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Interpretation of Airborne Radiometric data for possible hydrocarbon presence over Bornu basin and its environs, Northeast Nigeria using Thorium normalisation method

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Abstract

A new exploration technique called Thorium Normalisation Method has been applied on the airborne radiometric data of the Bornu basin and its environs to delineate favourable zones for hydrocarbon accumulations within the study area. This method is significant because it indicates the probable presence of hydrocarbon in a sedimentary basin. Separation of the radiospectrometric measurements over each lithologic unit and the estimation of the characteristic statistics of these units were carried out. The statistical treatment applied on the radioelements (K, eTh and eU) of the study area shows a relatively low coefficient of variability (CV%) value for K, eTh and eU signifying their high degree of homogeneity. The mean value of the radioelements (K ranging from 0.6 to 2.0 %; Th ranging from 9.6 to 15.9 ppm and U ranging from 2.2 to 3.8 ppm) obtained from the statistical analysis correlates with the mean of natural radioelement (K ranging from 0.1 to 2.7 %; Th ranging from 0.4 to 11.2 ppm and U ranging from 0.1 to 3.7 ppm) content of sedimentary rocks which corresponds to shale, the main source rock for hydrocarbon accumulation in the study area. The DRAD (delineation of radioactive anomalies) result ranges from -0.77 to 1.83. The positive values are indicators of favourable zones for the presence of hydrocarbon accumulations. These results suggest that the preliminary information obtained from the use of the thorium normalisation method will guide the exploration of hydrocarbon in the study area.

Keywords: *Airborne radiometric data, Bornu basin, Hydrocarbon accumulation, DRAD, Homogeneity, Radioelements.*

1. Introduction

It has been an ambition of the Federal Government of Nigeria to produce petroleum from its inland basins. Crude oil has been an important source of foreign exchange and has become an influence on Nigeria's economy. The country is blessed with several inland basins (Niger delta, Sokoto basin, Bida basin, Daomeh basin, lower and upper Benue Trough, Gongola basin and Bornu basin). However, one (Niger delta) produces a commercial quantity of crude oil for domestic use and export for foreign exchange. The Bornu basin (study area) is one of the sedimentary basins in Nigeria presumed to host hydrocarbon potential because of some favourable geological factors that correlate with the Termit Basin situated in the Niger republic where discoveries of commercial quantities of hydrocarbon (oil and gas) have been revealed and exploited (Genik 1993).

The search for hydrocarbon (oil and gas) in the Bornu basin started four decades ago and has drawn a lot of attention from different scholars who had used aeromagnetic and gravity data to determine the depth to the top of magnetic body (Sedimentary thickness) for possible hydrocarbon maturation and accumulation using spectral depth, Source parameter imaging, Wavelet analysis and Euler deconvolution (e.g., Cratchley and Jones 1965; Ajakaiye and Burke 1973; Benkhelil et al. 1989; Osazuwa 1998; Isogun 2005; Anakwuba et al. 2011; Nwankwo et al. 2012; Anakwuba and Augustine 2012; Ajana et al. 2014; Salako 2014; Lawal and Nwankwo 2014; Lawal et al. 2015; Salako and Udensi 2015; Aderoju et al. 2016).

Hydrocarbon deposition in the earth's crust influences the concentration and distribution of naturally occurring radioactive elements (K, Th and U) at the surface of the earth via combination groundwater, microseepage and electrochemical conventions cells (Walker et al., 2018). The naturally occurring radioactive elements (NOREs) produced beneath the earth manifest on the earth's surface through micro-fractures and microseep (Mazadiego 1994; Schumacher 2000; Shuyun et al. 2007; Yazdi et al. 2016; Bazoobandi et al. 2016; Mollai et al. 2019). Petroleum sources are commonly associated with high natural gamma-ray radiation. This creates an opportunity for the use of airborne radiometric data in this study to detect areas within the study area with possible hydrocarbon presence. This study will guide the generation of prospects for potential hydrocarbon drilling in the Bornu basin and its environs by employing a simplified thorium normalisation method. The success of the drilling will increase the number of inland sedimentary basins producing hydrocarbon and petroleum reserves in Nigeria.

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2. Location and the Geologic Settings of the Study Area

The area of study falls within the southwestern part of the Chad Basin locally known as Bornu Basin and its environs bounded by longitudes 11.00ºE to 14.00ºE and latitudes 11.00ºN to 13.00ºN in the North-eastern Nigeria with an estimated total area of 72,600 sq.km (Fig 1). The study area is bordered by the Republic of Niger, Chad, and Cameroun to the north, northeast and east respectively.

The geology of the Bornu basin has been explained by different scholars, such as (Furon 1960; Carter et al. 1963; Burke and Dewey 1974; Matheis 1976; deKlasz 1978; Avbovbo et al. Petters et al. 1982; 1986; Oteze and Foyose 1988; Okosun 1992 & 1995; Olugbemiro et al. 1997; Obaje 2009; Olabode et al. 2015; Yazdi et al. 2017). The Bornu basin falls in the southern part of the Chad basin, which is one-tenth of the whole Chad basin which extends to the Niger Republic, Chad and Cameroon. It forms part of the West Central African Rift system (WCAS) as a result of the mechanical division of the African Crustal blocks in the Cretaceous (Genik 1992). The basin belongs to the West African Rift System (WARS) component as WCAS (Okosun 1995). The Bornu Basin (study area) lies between latitudes 11.00ºN and 13.00ºN and longitude 11.00ºE and 14.00ºE, covering Borno State, part of Yobe State of Nigeria (Fig 2).

Geologically, the Bornu basin has been explained as a broad sediment-filled broad depression overlapping Northeastern Nigeria and adjoining parts of the Republic of Chad (Obaje 2009; Kheiri Namin et al. 2015). The sedimentary rocks of the area have a cumulative thickness of over 3.6 km and rocks consist of thick basal continental sequence overlaid by transitional beds followed by a thick succession of Quaternary Limnic, fluviatile and eolian sand and clays.

