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DETERMINATION AND DISTRIBUTION OF FORMATIONS THICKNESS IN BAGA/LAKE SUB-BASIN USING SEISMIC IMAGING AND WELL DATA, CHAD BASIN NIGERIA

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ABSTRACT

The Borno Basin is located in North-Eastern Nigeria, formed in the Early Cretaceous. Deposition of sediments in the basin occurred during rifting. The sediments are mainly lacustrine shales and sandstones. This work was undertaken by the integration of 3D seismic interpretations and the well data analysis of eight wells fairly distributed in the study area to determine the thickness of the formations within the sub-basin. Da-1 well used in this study was subdivided into stratigraphic units based on the regional stratigraphic subdivision of the Chad basin and was later correlated with other wells using the similarity of observed log responses. Density and sonic logs were used to generate synthetic seismograms for seismic to well ties. Five horizons were interpreted, representing the tops of the formations on the 3D seismic data covering the block, average velocity function with a maximum residual of 0.48% was used for the time to depth conversion in all the generated maps. There is a general thickening of sediments from the west to the east and the estimated thicknesses of the various Formations in the Baga/Lake sub-basin are; Chad (400-750 m), Kerri-Kerri (300-1200 m), Fika (300-1000 m) and Gongila (100-1300 m). The thickness of the Bima Formation could not be established because the deepest well terminates within the Formation. This is a modification to the previous and widely referenced studies of over fifty decades that based the estimation of formation thickness within the study area on the observed outcrops and the use of a few water boreholes.
***Keyword**: Baga/Lake sub-basin, Chad basin. Formation Thickness, Seismic, Velocity*

INTRODUCTION

The importance of hydrocarbon to the world economy and the need to increase reserves necessitate the Nigeria National Petroleum Corporation to pay more attention to the frontier basins in Nigeria of which the Borno basin is one. The Chad basin is believed to be a botched arm of the triple-junction rift system in the early Cretaceous leading to the opening of the South Atlantic and a subsequent parting of the South American and African continents (Burke *et al*. 1970, Ola *et al*., 2017). During the opening of south Atlantic and regional NE-SW extension, the NNW-SSE-oriented extensional basins developed extensively in two systems in western Africa (e.g. Niger) and in east-central Africa (e.g. Sudan). This was connected by the Central Africa Shear Zone dextral fault system and associated trans-tensional basins in central Africa (Figure 1) (Genik 1993, Yassin *et al*., 2017). Borno Basin is the North-Eastern extension of the Benue Trough, with a general NE-SW trend orientation. It is made up of three sub-basins namely Gubio and Maiduguri, in the southwest, and Baga/Lake, in the northeast of the Borno basin. The SW sub-basins are also called Upper Benue Trough while the northeastern sub-basin corresponds to the South Western flank of the Termit-Agadem basins located in Niger and Chad (Figure 1). This research was conducted using 3D seismic data and well logs within Baga/Lake sub-basin. 3D seismic is an important geophysical tool used to interpret the subsurface geology, the quality of the result is unmatched when integrated with closely or sparsely spaced well data in an area. The tool is very effective for both exploration of frontier basins and the development of brownfields such as mature oil-producing assets. Some studies conducted in the Chad basin by various researchers to aid the understanding of the basin include formation thickness (Carter et al 1963, Olugbemiro et al. 1997), source rock evaluation (Alalade & Tyson 2010: Johnson *et al*., 2014: Ola *et al*., 2017: Suleiman *et al*., 2017: Adedosu & Ogungbesan 2018), petrophysical evaluation (Adepelumi et al., 2010), structural style (Avbovbo *et al*., 1986: Okosun 1995: Nwankwo *et al*., 2012), lithological and palynological studies (Ola-Buraima & Abdulganiyu 2017), aeromagnetic study (Awoyemi *et al*., 1992). This paper outlines the results of 3-D seismic interpretation constrained with well data with major objectives of (i) interpreting the 3-D seismic cube covering an area of approximately 3891 square kilometers, (ii) interpreting the well-logs within the seismic cube, (3) performed seismic to well tie/synthetic seismogram generation, (iv) developed robust velocity model and (v) generating the subsurface maps of Chad, Kerri-Kerri, Fika and Gongila Formations (i.e. time, velocity, depth, isochron, and isopach) to accurately estimate the thickness of the formations.

