (Genik, 1992b; Khain, 1992b). Stretching of continental lithosphere generates a geometrical array of largely dip-slip normal faults that bound sedimentary basins. These fault arrays are subdivided into three major stages. According to (Khain, 1992b; Gawthorpe and Leeder, 2000; Jackson *et al.*, 2002; Gawthorpe*et al.*, 2003; Bell *et al.*, 2009; Bell *et al.*, 2012; Bell *et al.*, 2014b), the first stage results in the formation of numerous small normal fault segments that flanked small basins, and the displacement on these faults results in the accumulation of sediments in the hanging walls, with sediment being eroded from the uplifted and the displaced footwall. The second stage encompasses the relation of fault segments, bounding of relay ramps, and the generation of many fault systems. At this time, some faults may become passive in the stress shadows of larger faults. Finally, the last stage involves the formation of large depocentres bounded by major normal fault systems. Chad Basin was classified as extensional basin based on several evidences including presence of basement extensional force indicators (Table 1), random fault patterns, and lack of compressive features of the main rift event in Early Cretaceous – Tertiary (130 - 96 Ma) (Avbovbo*et al.*, 1986). Late Cretaceous Albian-Cenomanian rift (96 –75 Ma) gave rise to thermo-tectonic subsidence accompanied by Tethys sourced marine transgression through Mali and Algeria into western Niger with similar South Atlantic sourced marine transgression through Nigeria into Western Chad and Eastern Niger. The marine transgression attained its peak during the period 85 – 80 Ma was followed by regression because the of epeirogenic uplift which affected the basin and formed major fold and reverse fault system during the Santonian. The Santonian compression gave rise to the separation of the West and Central African Rift System (WCARS) (Figure 1) with several associated hydrocarbon trapping features (Genik, 1993) and folds in Benue Trough and Nigeria Chad Basin (Popoff*et al.*, 1983; Cratchley*et al.*, 1984; Avbovbo*et al.*, 1986; Benkhelil, 1988). The water boreholes and geophysical well logs carried out in the study area shows that the Upper Benue Trough is geologically related to the Nigeria Chad Basin. The Zambuk Ridge granitic inlier separates Nigeria Chad Basin from the Benue Trough (Figure 3) such that sedimentation in the basins were not the same (Avbovbo*et al.*, 1986; Alalade and Tyson, 2010; Adepelumi*et al.*, 2010, Okpikoro and

Olorunniwo, 2010).On the contrary**,** Hamza and Hamidu (2012) and Zaborski*et al*. (1997) opposed the theory of Zambuk Ridge separation and affirmed that the Northsouth trending Gongola Basin in the Upper Benue Trough was separated from the Nigeria Chad Basin by an anticlinal Dumbulwa-Bage High or Zambuk Ridge (Figure 3). There is interruption of the sand deposits in the depocentre of the Nigeria Chad Basin covering several kilometres in the basin. Evidence of Geophysical exploration indicated that the Benue rift valley was filled with about 5500 m of folded Cretaceous sediments extending northeast from the Niger Delta to the Chad Basin. The central axis of the Benue valley is known to have a positive gravity anomaly flanked by negative gravity anomalies on either sides. The negative anomalies were suggested to be due to influence of the crustal thinning, presence of igneous intrusions and shallow basement rocks (Cratchley and Jones, 1965).

Table 1: Paleotectonic evolution of the West African Subsystem (WARS) as it affected Chad Basin (Genik, 1993)



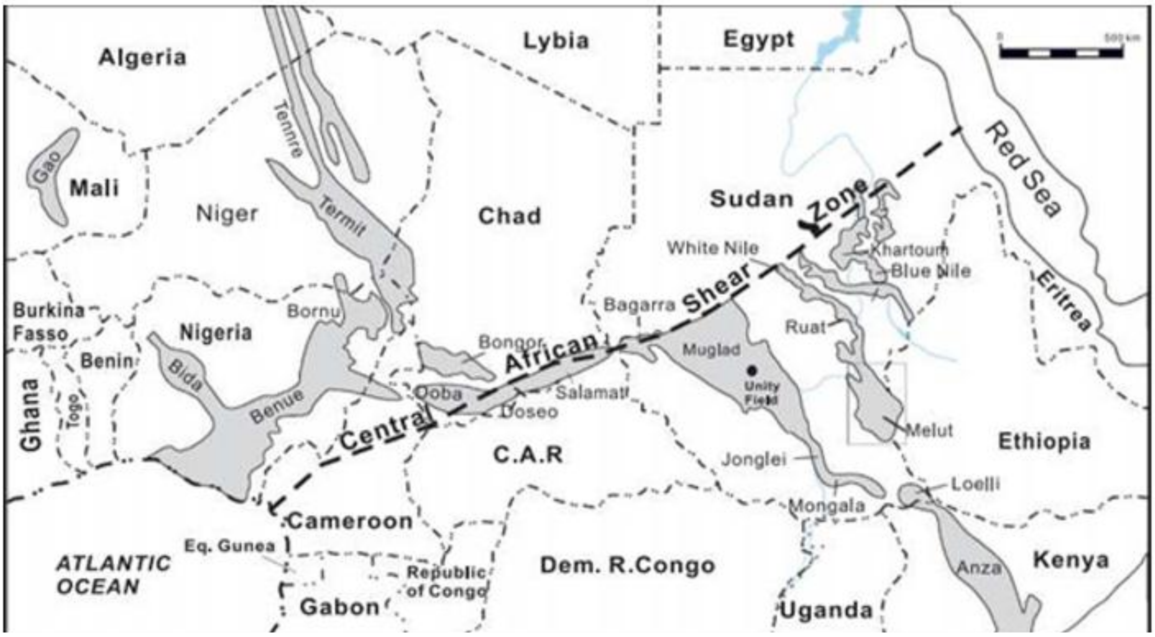


Figure 1: Regional map of West Central African Rift System Basins (WCARS) developed from the Cretaceous continental separation (modified from Dou et al., 2007).