The study area is made up of different formations (lithological units). The Chad formation which is predominant in the area occupies the northern and the eastern part of the study area overlying other formations, the Keri-Keri formation at the southern and southwestern part overlying the Yolde formation at the southern part and the Pindiga formation at the southwestern part of the study area, Gombe formation at the southwestern part overlying by the Chad formation, the Pindiga formation at the southern part intruded into the Chad formation; Yolde at the extreme southern part; and Bima formation overlying by Keri-Keri formation at the southern part of the study area (Fig 2).

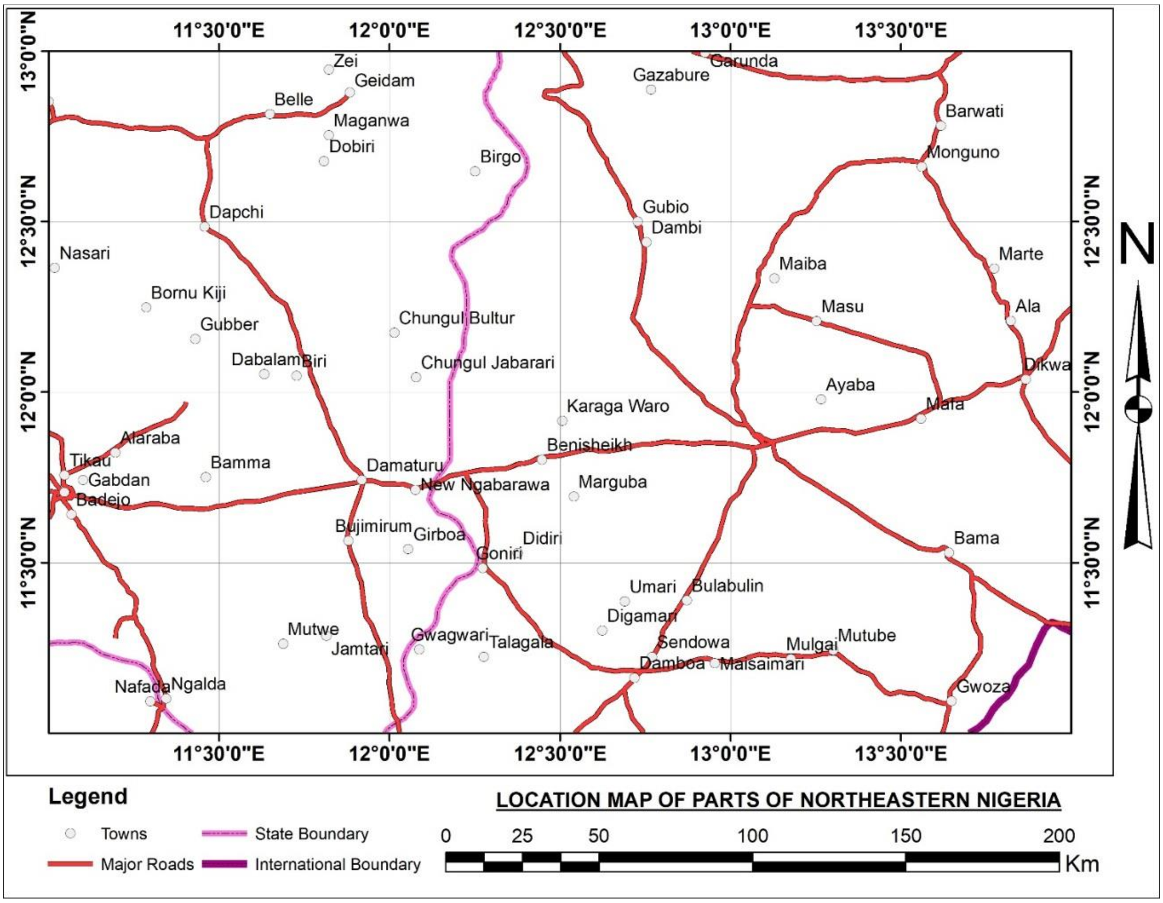

Fig 1. Location Map of the Study Area

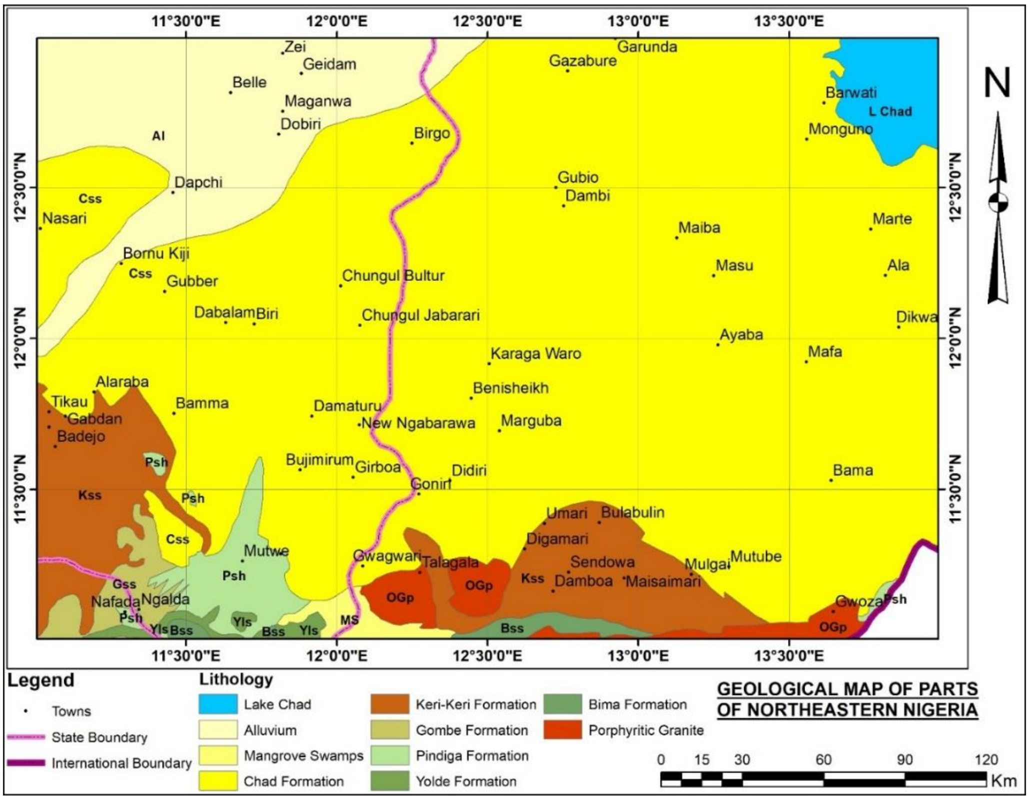

Fig 2. Geological map of the study area

3. Materials and Method

3.1. Data acquisition

Twenty-four (24) half degree by half degree airborne radiometric data were acquired from the Nigerian Geological Survey Agency (NGSA) Abuja. The sheet numbers with their respective locations are; Sheet 41(Gashua), Sheet 42(Geidam), sheet 43(Borgo), Sheet 44(Gazabura), sheet 45(Gudumoali), Sheet 46(Monguno), sheet 63(Dapchi), sheet 64(Biriri), sheet 65(Chungul-Bulturi), sheet 66(Gubio), sheet 67(Masu), sheet 68(Marte), sheet 86(Potiskum), sheet 87(Damaturu), sheet 88(Benisheikh), sheet 89(Marguba), sheet 90(Maiduguri), sheet 91(Mafa-Bama), sheet 109(Nafada), sheet 110(Mutwe), sheet 111(Goniri), sheet 112 (Damboa), sheet 113(Mutube) and sheet 114(Gwoza). The aero-radiometric dataset was obtained as part of the airborne survey carried out between 2005 and 2009 by Fugro on behalf of the Nigerian Geological Survey Agency. The data were obtained at an altitude of 100 m along with a flight line spacing of 500 m oriented in NW-SE and a tie line spacing of 2000 m. The maps are on a scale of 1:100,000 and half-degree sheets. The geomagnetic gradient was removed from the aeromagnetic data using the International Geomagnetic Reference Field (IGRF) of 2005.

3.2. Methods

The following steps were employed to achieve the aim and objectives of this study;

i. Assembling and knitting of the twenty-four aero-radiometric datasheets covering the study area to produce the equivalent concentration maps of Potassium (K), Thorium (eTh) and Uranium (eU) using Oasis Montaj software.

ii. Perform statistical analysis over each lithologic unit and determine the characteristic statistics of these units. The statistical parameters include the arithmetic mean (X), standard deviation (S) and coefficient of variability (CV %) to check the homogeneity and normality of distribution of the analysis for each rock unit.

iii. Determine the relative deviation of Potassium (KD%) and relative deviation of Uranium (eUD%).

iv. Using (iii) to determine DRAD, where DRAD = eUD% - KD%. Where positive DRAD values are favourable indicators for subsurface hydrocarbon accumulations in an area (Saunders et al. 1993; Al-Alfy 2009; Nigm et al. 2018).

3.2.1. Simplified Thorium Normalisation Method