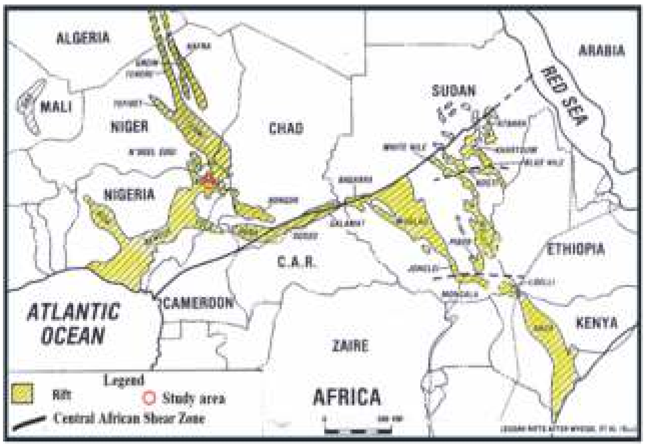

Figure 1: Location map of the research area (After: Genik 1993)

2.0 Geology of the study area

Block A is located in the Baga/Lake sub-basin within the Borno basin (Figure 2). The asset is fairly developed with eight wells drilled, from which five wells are within the valid seismic cube. The asset exhibits a typical example of structure and stratigraphy development observed in the Borno basin. The six Formations present are the Chad Formation (comprises of sandstones and clay sequence) which overlies the Kerri-Kerri Formation (grits, sandstones, and clays sequence) which unconformably overlies the Fika Formation (mainly marine shale inter-fingering with sandstones and limestone) which overlies the Gongila Formation (sequence of alternating sandstones and shale with fossiliferous limestone beds) which overlies the Bima Formation (mainly continental sandstones) and the basal Pre-Bima Formation is the oldest sediments in the basin which overlies unconformably on the crystalline basement, this formation is subdivided into upper, middle and lower Bima sandstone. It is made up of alternation of coarse-sandstones, fine-grained sandstones, calcareous sandstones interbedded with clays (Adegoke *et al*., 1986, Guiraud 1990, Genik 1992, Genik, 1993, Okosu 1995, Olugbenro, *et al*., 1997, Onuoha, 1999, Obaje, *et al*., 2004, Moumouni *et al*., 2007, Adepelumi *et al*., 2011; Adekoya *et al*., 2014, Ola *et al*., 2017) (Figure 3).

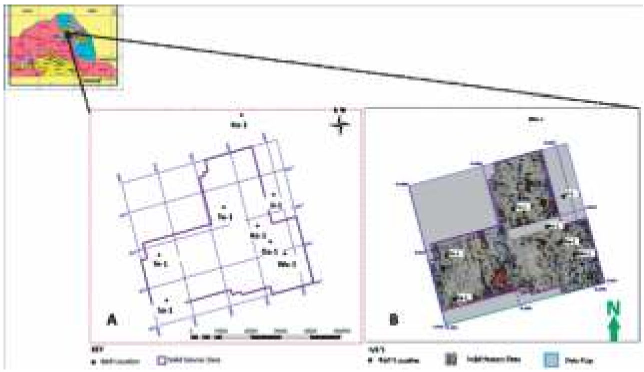

Figure 2: (a) 3D Seismic survey base map of the study area (b) 3D Seismic survey base map showing data gaps within the grid.

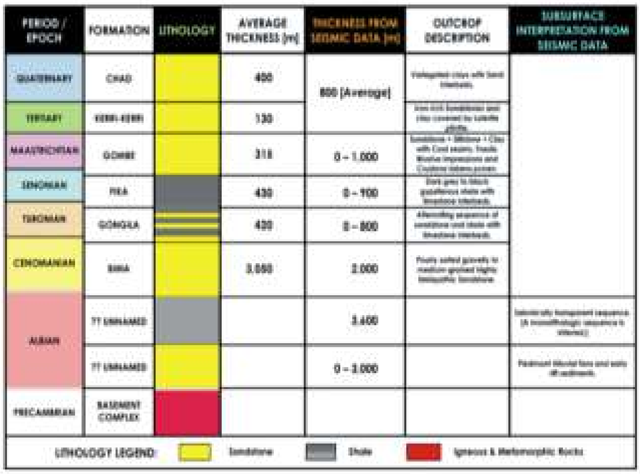

Figure 3:Generalized stratigraphic cross-section of Borno basin, N-E Nigeria (Carter *et al*., 1963; modified by Avobvo *et al*., 1986).