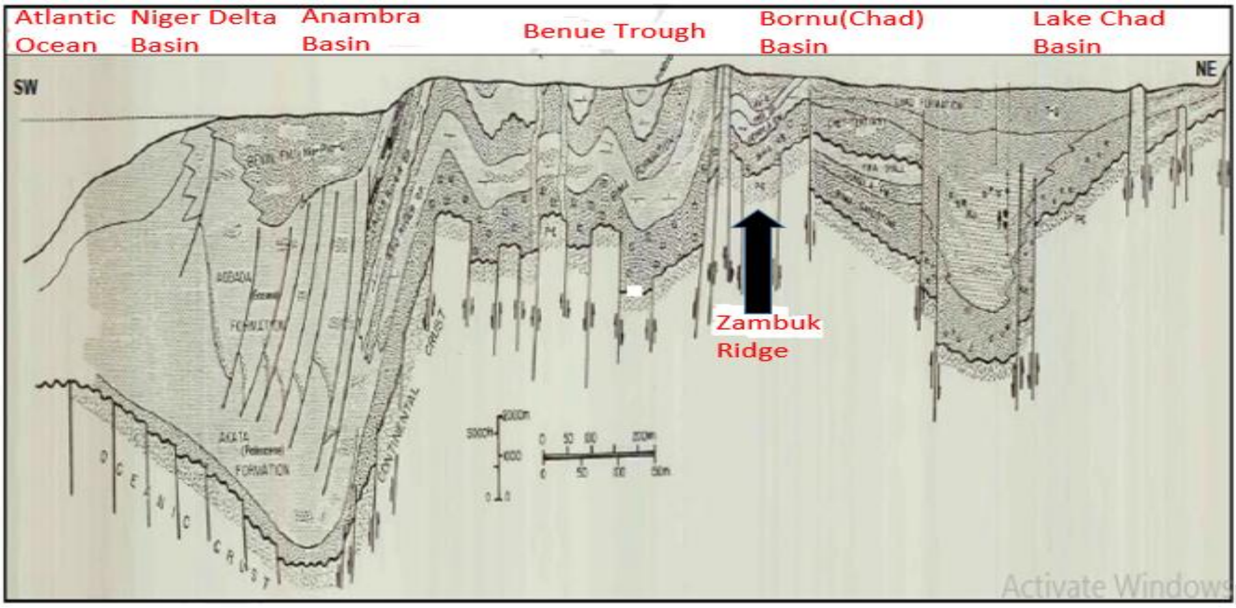


Figure 3: Sketch of tectonic and depositional setting of the Nigeria Chad Basin and adjoining basins (Modified from Peterson, 1985).

Structural Evolution of the Nigeria Chad Basin

The Cretaceous to Tertiary rifts of Central African Republic,Niger, Chad, and Nigeria make up a large part of the “West and Central African Rift System” (WCARS) (Genik 1993), this was further divided into two coeval, genetically related but physically separated rift systems known as the West African Rift Subsystem (WARS) and Central African Rift Subsystem (CARS). The Nigeria Chad Basin is small parts of the WARS basins which is called present day Bornu Basin. The origin of the WCARS could be traced bvack to the breakup of super continent Gondwanaland and the opening of the South-Atlantic Ocean and the Indian Ocean at about 120-130 Ma (Fairhead and Green, 1989) (Figure 4 a-b). The extensional deformation that occurred in the Late Maastrichtian lasted to the end of the Cretaceous period. This basin was later restructured into an elongate NE-SW graben system. The basin is characterised by flat topography and gentle slopes (Isiorho, and Nkereuwem, 1996) and with discontinuous bedrock outcrops especially in the northern parts towards the boundary. Tectonic inversion is one of the principle processes driving uplift and erosion in sedimentary basins. Inversion involves transpressional and/or compressional reactivation of pre-existing normal fault structures and initiation of new reverse faults (Turner and Williams, 2004; Bodin*et al.*, 2010; Jackson *et al.*, 2013b). The types of inversion structures that form depend on: (a) the geometry and mechanical properties of the faults (Sibson, 1995, Kelly *et al*., 1999, (Sibson, 1995), (b) the rheological properties of the basin fill and their total mechanical strength (Panien*et al.*, 2005) and; (c) the total magnitude of structural shortening (Jackson *et al*., 2013b). Three-dimensional seismic reflection studies further indicates a strong effects of the basin structural template on the inversion structural development (Guiraud and Bosworth, 1997; Kelly *et al.*, 1999; Jackson *et al*., 2013b). Most bedrock exposures were confined in the southern boundary with the Gongola Basin (Hamza and Hamidu, 2012).The African continent also contains four accommodation zones which contributed to the structural styles and development in the Chad Basin: (i) the Iullemeden rift, (ii) the Termit-Bongor rift, (iii) the Termit-Northern Benue Trough and, (iv) the Central African Shear Zone (CASZ). (Unternehr*et al*., 1988; Guiraud*et al.*, 2000; Torsvik*et al*., 2009; Moulin *et al*., 2010; Robles-Cruz *et al*., 2012; Heine *et al.*, 2013; Pérez-Díaz and Eagles, 2014). These zones initiated West and Central African Rift Systems (WCARS), that accommodated transmitted plate boundary stresses through extensional and strike slip movements (Figure 5) (Carter *et al.*, 1963; Fairhead, 1988; Benkhelil, 1989; Genik, 1992b; Torsvik*et al.*, 2009; Fairhead*et al.*, 2013).