In delineating radiometric signatures related to hydrocarbon accumulations in sedimentary basins, it is of necessity to develop a model to explain such signatures. Saunders et al. (1993) developed one of the most successful models called the ‘Simplified Thorium Normalisation Method’. Saunders et al. (1987) started the use of thorium content as a lithological control to explain ‘ideal’ potassium and uranium value for samples. The basic assumption of this method arises from the fact that anything done to influence the apparent concentration of equivalent thorium also affects uranium and potassium concentration in the same vein and predictable ways. If hydrocarbons are not present, the radioactive elements (K, Th & U) should be in natural and constant proportions (Saunders et al. 1993; Al-Alfy 2009; Nigm et al. 2018). This method has proven helpful as a guide for delineating hydrocarbon accumulation and has further being used by different researchers as a guide for petroleum exploration (for example, Saunders 1989; El-Sadek 2002; El-Sadek et al. 2007; Al-Alfy 2009; Al-Alfy et al. 2013; Nigm et al. 2018; Skupio and Barberes 2017; Shawn et al. 2018; El-Khadragy et al. 2018; Salazar et al. 2018). Based on previous works, this present study attempts to use this method as a guide for delineating possible hydrocarbon accumulations within the study area.

Normalising the thorium concentration will attenuate the lithological units and also affect the environment. This similarity in behaviour gives room for the use of thorium values to roughly predict the presence of uranium and potassium by determining their general relationships (Saunders et al. 1993). Significant variations between the predicted uranium and potassium concentration and the real values must be responsible for factors than lithology, soil moisture, vegetation or counting geometry. By knowing these secondary effects, possible hydrocarbon accumulation can be delineated (Saunders et al. 1991 and 1993). Adopting the Saunders et al. (1993) procedure, the equivalent concentration of uranium and potassium from the airborne radiometric spectral profiles of the study area can be normalised to the equivalent thorium data from the following; plots were made of the field measure K_s (%) versus Th_s (ppm) and Us versus Th_s (ppm) values for all stations. Thereafter, various linear logarithm and second-order curve fitting procedures were tried and the simplest effective equations (1.0) and (2.0) relating these variables were determined to be linear and passing through the origin. The slopes of the lines were determined by the ratios of the mean K_s **(%)** to the mean eTh_s (ppm), or the mean eU_s (ppm) to the mean eTh_s (ppm). The equations are represented below:

$$K_i = \left(\frac{mean\ K_s}{mean\ eTh_s}\right) eTh_s \quad (1)$$

$$U_i = \left(\frac{mean\ U_s}{mean\ eTh_s}\right) eTh_s \quad (2)$$

where K_i is the calculated equivalent thorium defined potassium value from the station with actual thorium value of eTh_s, and U_i is the calculated equivalent thorium defined equivalent uranium value for that station.

Adopting the approach discussed above, the equations were calculated directly from the data, and quick field evaluations may be made without preparing the plots and restoring to curve fitting. Deviation of the actual values from the calculated values for each station can be obtained from the given equation (Saunders et al. 1993):

$$KD\% = (K_s - K_i)/K_s \quad (3)$$

$$eUD\% = (eU_s - eU_i)/eU_s \quad (4)$$

Where K_s and eU_s are the measured potassium and equivalent uranium values at the station respectively.