3.0 Materials and methods of study

Materials

The data used for this study comprises 3891 square kilometers of 3D Seismic volume with inline and crossline in the range of 5047 to 6047 and 4885 to 7020 respectively and a bin size of 25 m between the lines, well information for 8 wells including deviation profile, well logs in Las format, Check shot data for 8 wells, *viz:* Ka-1, Wa-1, Da-1, Te-1, Tu-1, Ku-1, Ji-1 and Sa-1, and the biostratigraphy summary report for Ak-1, Ga-1, Wa-1, Da-1 & Ye-1 wells. Figure 2 is the base map for the study area showing 3D seismic data coverage and well locations.

Methods of study

Well Correlation was done in three phases. First, the deepest well (Da-1 @ 4760.9 m TVDss) was chosen as type-well for the correlation, this is because the well encountered more stratigraphic section across the area and would best fit for correlating other wells (Figure 4). Thereafter, the well was sub-divided into stratigraphic units based on the regional stratigraphic sub-division of the Chad Basin described by

Carter *et al*., 1963 and modified by Avobvo *et al*., 1986 which sub-divided the section into the genetic composition of stratigraphic layers as seen from outcrops. Finally, the stratigraphic subdivision of the Type-well was then extended to other wells using the similarity of observed log responses (Figure 5).

Seismic-well-tie, out of the eight check-shot data available for this study, six wells with necessary curves (density and sonic logs) were used in generating synthetic seismograms as a way of initiating the seismic to well tie. First, a sonic data calibration with respect to available check-shot was employed as a quality control method for data consistency and check for invalid velocity information. It was observed that velocity information followed expected trends, with no abnormal velocity variation. Then a reflectivity co-efficient log was generated and convolved with a synthetic wavelet to obtain a synthetic seismogram for each well. The synthetic seismogram was then compared with a set of traces around the wellbore and the degree of correlation was examined (Figure 6). No bulk time shift was applied in any of the wells to avoid distorting the velocity information as validated from the initial check-shot data. The seismic to well tie process for Ka-1, Ku-1, and Ji-1 wells was skipped as they lie within a data gap (blank seismic) region of the 3D seismic data. For wells without Check-shot information, Check-shot data from nearby well was shared to place the wells within the time domain only. No seismic to well tie process was carried out for such wells.

Fault and Horizon Interpretations - Fault plane indications as observed on seismic lines were mapped and subsequently grouped based on similar deformation direction and geometry. Both normal and reverse fault patterns were identified within the area of the survey. Horizon interpretation was carried out by extrapolating well information to seismic data using the established cross-sections used for validating the seismic to well tie process. A 20x20 lines interpretation grid was used for mapping the top of the formations within the 3D seismic survey area. The top of five Formations namely Chad, Kerri-Kerri, Fika, Gongila, and Bima were interpreted with a high degree of reliability as they show fairly good reflections on the seismic data. The seismic data set was interpreted as an 8-bit zero-phase reflectivity according to the normal Society of Exploration Geophysicists (SEG) polarity.

Time to depth conversion – average velocity function was adopted and the process involves the generation of average velocity maps for each individual interpreted horizon after the seismic-well tie process. The average maps are obtained from a simple grid of average velocity values calculated at well locations based on the time-depth relationship (TDR) of time grids (in time) and related well tops (in-depth). Thereafter, a depth map for a corresponding time grid is obtained by simple multiplication with average velocity maps generated across the area of interest. The initial depth maps obtained from this process are finally flexed to well data and residuals obtained are documented.

4.0 Results

A total of four well correlations were generated in this study, viz: X-section along Te-1 and Sa-wells, X-section along Te-1, Tu-1 and Ji-1 wells, X-section along Tu-1, Ka-1, Da-1, and Wa-1 wells, and X-section along Sa-1 and Wa-1 wells. Figure 4 is a type-well (Da-1) generated for this study based on the regional stratigraphic subdivision defined by Carter *et al*., 1963 and modified by Avobvo *et al*., 1986. Figure 5 is a sample section of the final well correlation views across the asset. Figure 6 shows the sonic log to check-shot data calibration and the synthetic seismogram of the Da-1 well. Validating the consistency of both well correlation and seismic-well-tie processes, arbitrary seismic-well tie lines in different directions were selected and quality checked.

