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Full Length Research Paper

Geothermal gradients in the Chad Basin, Nigeria, from bottom hole temperature logs

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Bottom Hole Temperature (BHT) data from 21 oil wells in the Nigerian sector of the Chad Basin were analyzed and interpreted to investigate the thermal structure of the basin. A regional average geothermal gradient of 3.4°C/100 m geothermal gradients in the range of 3.0 to 4.4 °C/100 m were obtained. The gradients are relatively lower at the Northeast and Southwest axis and maximum at the North-centre. These differences in geothermal gradients may reflect changes in thermal conductivity of rocks, groundwater movement and endothermic reactions during diagenesis. Also the presence of Tertiary intrusive that is prevalent in the basin may be connected with the variations in the computed geothermal gradient values. The study also reveals that sediments with relatively higher geothermal gradients (3.5 to 4.4°C/100 m) mature earlier (low oil window) than those with low gradient values. Thus, under normal circumstances a high geothermal gradient enhances the early formation of oil at relatively shallow burial depths, but it causes the depth range of the oil window to be quite narrow, while low geothermal gradient causes the first formation of oil to begin at fairly deep subsurface levels, but makes the oil window to be quite broad.

Key words: Chad basin, well logs, bottom hole temperature, geothermal gradient, oil window.

INTRODUCTION

The present day national petroleum reserves in Nigeria are derived solely from the onshore and offshore Niger Delta. However, the continual search for oil and gas in the Nigerian Chad Basin sector in the last two decades by the Nigerian National Petroleum Corporation without any meaningful discovery has necessitated the analysis of all available data from the area that can help in future decisions for successful exploration of oil and gas in the region. Geothermal gradients are very useful; as indicators of subsurface temperature distribution; in the understanding of regional and subregional tectonics and in the assessment of geothermal resource potentials of an area. Temperature is one of the primary factors controlling hydrocarbon generation, sediment diagenesis and migration of hydrocarbons and other pore fluids (Nwankwo, 2007).

Bottom Hole Temperature data from 21 petroleum exploration well logs in Nigerian Chad Basin were collected for thermal evaluation of the study area. With the available corrected bottom hole temperature data, the geothermal gradient of the sediments were determined. With the calculated temperature gradient values, the oil window estimate for each well was computed. An oil window in a sedimentary basin is a zone of active oil generation.

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GENERAL GEOLOGIC SETTING

The Chad Basin which is located on Lake Chad is the largest inland basin in Africa occupying an area of approximately 2,500, 000 km^2 extending over parts of the Republic of Niger, Chad, Sudan and the Northern portions of Cameroon and Nigeria. The Nigerian sector of the Chad Basin (Figure 1) covers about 152, 000 km^2 of territory in Bornu, Bauchi, Plateau and Kano states and constitutes only about 6.5% of the entire basin (Oteze and Fayose, 1988). The basin contains about 4.65 km of marine and continental sediments made up of the Bima Sandstone, Gongila Formation, Fika Shale, Kerri Kerri and Chad Formations (Okosun, 2000). The basin is rimmed by crystalline basement rocks mainly of granitic