KD% and eUD% are the relative deviations expressed as a fraction of the station values. From experience, KD% yields small negative values and eUD% yield smaller negative or sometimes positive values over the hydrocarbon accumulations (Saunders et al. 1993). Emphasising these two relationships, Saunders et al. (1993) defined a new parameter, called DRAD:

$$DRAD = eUD\% - KD\% \quad (5)$$

Therefore, positive DRAD values are favourable indicators for subsurface hydrocarbon accumulations in an area (Saunders et al. 1993).

3.2.2. Statistical Evaluation of the Profile Data

A statistical evaluation was applied to the three variables (K, eTh and eU) for each rock unit with respect to the geological map (Fig. 2) of the study area. This statistical evaluation depends solely on the application of the coefficient of variability (CV) as shown in equation (6). For a certain variable in the study area, if the (CV %) is less than 100%, the variables tend to exhibit a normal distribution.

$$CV\ \% = \left(\frac{SD}{X}\right) x100 \quad (6)$$

Where SD is the standard deviation and X is the arithmetic mean.

The lower CV % corresponds to a higher degree of homogeneity. In this present study, the relatively lower values of CV % for K, eTh and eU mean a higher degree of homogeneity.

4. Results and Discussion

Fig 3, 4 and 5 are the gamma-ray spectrometric maps that emphasize the nature of the radioelement distribution and are thus suited to the recognition of the geological features within the study area. These maps (K, eTh and eU) are characterised by a high, intermediate and low concentration and also reveal a general relation to the rock units in the study area. Fig 3 shows high concentration of potassium at the southeastern part, southern part and the eastern part corresponding to Bama; Mutube, Damboa, Nafada; Dikwa, Mafa, Ayaba respectively. While intermediate concentration at the central, western and northwestern part correspond to Chungul Bu, Karaga, Benisheikh; Nasari, Potiskum, Badejo, Alaraba; and Gashua, Nasari, Dapchi and Bornu Kiji respectively. The low concentration occurs in the northern part and northeastern part corresponds to Gazabure and Monguno respectively. The concentration value of potassium ranges from 0.12 % to 2.70 %. Fig 4 and 5 are the equivalent thorium and Uranium concentration maps respectively. The equivalent thorium and uranium concentration value range from 2.60 ppm to 22.32 ppm and 0.53 ppm to 4.68 ppm respectively. A close inspection of these maps shows that the regions of high, intermediate and low concentrations correlate with Fig 3. This shows that the three radio elements have the same distribution in the study area.