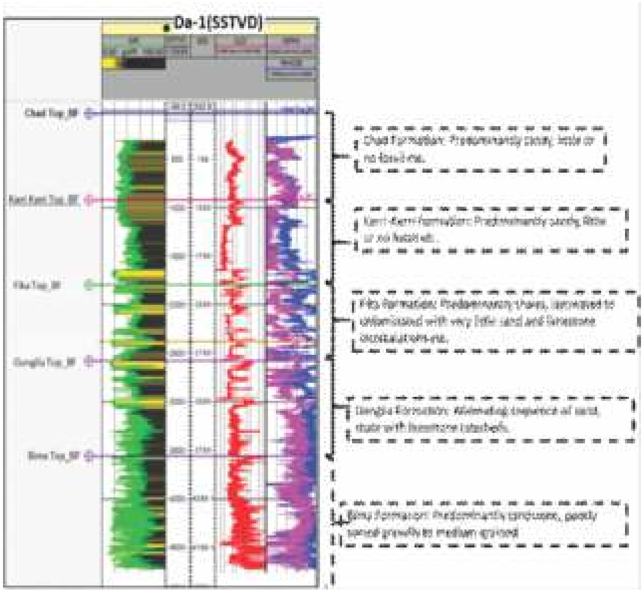

Figure 4: Regional Stratigraphic (Type-well) subdivision of Da-1 well

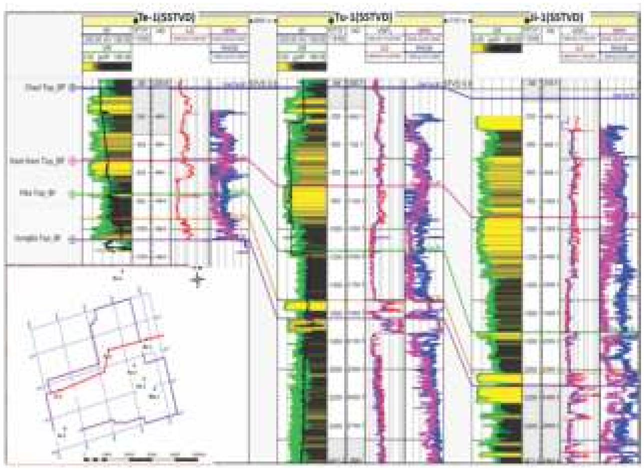

Figure 5a: Structural well correlation X-section along Te-1, Tu-1 and Ji-1 wells

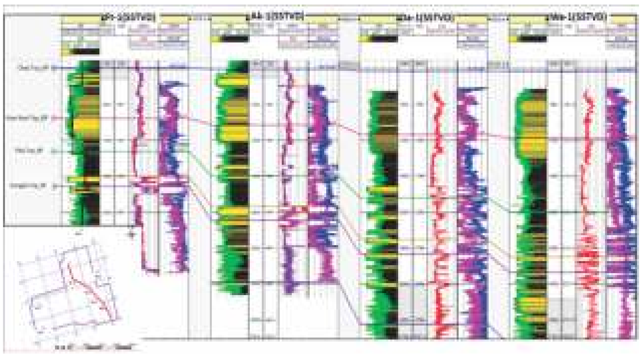

Figure 5b: Structural well correlation X-section along Tu-1, Ka-1, Da-1 and Wa-1 wells

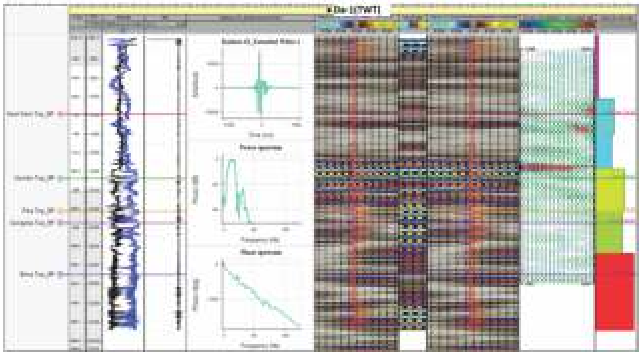

Figure 6: Synthetic seismogram generation and seismic to well tie process panel for Da-1 well

5.0 Discussions

Mapping

Fault deformation planes were mostly linear in nature, of short-range, and only in few cases do they extend to the near-surface layers. They were thus deduced to be mostly stress-relieving faults and less likely to be due to depositional/deformational in nature (Mencos *et al*., 2015). Figure 7 shows the fault and horizon interpretation across some lines chosen within the 3D volume.