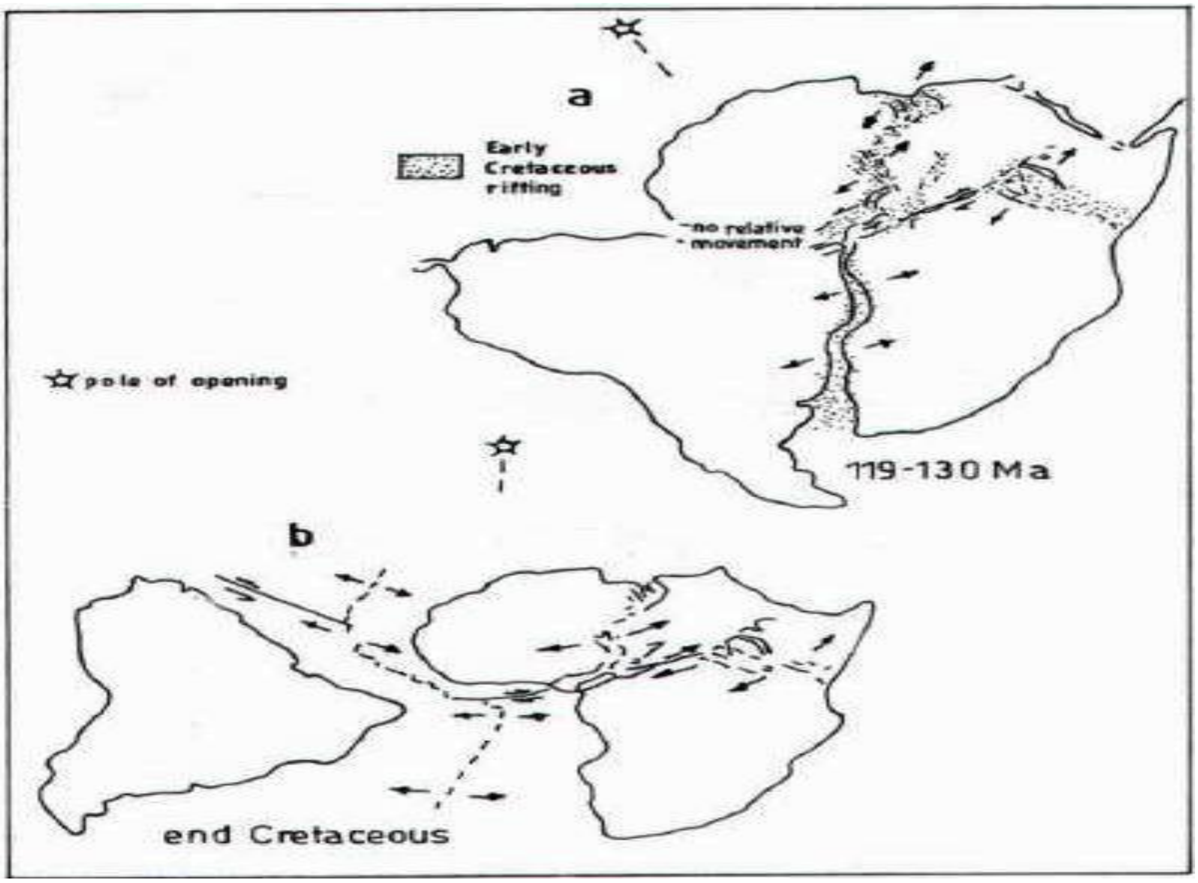


Figure 4a: Model showing the possible extension of the opening of the South Atlantic through Nigeria and Eastern Niger into Kufra and Sirte Basins in Libya (After Fairhead and Green, 1989). Figure 4b: Model showing the possible link between the opening of the central Equatorial and South Atlantic Oceans and development of the Caribbean and WCARS during the Late Cretaceous, (After Fairhead and Green, 1989).

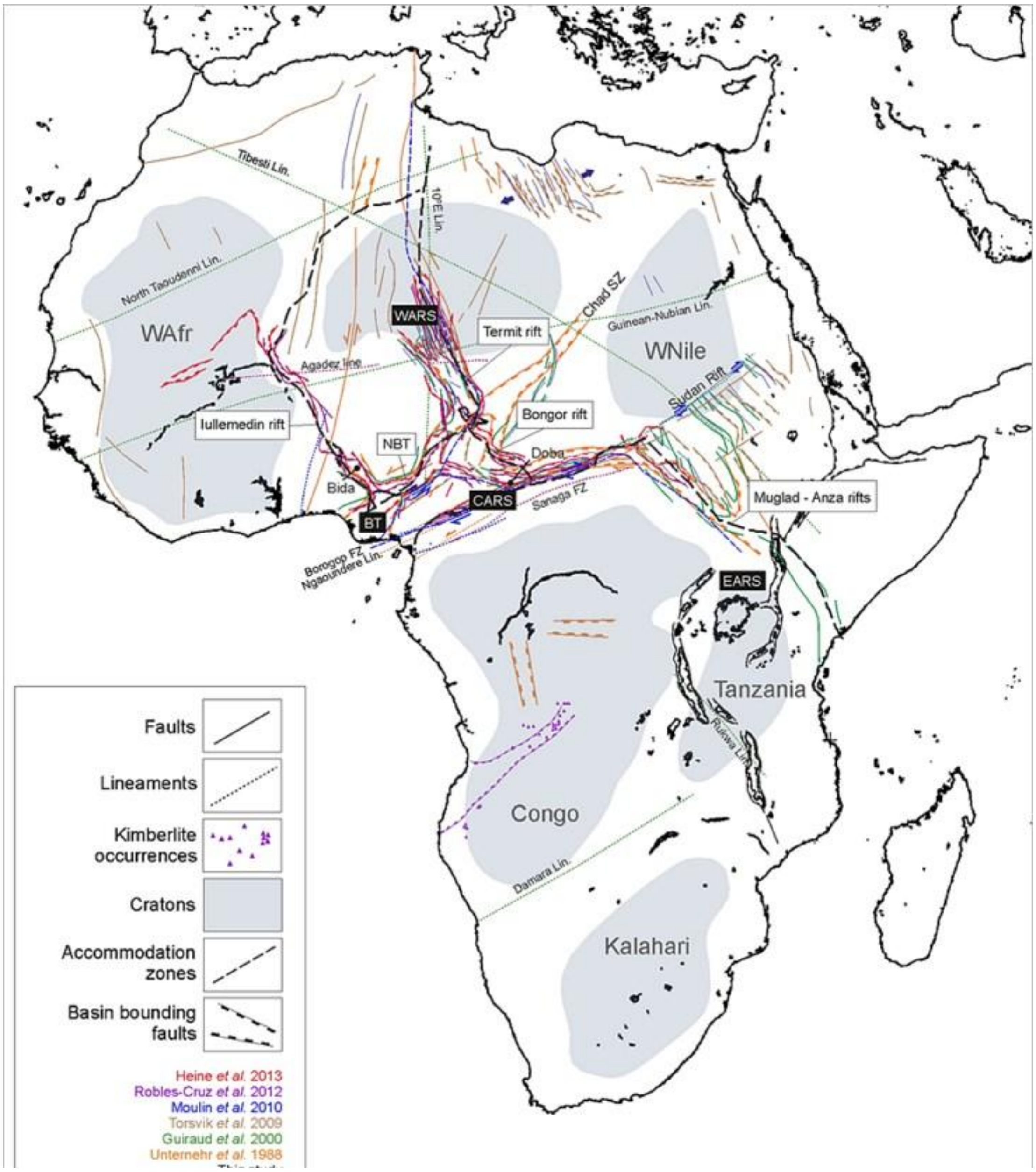


Figure 5: African map with the selected stress accommodation zones for the model in (a) Iullemeden rift (b) Termit-Bongor rift (c) Termit-Northern Benue Trough (d) Central African Shear Zone (CASZ)-Muglad- Anza rift (Pérez-Díaz and Eagles, 2014)