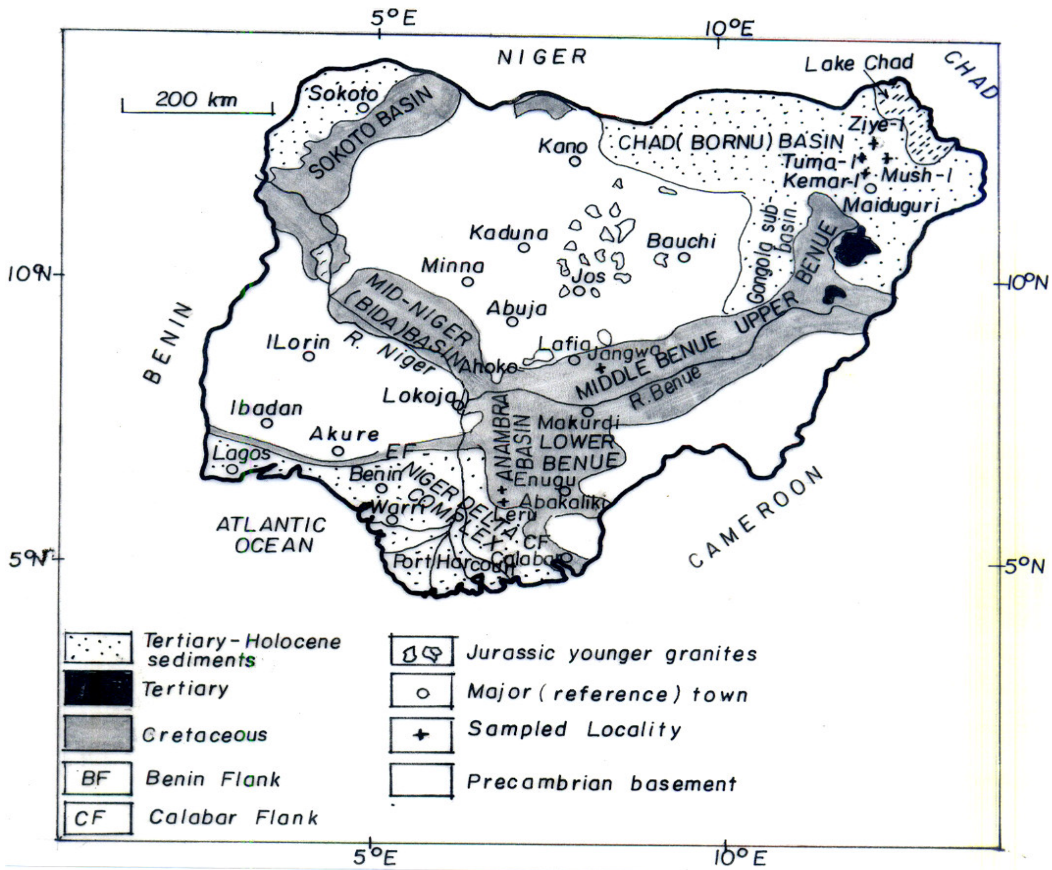

Figure 1. Geologic map of Nigeria showing the Chad Basin (adapted from Obaje et al., 2004).

and gneissic compositions with some mica schists. Basalts, minor basic and acidic intrusions (particularly of Tertiary age) occur commonly within parts of the basin as sills and plugs. These intrusions (sill and plugs) on Tertiary rocks could change the heat flow and temperature (Nwankwo et al., 2009). They influence the geothermal gradient of the Chad Basin. No rocks of Paleozoic age outcrop in the Nigerian sector of the Chad Basin but it is believed that these sediments may be preserved in the lower depressions and grabens, which characterize the basin's floor topography (Zarma, 2004).

METHODOLOGY

Bottom Hole Temperature (BHT) corrections

Measured subsurface formation temperature from open hole logs is always lower than the true or static formation temperature. During the drilling of oil wells, a large quantity of mud is circulated in the borehole to facilitate the drilling, evacuate the cuttings and stabilize the hole. The influence of this circulation and other drilling effects like thermal properties of the drilling fluid, nature of heat exchange between borehole and the well, duration of drilling, non-equilibrium temperature at the time of temperature measurements etc, on the formation were reasons why bottom hole temperature data was rarely used in geophysical studies in the past. Several correction methods have been proposed by many authors (Henrikson and Chapman, 2002; Onuoha and Ekine, 1999). In this study the BHT drilling effects were corrected by using an AAPG gradient correction factors (Table 1). The approach allows corrections to be made on individual recorded BHT data.

By assuming a linear relationship of temperature and depth, the geothermal gradient is determined from the regression formula:

$$y = A + Bx \tag{1}$$

where; y = depth in metres; A = constant term; x = temperature and B = regression coefficient.

$$G = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - \left(\sum x\right)^2} \tag{2}$$

Where; x and y bear the same meaning as above and n is the number of data.

Geothermal gradient determination

Various methods exist in literatures that are used in calculating thermal gradients, especially when continuous temperature log data are available. Such methods like the thermal resistance method and

Table 1. Additions for correction of logged bottom hole temperatures to true formation temperatures based on API method (Neglia, 1979).

Depth (m)	Added temperature quotient (°C)
500	4.0
1000	7.5
1500	11.0
2000	14.0
2500	16.0
3000	17.5
3500	18.0
4000	18.0
4500	17.0
5000	15.0
5500	11.0
6000	4.5

the simple gradient method are most common. However, in estimating the geothermal gradient in this study, a regression formula (Equation 2) has been used based on the type of available data. Knowledge of subsurface temperature distribution is valuable in understanding the geologic and geophysical processes in the sedimentary basin, including the study of hydrocarbon maturation and migration.

Oil window concept

The source rock maturity of a sedimentary basin can be assessed based on the average depth to the oil floor calculations (Nwankwo, 2007). Below the diagenetic zone of buried sediment, the oil ceiling,or depth of intense oil generation, is defined as that depth below which oil generation begins to increase substantially, while the depth and associated temperature at which oil is no longer gene-rated and gas begins to dominate (zone of metagenesis) is known as the oil floor. These two depths bound the oil generative window (zone of catagenesis). An oil window is therefore the space-time continuum inside which liquid hydrocarbons are generated and preserved. The oil window for hydrocarbon generation lies between 70° and 100° within a given geothermal gradient; this oil window is between 2 and 3.5 km depth (Spalleti, 2009).