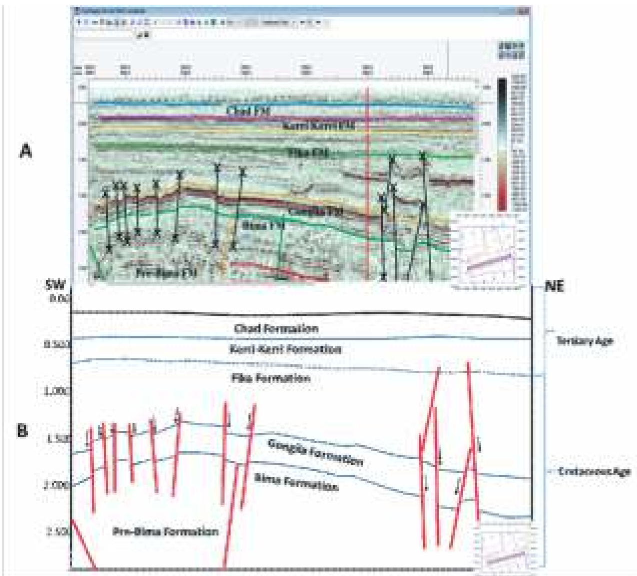

Figure 7: NE-SW seismic section (A) and its interpreted geologic equivalence (B)

Time and depth structure maps

For Chad and Kerri-Kerri Formations top time and depth structure maps, there is a general increase in TWT from the southwestern portion of the research area to the eastern part with the shallowest point (crest) at Sa-1 well and the lowest point (deepest part) at the Wa-1 and Da-1 wells in the southeastern part of the study area. The presence of faulted anticlinal structure with four-way dip inferred closure located in the stratigraphically high setting in the southwestern portion of the research area could be seen in Fika, Gongila, and Bima Formations top time and depth structure maps. The crest of the anticline was observed around Te-1 and Sa-1 wells at the southwestern part of the study area while the deepest part could be seen at the Wa-1 well (Figures 8a and 9a). The crest beneath Te-1 and Sa-1 area could be due to the regional uplift of sediment during Santonian deformation (Okosun, 1995).

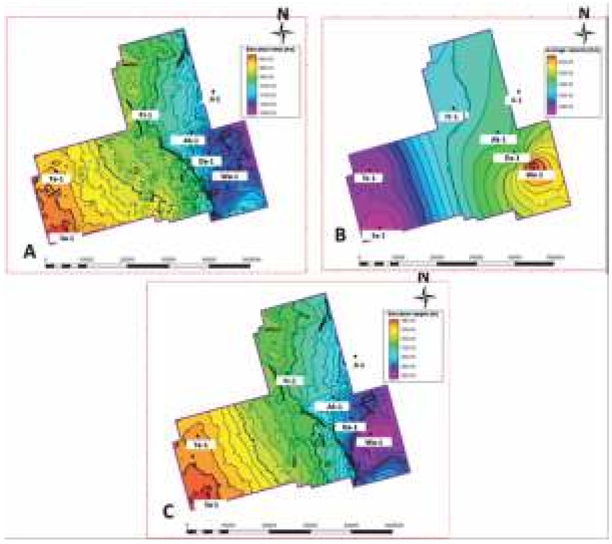

Figure 8: (A) Time structure map of top of Kerri-Kerri Fm. (B)Average velocity map (C) Depth structure map.