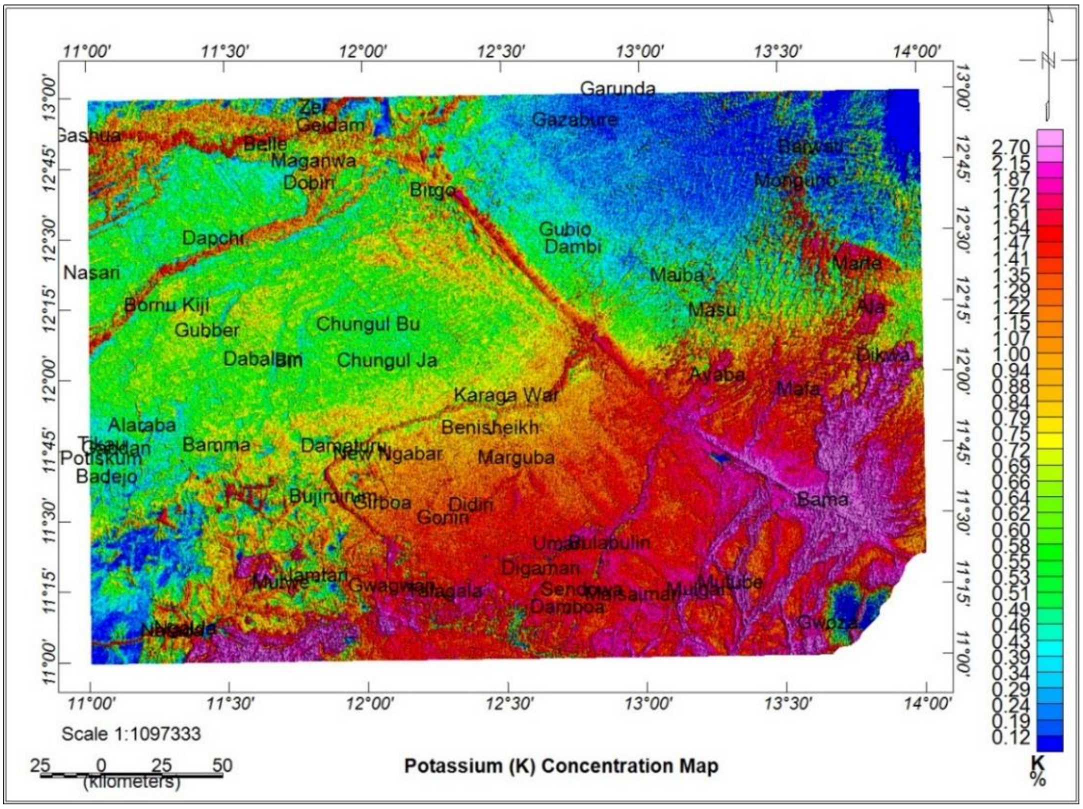

Fig 3. Potassium concentration (K %) map of the study area

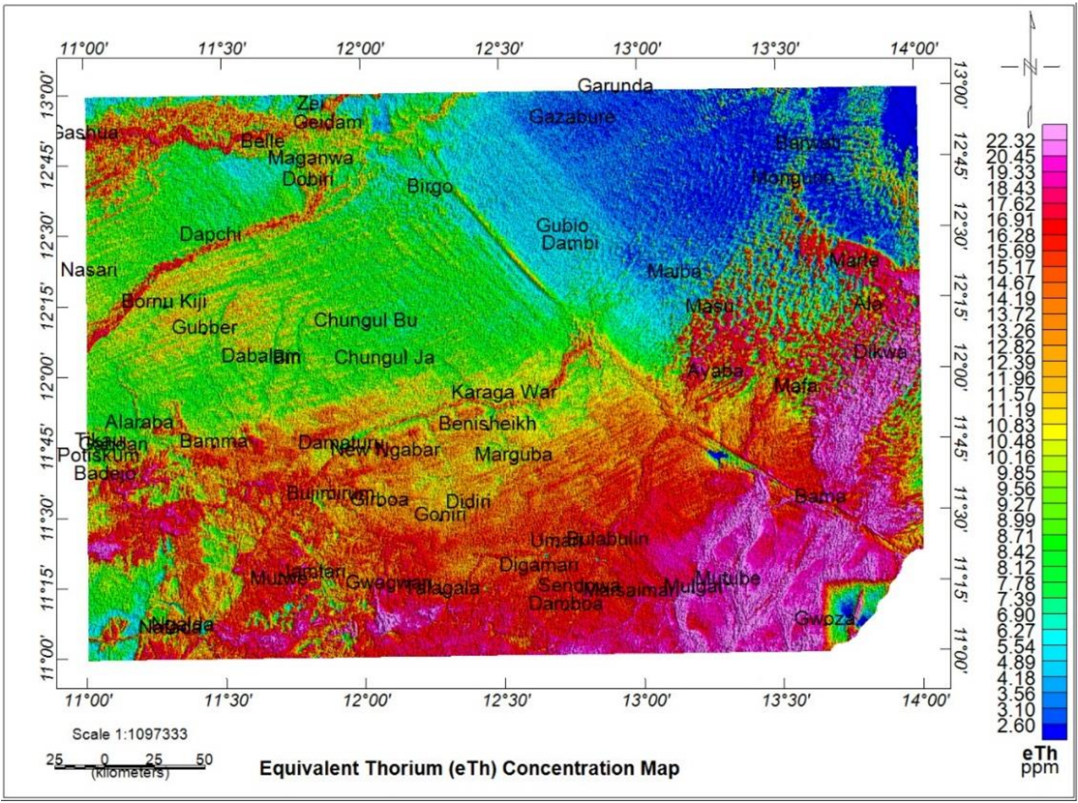

Fig 4. Equivalent Thorium (eTh) concentration map of the study area

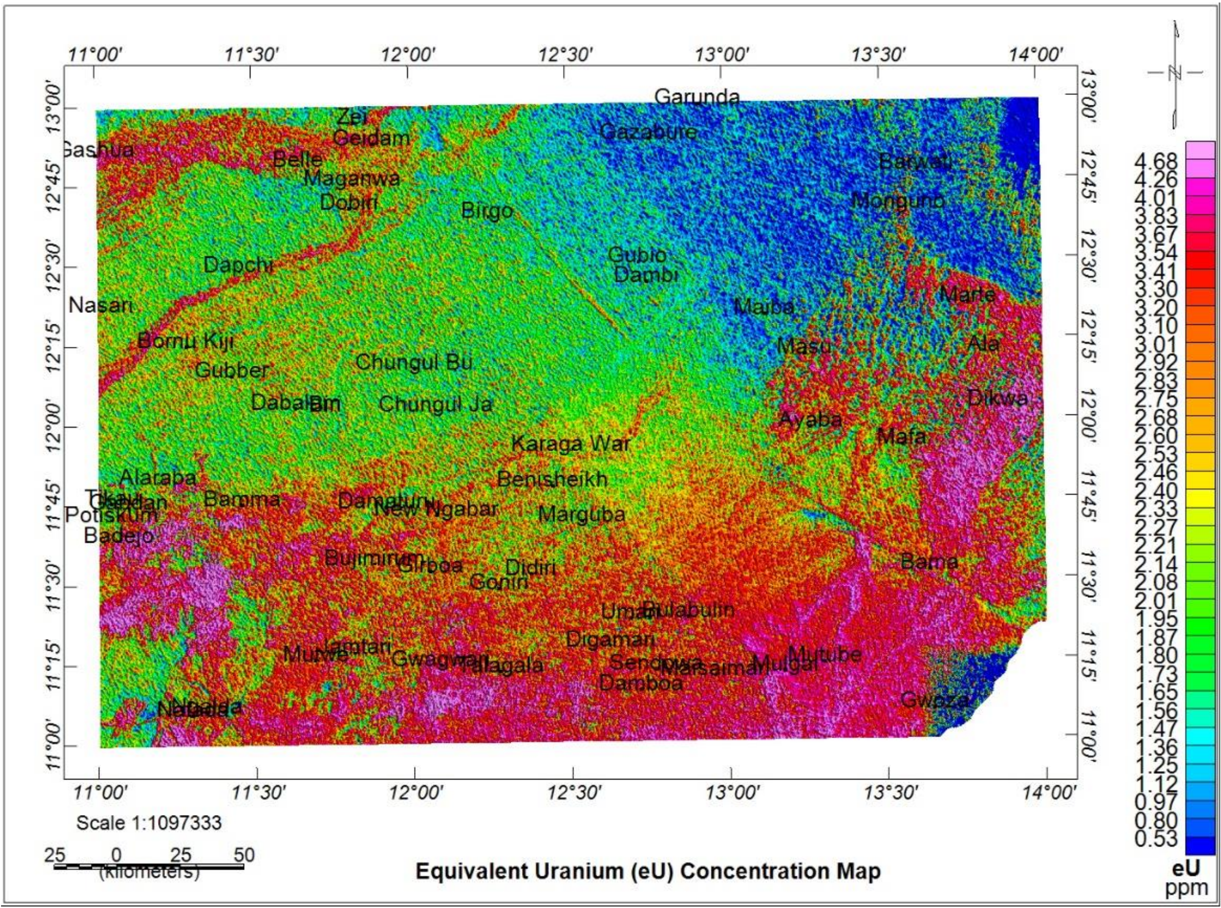

Fig 5. Equivalent Uranium (eU) concentration map of the study area

4.1. Quantitative Interpretation

Table 1 summarizes the statistical results of the three variables over the seven rock units of the study area. The study area comprises of Alluvium deposits, Chad, Keri-Keri, Pindiga, Yolde, Bima, and Gombe formations (Fig 2). Chad formation is the dominant formation in the study area. The coefficient of variability (CV %) of the three variables (K, eTh and eU) of each rock unit of the study area is less than 100 %. This shows that the variables (K, eTh and eU) exhibit normal distribution as revealed in Fig 3, 4 and 5. The relative lower values of CV % for the eTh and eU shows a higher degree of homogeneity viz-a-vis the values of CV % for K. Comparing Table 1 with Table 2 (mean of natural radioelements content of sedimentary rocks adapted from Galbraith and Saunders 1983) shows that the mean of radioelement contents of Keri-Keri formation, Pindiga formation, Yolde formation, Bima formation, and Gombe formation fall within the mean of radioelements for shale which is the main source rock for hydrocarbon accumulations in a sedimentary basin.