Structural style of the Nigeria Chad Basin

Studies in Nigeria Chad Basin revealed significant juxtaposition of faults, horst, graben, folds and unconformity surfaces. The structural orientation of the basin is mainly in the northeast-southwest trend which is parallel to the surface structural pattern in the contiguous Benue Trough. The faults in the basin consist of both basement-involved faults and detached faults. The folds are simple symmetrical structures, restricted to the deeper parts of the basin. Concomitant compressive structures are notably scarce. The structural pattern is complicated further by the presence of intrusions that were presumed to be the subsurface extension of volcanic outcrops that terminated in the Southeastern part of the Nigeria Chad Basin. The consequence of a dominantly active tensional stress is crustal stretching and thinning, development of fractures / high angle normal faults, graben / rift valley, horst, magmatic intrusion and eventually reverse faults. Avbovbo*et al.* (1986), had presented the stages of development of structural features in the Chad Basin based on rifting model (Figure 6). Seismic reflection data also reveal distinguishable seismic sequences that correlate with the established stratigraphic sequence of the basin. The apparent structure and the seismically derived stratigraphy suggest a rift origin for the basin. Furthermore, the seismic stratigraphy, sedimentologic implications, and seismically determined structural features suggest that the Nigeria Chad Basin might have good prospects for hydrocarbon plays in the Cretaceous rocks, with high potentials for both structural and stratigraphic traps (Okpikoro and Olorunniwo, 2010).

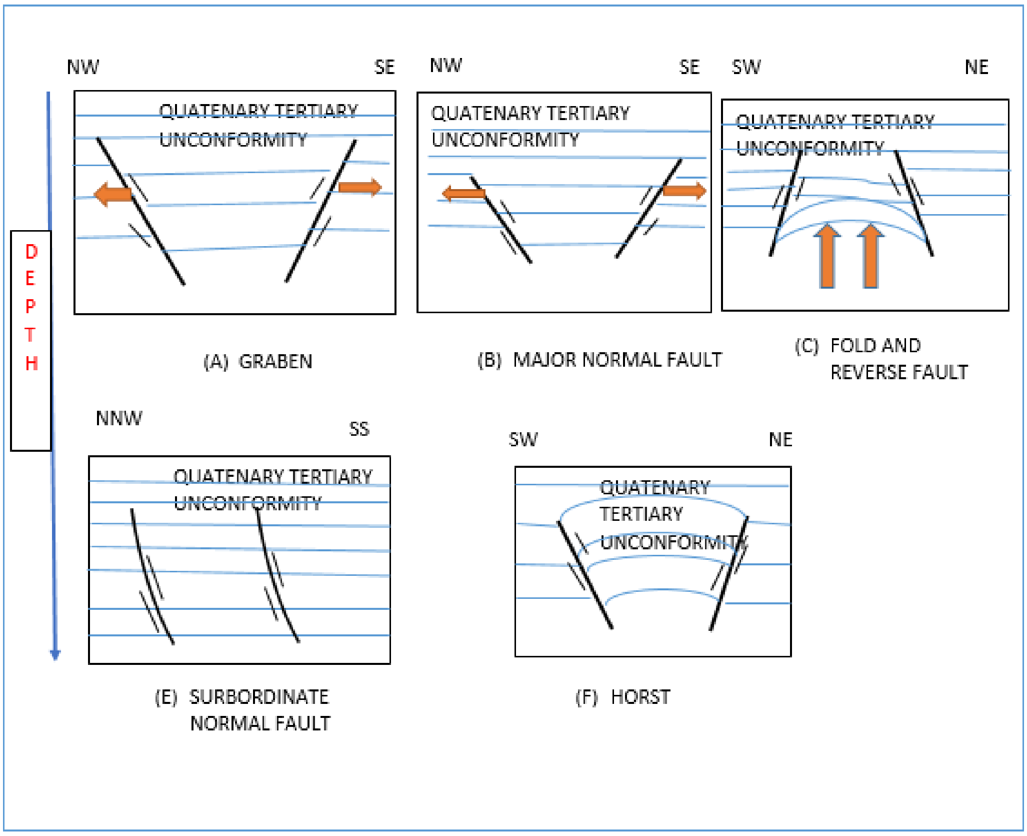


Figure 6: Structural style of the Nigeria Chad Basin (Avbovbo*et al.*, 1986).

II. Material and 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. This helps in the generation of the time and depth structural maps upon which fault modeling was done.

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 x 10 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 3.5). 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.

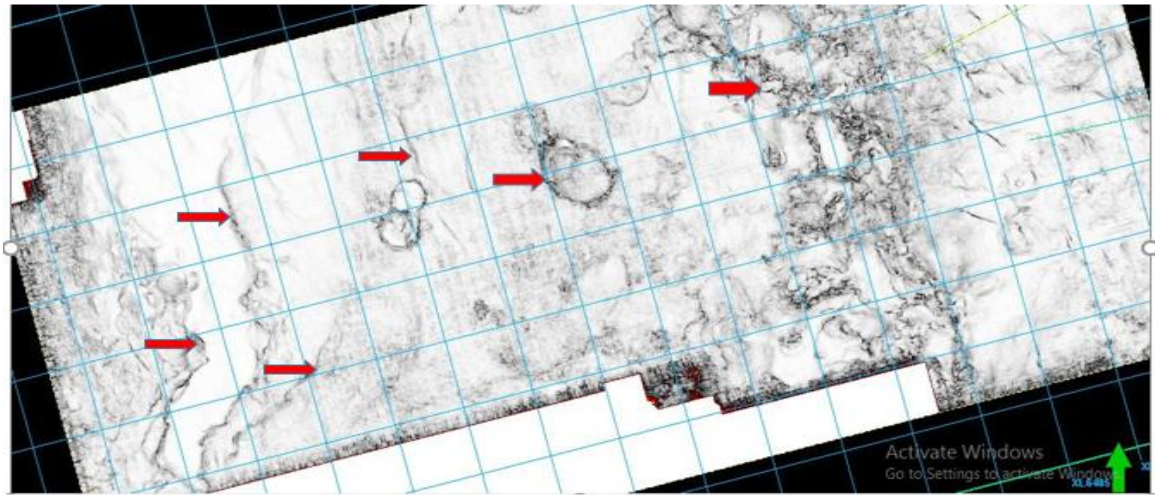


Figure 7: Display of Variance slice at 1476ms highlighting most of the faults. Red arrows indicate the faults