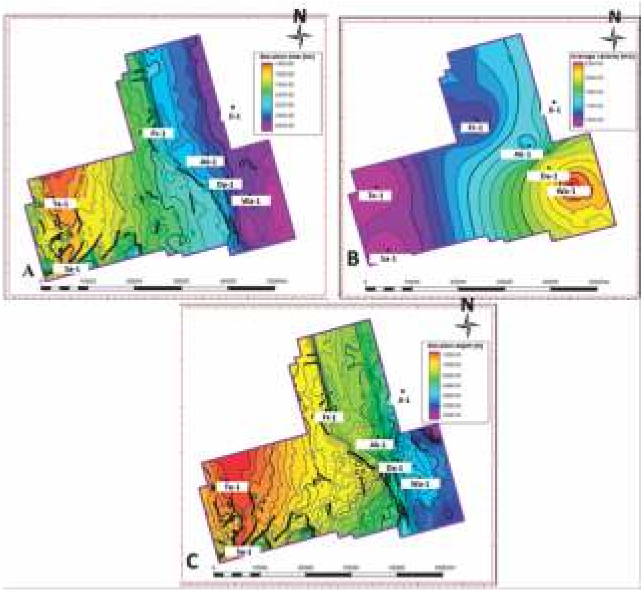

Figure 9: (A) Time structure map of top of Gongila Fm. (B) Average velocity map (C) Depth structure map using Average Velocity function.

Average velocity maps

A total of five average velocity maps were generated representing the tops of each formation. In general, there is an increase in average velocity from the west to the east in the five maps. For the velocity map of the top of Kerri-Kerri Formation, the least average velocity of 1240 m/s was observed around Te-1 and Sa-1 wells at the southwestern section and there is a gradual increase towards the east and peaked at about 1640 m/s near Wa-1 well at the southeastern part of the block (Figure 8b). The Gongila average velocity map also follows the same velocity pattern with an average velocity of about 1560 m/s at the southwestern part and about 2240 m/s at the southeastern part of the block (Figure 9b). The average residual value obtained after depth conversion increases from -0.12 m at Kerri-Kerri Formation top to 1.45 m at Gongila Formation top (Table 1).

Table 1: Residual values obtained after flexing of average velocity analytical function: (A) Kerri-Kerri Top Formation (B) Gongila Top Formation.

Well	Measure Depth	Z-value	Horizon before	Error	Horizon after	% Error
Da-001	11.43.99	-854.97	-916.73	1.24	-854.97	-0.15
Ft-001	999.09	-692.37	-693.72	1.35	-692.37	-0.19
Ak-001	1089.17	-782.46	-782.93	0.47	-782.46	-0.06
Sa-001	768.84	-470.53	-472.02	1.5	-470.53	-0.32
Wa-001	1262.16	-970.34	-965.69	-4.65	-970.34	0.48
Te-001	812.14	-515.53	-515.5	-0.03	-515.53	0.01

A

Well	Measure Depth	Z-value	Horizon before	Error	Horizon after	% Error
Da-001	1942.17	-1635.44	-1634.63	-0.81	-1635.44	0.05
Ft-001	1373.78	1077.15	-1077.78	0.62	-1077.15	-0.06
Ak-001	2414.55	-2107.82	-2107.75	-0.07	-2107.82	0.00
Sa-001	1429.69	-1131.36	-1132.62	1.26	-1131.36	-0.11
Wa-001	2868.63	-2579.60	-2581.05	1.45	-2579.60	-0.06
Te-001	3129.53	-2837.69	-2836.69	-1	-2837.69	0.04

B

Formation Thickness

The predominant source of sediments deposited in the depocenters is believed to be from the west to the eastern parts of the sub-basin. Due to paleo-geomorphologic imprints, strata thicknesses vary from west to east, with thicker sections in the latter segment of the basin (Figure 10). Each depocentre is considered a distinct entity with similar age, sedimentation, and structural development. The orientation of the structural high observed in Gongila and Bima Formations is approximately north-south separated by faults with the highest point located at the southwestern portion of the research area. The high could be associated with the development of structural uplift that is tectonic in origin or is associated with deep-seated high-pressure soft shale, which later in the geologic history, pushed up the overlying shallower strata in the process.

Most researchers in the study area referenced the work of Carter *et al*. (1963) on the thickness of Chad, Kerri-Kerri, Gombe, Fika, Gongila, and Bima Formations. Notable ones are Avbovbo *et al*. (1986) that referenced the formation thicknesses in full while Olugbemiro *et al*. (1997) referenced part of the work and deduced other thicknesses such as Fika, Gongila, and Bima Formations from the lithostratigraphic study of Kanadi-1 and Al Barka-1 wells. It is worthy to note that Carter *et al*. (1963) based their findings on the study of outcrops and boreholes at various localities within the basin such as Bima Formation at Larmurde anticline, Gongila Formation at Gongila village, Fika Formation at Damagun village, Gombe Formation at Kware stream in Gombe and Kerri-Kerri Formation near Kerri-Kerri plateau. This research highlighted the methodology and the variation in the thicknesses of these formations.