Comparative units of KD%, eUD% and DRAD were plotted after separation and statistical parameters were computed as a minimum, maximum, mean (X), standard deviation (SD), and (X+3SD) for each rock unit to illustrate the typical crossover anomalies over the expected hydrocarbon accumulations (Table 3). A conservative estimate of the statistical parameters is based on the samples derived from the population. The grand DRAD arithmetic means plus the three standard deviations (X+3δ) reaches 5.5, 31.7, 23.5, 2.8, 5.7, 13.4 and 14.9 over the Alluvium deposit, Chad formation, Keri-Keri formation, Pindiga formation, Yolde formation, Bima formation, and Gombe formation respectively. Any DRAD value for these rocks greater than this quantity possesses a probability of 99.87% representing a valid anomaly that is not caused by random variations in the background values (Saunders 1989 & 1993; El-Sadek 2002; El-Sadek et al. 2007; Al-Alfy 2009; Al-Alfy et al. 2013; Nigm et al. 2018).

The KD%, eUD% and DRAD anomaly maps of the study area (Fig 6 -8) reveal the residual KD%, eUD% content and DRAD anomalous zones over the study area (Bornu basin and its environs). These maps show thirteen distinctive anomalies that may be indicative of probable hydrocarbon accumulation zones. According to Saunders et al. (1993), hydrocarbon accumulations are characterised by negative KD and positive DRAD.

These zones are clearly shown on the DRAD anomaly map (Fig 8). Anomalous values are expressed as positive numbers, where the more positive are the more anomalous. The possible hydrocarbon accumulation zones and their relation with the respective lithologic units and their locations and corresponding locations are presented in Table 4.

Table 1. Statistical analysis of the variables in different lithologic units of the study area

Rock Type	Lithologic Rock Units	Geological Age	Radioelements	Min	Max	Mean	S.D	(CV %)
Sedimentary	Alluvium Deposits	Cretaceous	K (%)	0	1.8	0.7	0.3	42.85
			eTh (ppm)	3.8	21.3	9.6	2.6	27.08
			eU (ppm)	0.4	5.4	2.3	0.7	30.44
	Chad Formation	Pleistocene	K (%)	-0.1	4.2	0.9	0.7	77.78
			eTh (ppm)	-0.1	32.4	10.3	5.3	51.45
			eU (ppm)	-0.7	6.5	2.2	0.9	40.9
	Keri-Keri Formation	Palaeocene	K (%)	-0.1	2.8	0.9	0.6	66.67
			eTh (ppm)	2.9	26.3	14.6	3.8	26.03
			eU (ppm)	0.5	9.8	3.3	1.1	33.33
	Pindiga Formation	Cenomanian-Turanian	K (%)	0	4.8	1	0.6	60
			eTh (ppm)	3.9	46.1	14.1	3.5	24.82
			eU (ppm)	0.7	8.3	3.2	1	31.25
	Yolde Formation	Cenomanian	K (%)	0	4.5	1.3	0.9	69.23
			eTh (ppm)	5	22.6	15.5	3.1	20
			eU (ppm)	0.9	6.4	3.8	1	13.2
	Bima Formation	Albian-Turanian	K (%)	0	3.5	2	0.8	21.05
			eTh (ppm)	8.5	22	15.9	2.1	13.2
			eU (ppm)	1.7	5.4	3.4	0.6	17.64
	Gombe Formation	Quaternary	K (%)	0	2.5	0.6	0.4	66.67
			eTh (ppm)	3.8	20	12	3.1	8.33
			eU (ppm)	0.3	6.4	3.1	1.1	35.48

Table 2. Mean of natural radioelement content of sedimentary rocks. (Adapted from Galbraith and Saunders 1983)

Rock Type	Th (ppm)	U (ppm)	K (%)
Evaporite	0.4	0.1	0.1
Carbonate	1.6	1.6	0.3
Sandstone	5.7	1.9	1.2
Shale	11.2	3.7	2.7

Table 3. Statistical analysis computed for the KD, eUD and DRAD for each rock unit to identify probable hydrocarbon accumulation zones in the study area

Rock Type	Lithologic Rock Units	Geological Age	Indications Calculated	Min	Max	X	δ	X+3δ
Sedimentary	Alluvium Deposits	Cretaceous	KD (%)	-35	75.7	-0.3	1.1	3
			eUD (%)	-5.3	0.5	0.1	0.2	0.7
			DRAD (%)	-74.2	124.7	0.4	1.7	5.5
	Chad Formation	Pleistocene	KD (%)	-78.5	1824	0	10.6	31.8
			eUD (%)	-97.4	55	0	1.4	4.2
			DRAD (%)	-1509	117	-0.1	10.6	31.7
	Keri-Keri Formation	Palaeocene	KD (%)	-219.6	227.5	-1.4	7.1	19.9
			eUD (%)	-5.3	0.6	0	0.3	0.9
			DRAD (%)	269.6	138	1.3	7.4	23.5
	Pindiga Formation	Cenomanian-Turanian	KD (%)	-10.9	0.8	-0.4	0.8	2
			eUD (%)	-1.3	0.6	0	0.2	0.6
			DRAD (%)	-1.7	9.1	0.4	0.8	2.8
	Yolde Formation	Cenomanian	KD (%)	-16.8	0.7	-0.3	1.7	4.8
			eUD (%)	-0.8	0.4	0	0.2	0.6
			DRAD (%)	-1.4	17	0.3	1.8	5.7
	Bima Formation	Albian-Turanian	KD (%)	-101.1	0.7	-0.3	4.7	13.8
			eUD (%)	-0.9	0.3	-0.1	0.2	0.5
			DRAD (%)	-0.9	88.1	0.2	4.4	13.4
	Gombe Formation	Quaternary	KD (%)	-101.5	254.9	-1.5	7	19.5
			eUD (%)	-0.8	0.6	0.2	0.2	0.8
			DRAD (%)	-76.5	68.1	1.7	4.4	14.9