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 wascorrelated 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 horizon 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 pinchout 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 10 x 10line spacing, and 5 x 5line 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 checkshot to generate a lookup function by plotting Two-way-time (ms) against depth (m) (Figure 8). 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

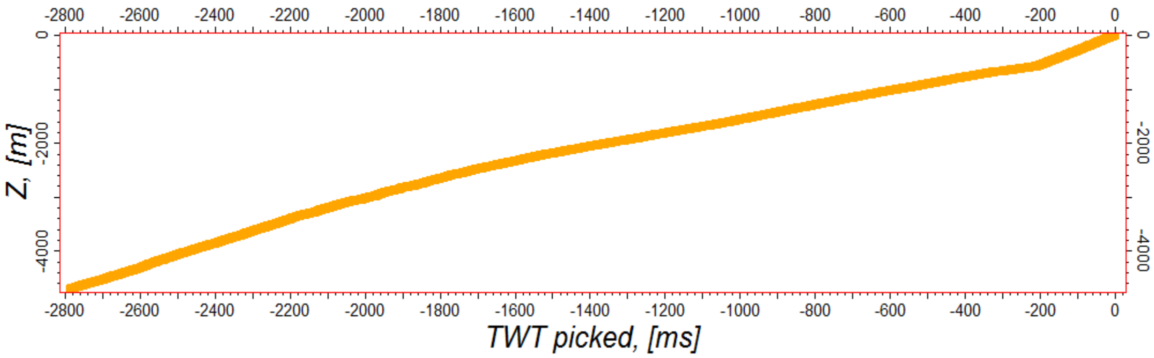


Figure 8: Lookup function plot of Z (m) vs TWT (ms) used for time-depth conversion

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 9a-c). 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).

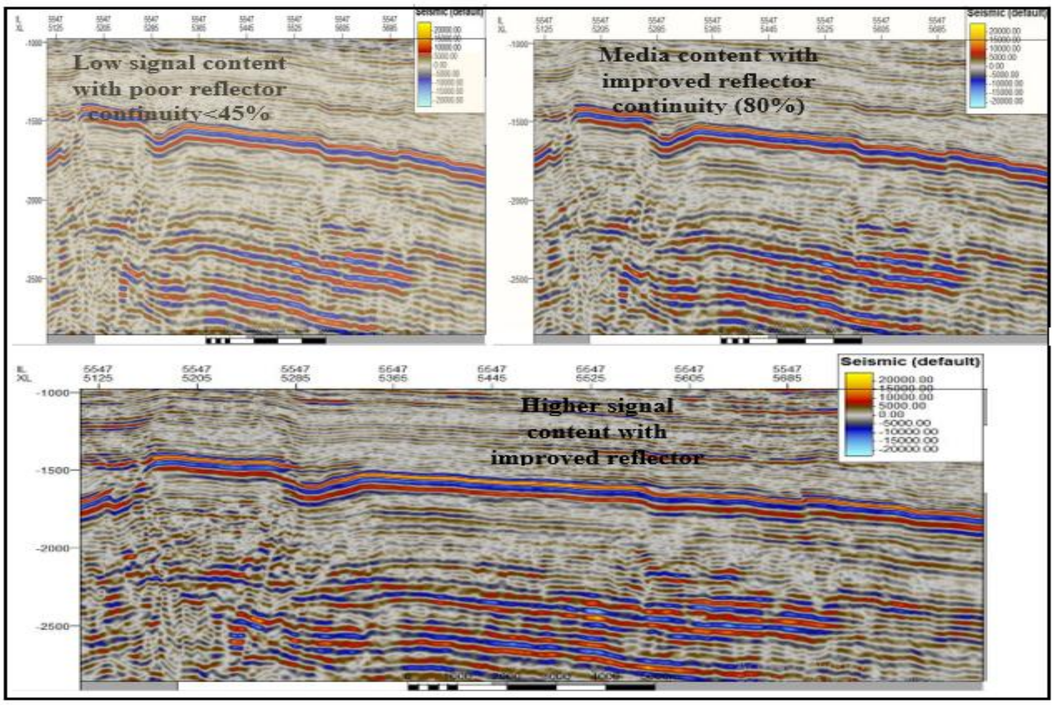


Figure 9: Display of seismic dip line 5547 showing (a) Original Seismic, (b) Media filter attributes (c) Structural smoothing.

III. Results and discussion

Tectonic structures

These are the structures formed as a result of tectonism such as fault, fold, intrusion, horst and graben. These structures were identified in the study area. The fault identified in this area are trending northeast - southwest direction and northwest - southeast direction. About twenty faults were mapped in the study area and are mainly normal and reverse faults. The normal faults are evidence of extensional tectonics whereas the reverse faults are evidence of compressional tectonics and inversion. The anticlinal fold identified at the west shows evidence of compressional tectonics. Horst and graben identified are shown with upward black and downward red arrow respectively. Igneous intrusions were identified within the areas of chaotic reflections and are evidence of both compressional and extensional tectonics (Figure 10).