In general, sediment thickness varies for individual levels in the study area with an overall thickening in the NE (west of Ji-1 well) and southeast section (Ka-1, Da-1, and Wa-1 wells) of the Baga/Lake sub-basin. The sediment thickness of each of the Formations is documented thus: Chad Formation varies from 400 m in the west (Sa-1 well) to about 750 m in the southeast around Wa-1 well (Figure 10). The thickness of the Kerri-Kerri Formation varies from 300 m in the west around Te-1 and Sa-1 wells to 1200 m northeast of the Da-1 well at the southeast of the study area. Fika and Gongila also exhibited the same trend with thickness vary between 300–1000 m and 100-1300 m respectively (Table 2). The thickness of the Bima Formation could not be established because all the deep wells terminate within the Formation.

Table 2 The Formation Thickness estimated for Baga/Lake sub-basin

Interpreted Levels	Sediment Thickness Range (m)	Sediment Thickness Range (m)
Chad Formation	400 - 750	575
Kerri-Kerri Formation	300 - 1200	750
Fika Formation	300 - 1000	650
Gonjila Formation	100 – 1300	700
Bima Formation	2000	3050
	(Carter et al 1963)	(Carter et al 1963)

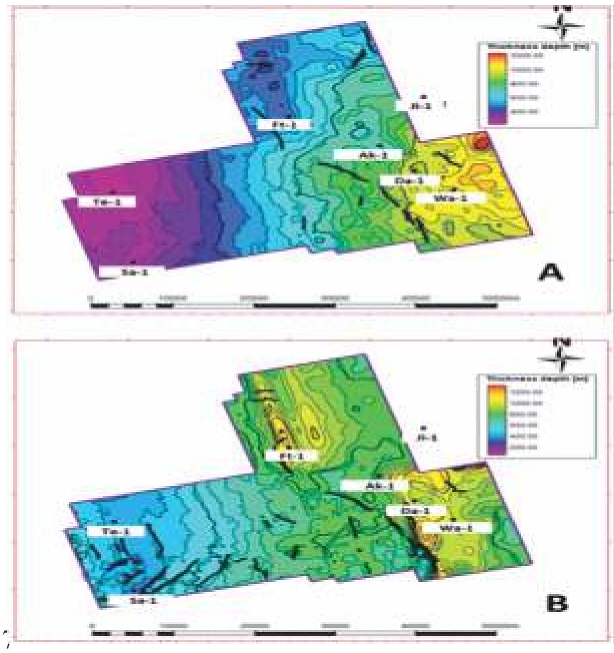

Figure 10: Isopach maps in Baga/Lake sub-basin: (A) Kerri-Kerri Formation (B) Gongila Formation

6.0 Conclusion

Borno basin in the southeastern part of the Mega Chad basin is understood to be the failed arm of the triple-junction rift system (Burke 1976, Genik 1993; Avbobvo *et al*., 1986). This study was conducted using 3D seismic and well data within the Baga/Lake sub-basin of the Borno basin. The fault distortion planes are short-range and are mostly linear and generally limited to the Early Cretaceous sediments below the unconformity that separates them from Tertiary formations above. It could be postulated that the faults are mostly stress relieve related that could be due to depositional/deformational in nature. This study revealed variation in the chunkiness of each of the formations with general strata thickness increase from west to east within the sub-basin. Using average velocity function for time-depth conversion the following thickness of Formations were estimated thus: Chad Formation (400-750 m), Kerri-Kerri Formation (300-1200 m), Fika Formation (300-1000 m), and Gongila Formation (100-1300 m). Compered the result above with those obtained from other workers who have worked within the basin shows that the formations (Chad, Kerri-Kerri, Fika, and Gongila) evaluated are thicker in Baga/Lake sub-basin than formally reported by the previous researches that based their study on based on field mapping of outcrops and water boreholes, the result of this research is a modification to the widely referenced study by carter *et al*., 1963 and other workers.

7.0 Acknowledgment

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