Table 4. Probable hydrocarbon accumulation zones in the study area

S/N	Location	Corresponding location	Exposed rock unit	Anomaly from	UTM of Anomaly Centre	
					X	Y
1	Eastern	Logomani	Chad formation	+ve DRAD and –ve KD	1038266.87	1350838.85
2	Southwestern	J.Kuka	Keri-Keri formation	+ ve DRAD and –ve KD	723407.907	1231140.4
3	Southwestern	Kadi	Keri-Keri formation	+ve DRAD and –ve KD	722106.837	1261932.36
4	Southwestern	Bulakos	Keri-Keri formation	+ve DRAD and –ve KD	729913.257	1280581.06
5	southern	Chole	Pindiga formation	+ve DRAD and –ve KD	751597.759	1221599.22
6	Southwestern	Badejo	Keri-Keri formation	+ve DRAD and –ve KD	724275.287	1288821.17
7	southwestern	Gaba	Keri-Keri formation	+ve DRAD and –ve KD	743791.338	1290989.62
8	Southwestern	Zoro	Keri-Keri formation	+ve DRAD and –ve KD	747260.859	1294892.83
9	Northeastern	Karba	Chad formation	+ve DRAD and –ve KD	990925.753	1417499.48
10	Northeastern	Gidimbari	Chad formation	+ve DRAD and –ve KD	948772.703	1435738.74
11	Central east	Masu	Chad formation	+ve DRAD and –ve KD	968227.957	1346163.51
12	Western	Alaraba	Keri-Keri formation	+ve DRAD and –ve KD	745852.757	1309082.74
13	Northern	Gabazure	Chad formation	+ve DRAD and –ve KD	918949.054	1432884.57

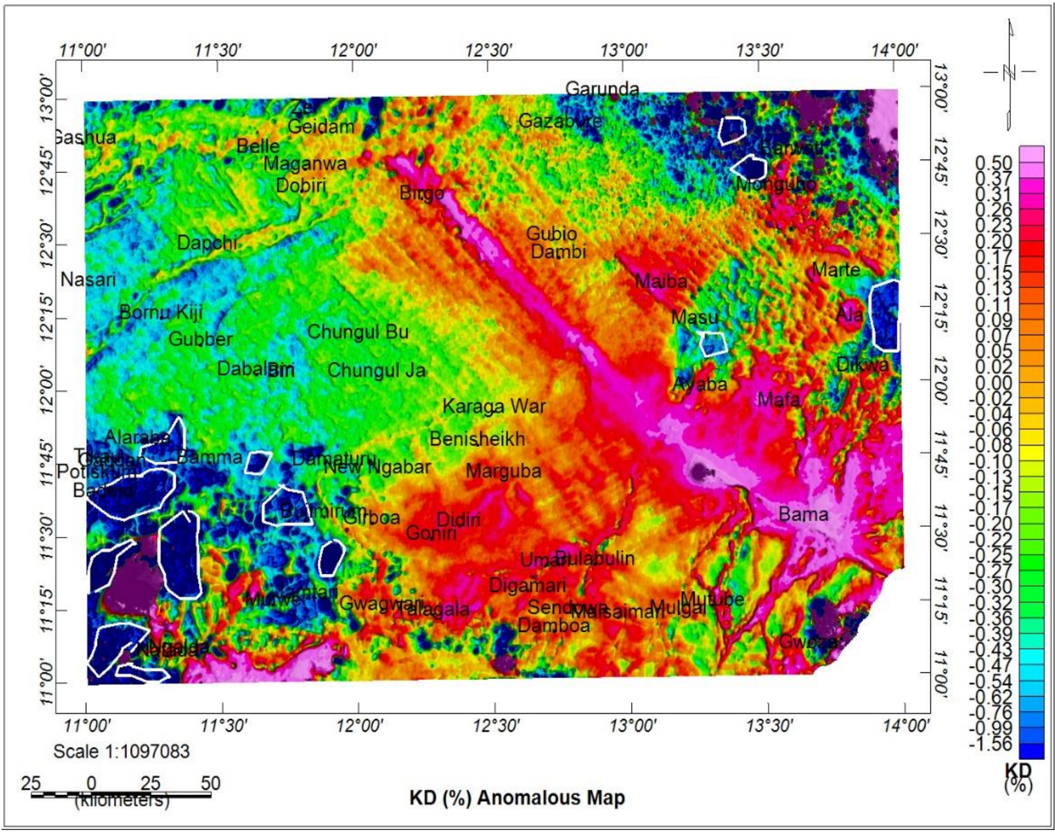

Fig 6. KD% anomaly map of the study area (white circles refers to negative KD anomalies)