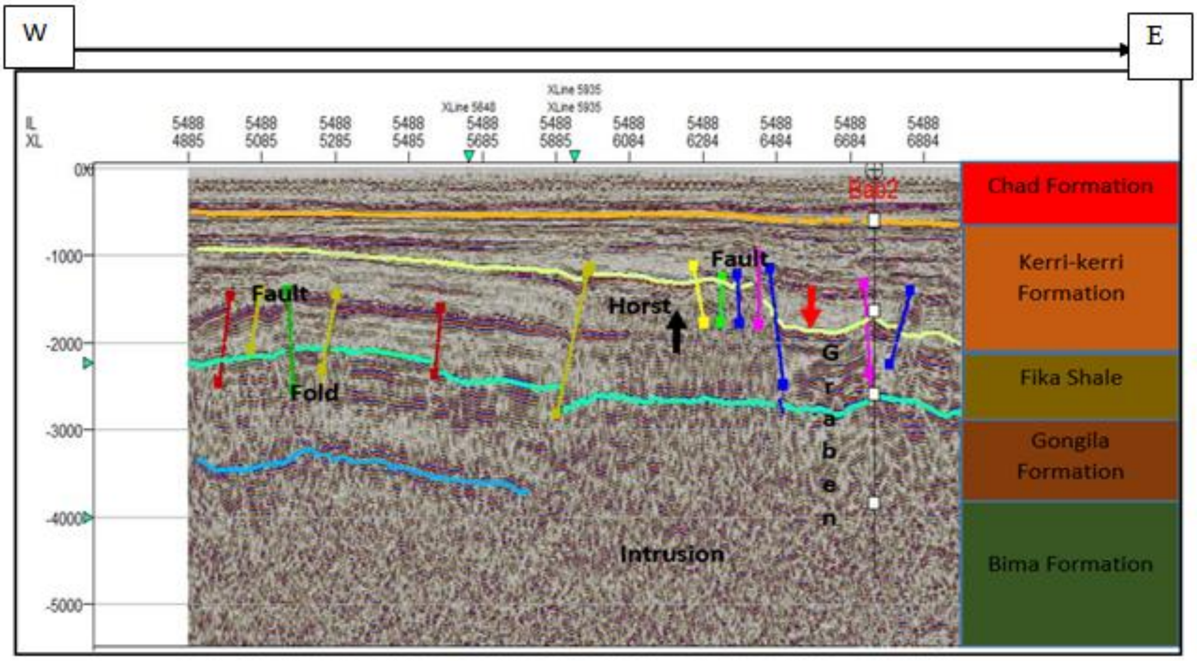


Figure 10: Tectonic structures across the horizon mapped at dip inline 5488

Non-tectonic structures

These are the structures that are not formed directly by the effect of tectonic activities and they are channels, unconformity, pinchout and sandbars. In this study only unconformity and pinchout were identified using the reflection geometry and the knowledge of the geology of the area. There is an unconformity surface between Bima Sandstone and the igneous rock, Gongila Formation and the igneous intrusion which is known as nonconformity. Moreover, another period of non-deposition occurred between Kerri-kerri Formation and Gongila Formation because another formation known as Gombe Sandstone is missing in between the two formations. Pinchout have been identified in kerri Kerri Formation and Fika Shale (Figure 11). The summary of tectonic and non-tectonic structures identified across each formation are in Table 2

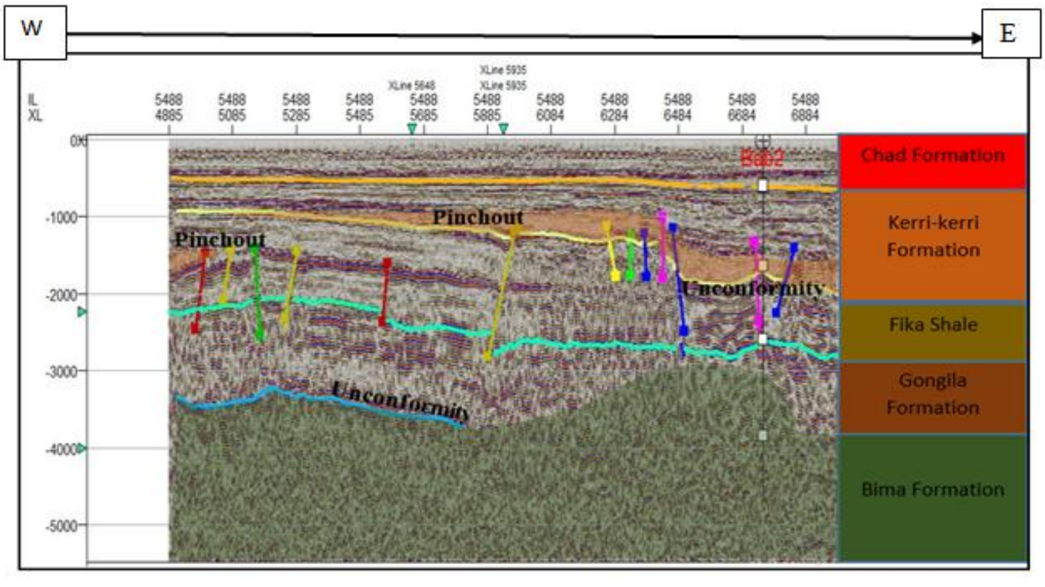


Figure 11: Non-tectonic structures across the horizon mapped at dip inline 5488

Fault modelling

Fault modelling was done in order to visualize the faults geometry within the study area. There are down to basement faults within the study area, such as fault (F8) and fault (F9), trending in opposite directions to each other (Figure 12). The geometry of the faults was modelled in x and y plane, that is two dimensional view (Figure 13) and as well as in x, y, and z plane, that is three dimensional view (Figure 14) in order to ascertain the shapes of the faults in both planes as shown in 2D and 3D window respectively. The trend of the faults was automatically generated with petrel tool called Stereonet, and the results showed that the faults are trending Northeast -Southwest direction, Northwest-Southeast direction, north, north, west to south, south, east directions (NNW-SSE)(Figure 15)

Table 2: Tectonic and non-tectonic structures found in each station at inline 5488

Time (ms)	**Formation**	**Tectonic structures**	**Non-tectonic structures**
0-500	Chad	None	Parallel beddings
500-900	Kerri-Kerri	Fault, horst, and graben	Sub parallel bedding pinchout and unconformity
900-2200	Fika	Fault	Sub parallel bedding pinchout and unconformity
2200-3300	Gongila	Fault, fold, and igneous intrusion	Sub parallel beddings
3300-5500	Bima	Igneous intrusion	None