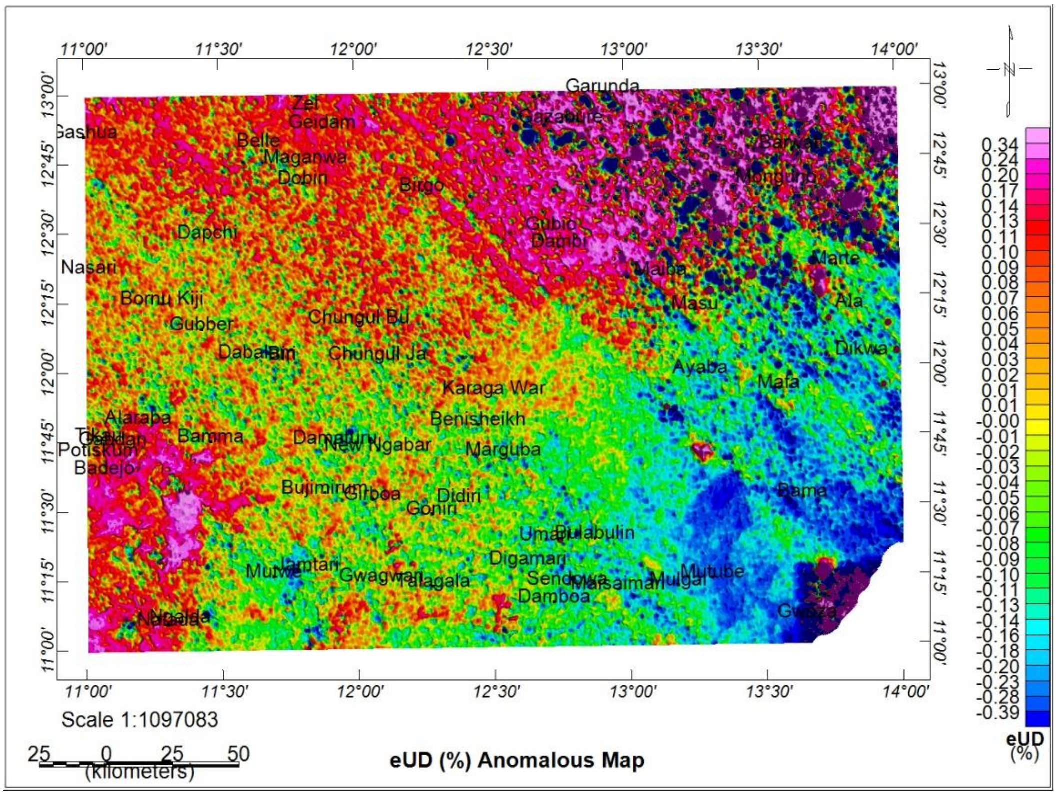

Fig 7. eUD% anomaly map of the study area

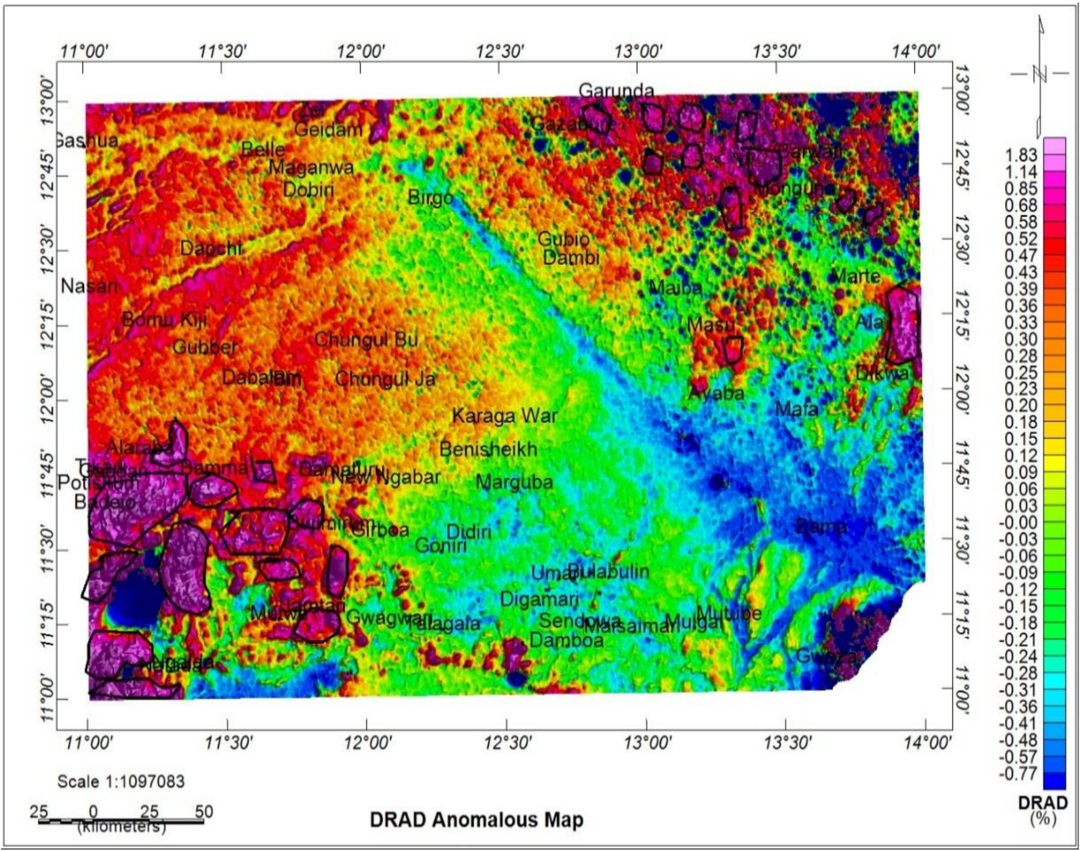

Fig 8. DRAD anomaly map of the study area (black circles refers to the positive DRAD anomalies)

5. Conclusion

The analysis and interpretation of airborne radiometric data as a guide for probable potential hydrocarbon accumulations over the Bornu basin and its environs has been successfully carried out using the Thorium normalisation technique to delineate favourable zones for hydrocarbon accumulations within the study area. The statistical treatment applied on the three variables shows relative lower values of CV % for the K, eTh and eU signifying a higher degree of homogeneity and also exhibit normal distribution over each lithologic unit. The mean values of the radioelements obtained from the statistical analysis correlate with the mean of natural radioelement content of sedimentary rocks adapted from Galbraith and Saunders (1983) which corresponds to shale, the main source rock for hydrocarbon maturation in the study area. From the DRAD map, positive values are an indicator of favourable zones for the presence of hydrocarbon accumulations. This has led to the delineation of several spots within the study area as favourable zones for hydrocarbon accumulations. It can therefore be concluded in this study that the preliminary information obtained from the thorium normalisation method will guide the exploration of hydrocarbon in the study area.

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