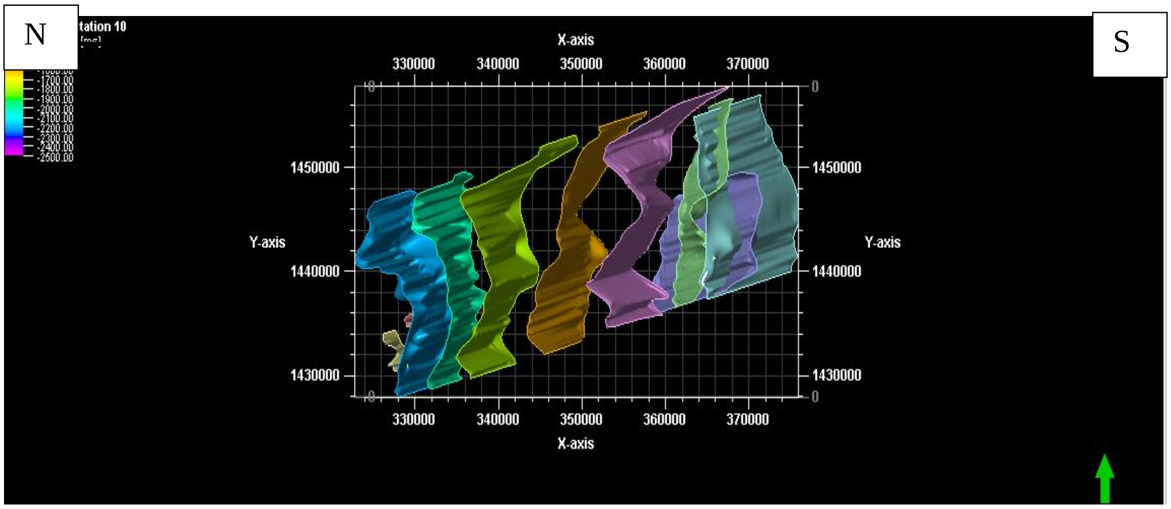


Figure 12: Fault model in 2D window

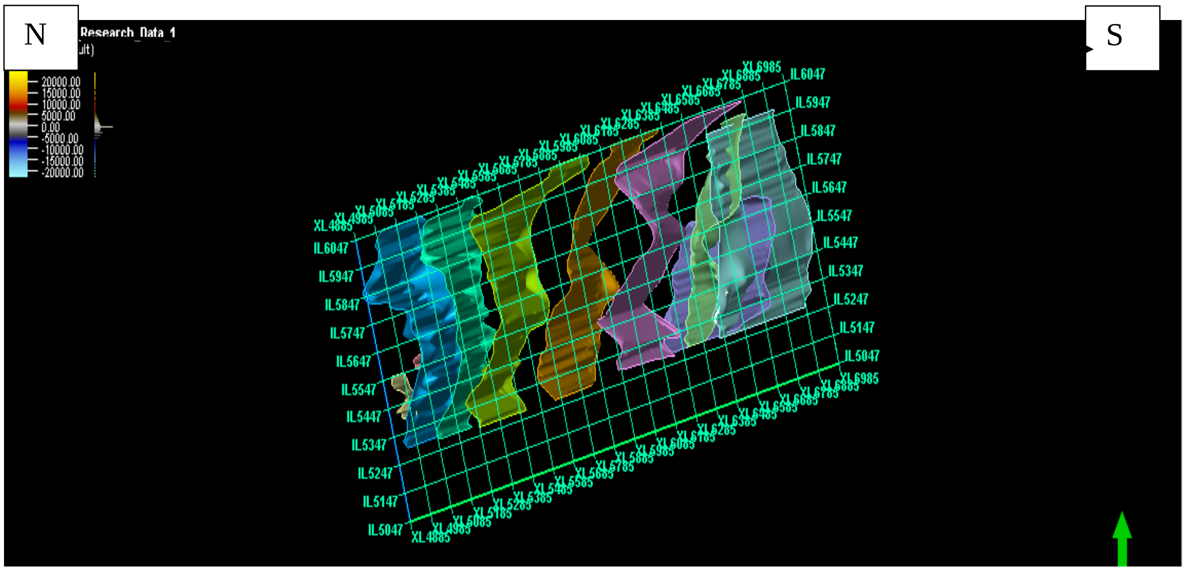


Figure 13: Fault model in 3D window

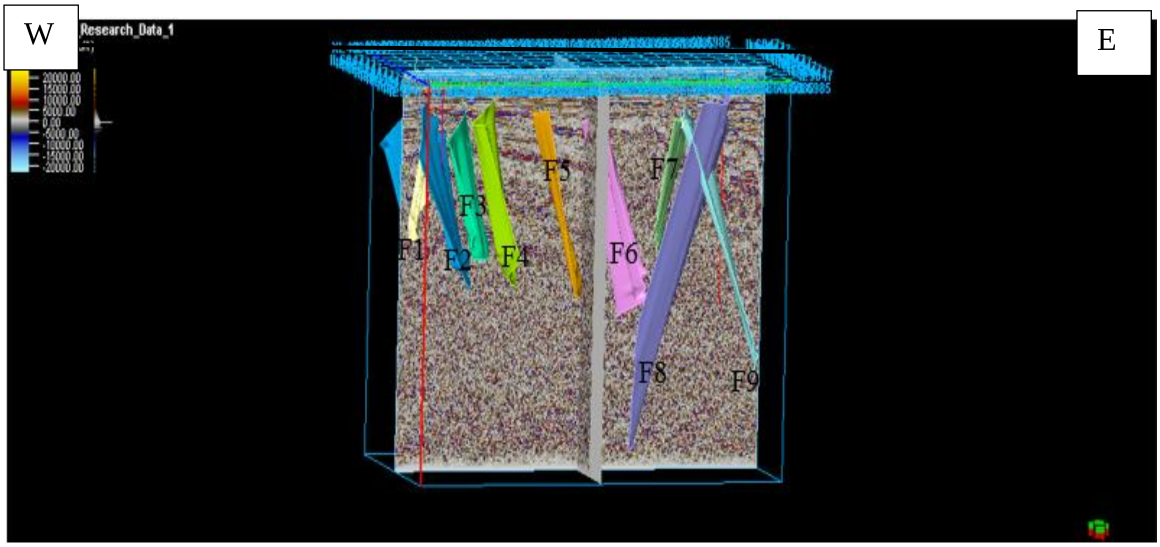


Figure 14: Fault model across the seismic volume in 3D window, inline 5507 and crossline 5935.

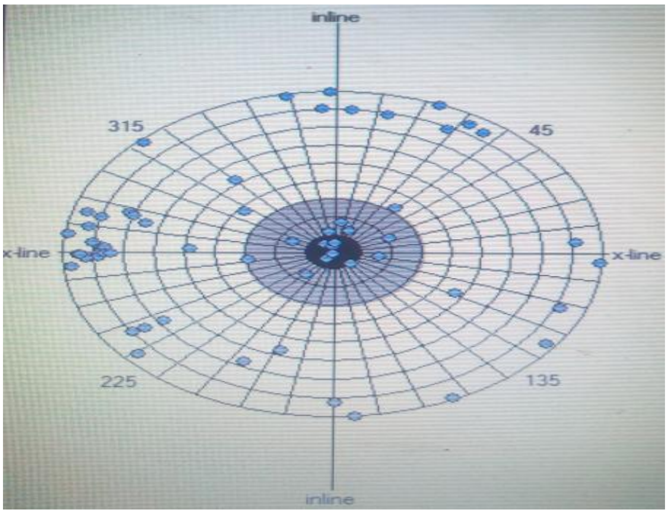


Figure 15: Stereonet diagram of the faults. (The triangular dots show the location of the faults)

Structure contour maps

The structure contour maps of the interpreted surfaces are presented in Figures 16a-d to 17a-d for both the time and depth structural maps. The maps exhibit both structural highs and lows, with the highs concentrated mostly towards the western partof the maps. Series of faults occur within the generated surfaces which form horst and graben. The faults are denoted by the black lines and black dots, while the wells are represented with circular plus sign. Surfaces were generated for the formations of interest which are Gongila Formation surface, Fika Shale surface, kerri-kerri Formation surface, and Chad Formationsurface.

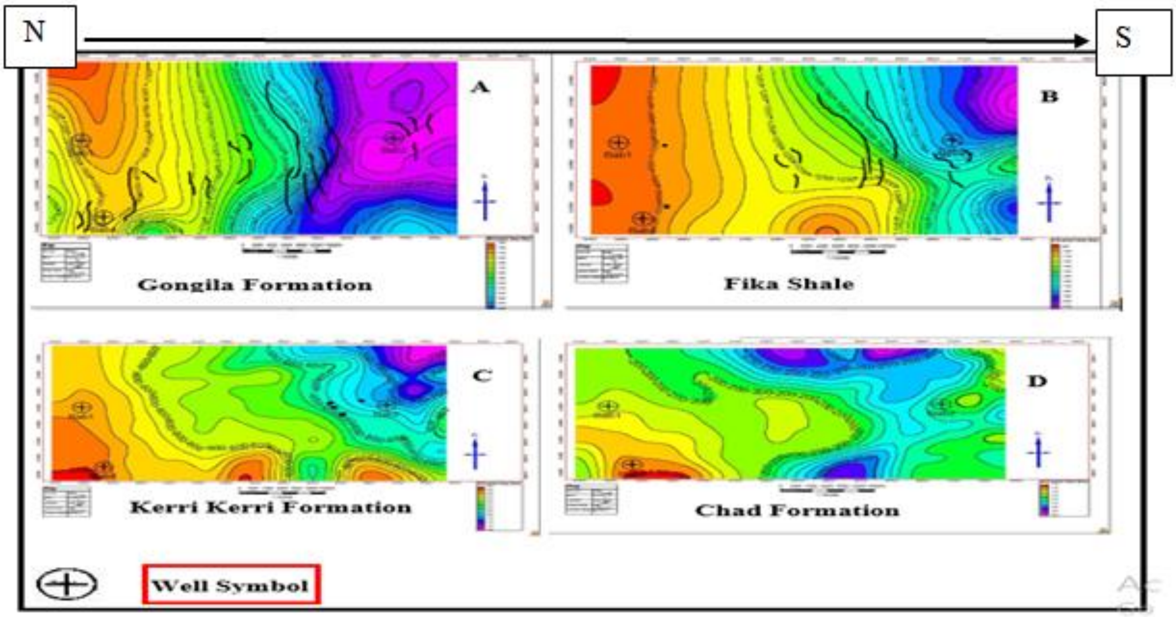


Figure 16: Time surface maps generated for the study area (a) Gongila Formation, (b) Fika Shale, (c) Kerri Kerri Formation, and (d) Chad Formation

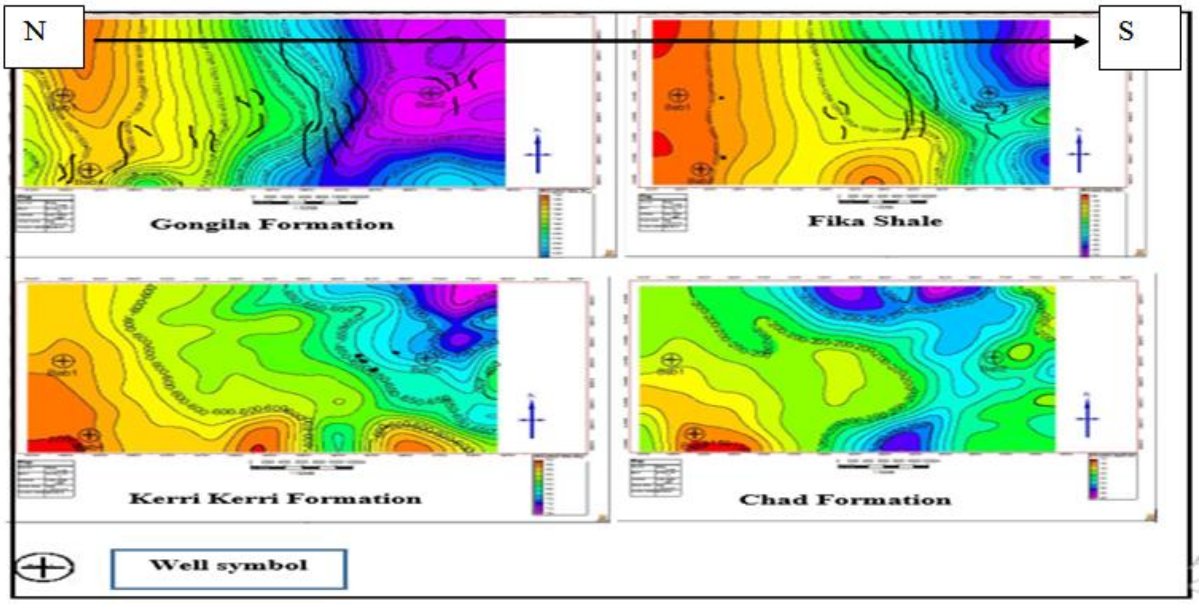


Figure 17: Depth surface maps generated for the study area (a) Gongila Formation, (b) Fika Shale, (c) Kerri Kerri Formation, and (d) Chad Formation

IV. Conclusion

Nigeria Chad Basin has petroleum system elements such as seal, trap, reservoir, trap and migration pathways that could the easiest exploration of hydrocarbon within the study area. The serious tectonic events suggested that the basin has a lot igneous structures that could act as seal to hydrocarbon migration. The reverse faults and folds are obvious evidence of compressional regime, while normal faults, horst, and graben indicated the evidence of extension tectonic regimes within the study area.

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