Depths for the oil ceiling (Doc) is given by Piggot (1985) as:

$$Doc = 100(T - T_s) / (dT/dZ) \quad (3)$$

where T_s is mean surface temperature and dT/dZ is the geothermal gradient in °C/100 m.
T is the oil threshold temperature in °C determined from Arrhenius relationship as a function of sediment age, t. T is expressed as:

$$T = 164.4 - 19.39 \ln t \quad (4)$$

Similarly, the depths to oil floor is calculated from the relationship

$$Dof = 100(150 - T_s)/(dT/dZ) \quad (5)$$

and

$$\text{Oil window} = Dof - Doc \quad (6)$$

By assuming a mean annual temperature of 27°C and the age of the basin to be Top Maastrichtian (64.4 Ma), the depth to the oil window for the basin was calculated (Table 2).

RESULTS AND DISCUSSION

Figure 2 shows the location of the wells used in the study and their corresponding geothermal gradient distribution. Figure 3 shows some representative bottom hole tempe-rature variation with depth from some exploratory wells in the basin, while Table 2 depicts the geothermal gradients variation and the corresponding oil window kitchen for the wells in the Chad basin.

The contour map for the geothermal gradients in the basin is shown on Figure 4. The gradients are relatively lower at the Northeast and Southwest axis. These differences in geothermal gradients may reflect changes in thermal conductivity of rocks as computed from sonic log for the various well locations (Table 2), groundwater movement and endothermic reactions during diagenesis. With a relatively high geothermal gradient across the wells in the basin, the sediments are characterized by early inception of the principal phase of hydrocarbon generation. However, the high gradient values observed in the basin may have resulted from high heat flows due to tectonic activities in the basin (Nwankwo et al., 2009) or from low erosional phase.

The geothermal gradient for Chad Basin ranges from 3.0 to 4.4°C/100 m with an average of 3.4°C/100 m. The obtained gradient values in this study and the heat flow values calculated by Nwankwo et al. (2009) are relatively higher than those of the adjoining Benue Trough, Anambra and Niger Delta Basins. This suggests the influence of tectonic activity on the basin and hence the basin can be considered unstable. A geothermal gradient range of 1.5 to 2.7°C/100 m (Uko, 1996) has been com-puted for Benue Trough (Northern Niger Delta). A mean gradient of 3.2°C/100 m was obtained for the Anambra Basin by Onuoha and Ekine (1999). A gradient range of 0.82 to 4.6°C/100 m (Akpabio et al., 2003) has been reported for the Niger Delta. Uko et al. (2002) have also observed a geothermal gradient ranging from 1.5 to 3.4°C/100 m for South-East Niger Delta. There was no defined trend in the variation of geothermal gradients obtained in this study. However, the geothermal gradient values are relatively higher at the center and lowest in the wells located at the Northeast and Southwest region.

IMPLICATIONS FOR HYDROCARBON POTENTIAL

The relatively high geothermal gradients across all the wells in the Nigerian sector of the Chad Basin indicates that the basin is expected to have shallow levels of hydrocarbon occurrence which causes the depth range of the oil window to be quite narrow. Low geothermal gradient causes the first formation of oil to begin at fairly

Table 2. Geothermal gradients and estimated oil Window values for wells in Chad Basin.

S/No.	Wells	G/L Elev. (m)	dT/dZ $^{o}C/100$	K ($Wm^{-1}\,^{o}C^{-1}$)	Doc (m)	Dof (m)	Oil Window (m)	TD (m)
1	Al-Barka-1	306.0	3.3	1.93	1697	3727	2030	3477.6
2	Bulte-1	296.63	3.4	2.16	1647	3618	1971	1466.9
3	Faltu-1	288.54	3.1	2.0	1806	3968	2162	3164.6
4	Gubio S.W-1	318.47	3.0	1.98	1867	4100	2233	3646.6
5	Herwa-1	282.34	3.5	2.98	1600	3514	1914	4713.7
6	Kadaru-1	-	3.2	2.07	1750	3844	2094	5013.0
7	Kanadi-1	306.14	3.8	2.22	1474	3237	1763	3047.9
8	Kasade-1	298.06	4.4	1.70	1273	2795	1522	1898.0
9	Kemar-1	172.14	3.7	2.0	1514	3324	1810	1790.0
10	Kinasar-1	-	3.6	2.13	1556	3417	1861	4663.0
11	Krumta-1	299.54	3.4	2.10	1647	3618	1971	2950.5
12	Kuchalli-1	-	3.1	2.09	1806	3968	2162	3200.0
13	Masu-1	304.6	3.5	1.82	1600	3514	1914	3100.0
14	Mbeji-1	286.13	4.0	2.26	1400	3075	1675	3725.7
15	Murshe-1	301.0	3.0	2.82	1867	4100	2233	3926.6
16	Ngamma E-1	320.03	3.6	2.51	1556	3417	1861	3260.0
17	Ngor N-1	323.53	3.1	2.35	1806	3968	2162	3399.2
18	SA-1	313.14	3.3	2.15	1697	3727	2030	2458.7
19	Tuma-1	308.23	3.4	3.10	1647	3618	1971	3227.6
20	Wadi-1	308.53	3.2	2.70	1750	3844	2094	3227.6
21	Ziye-1	303.0	3.0	2.50	1867	4100	2233	3358.0

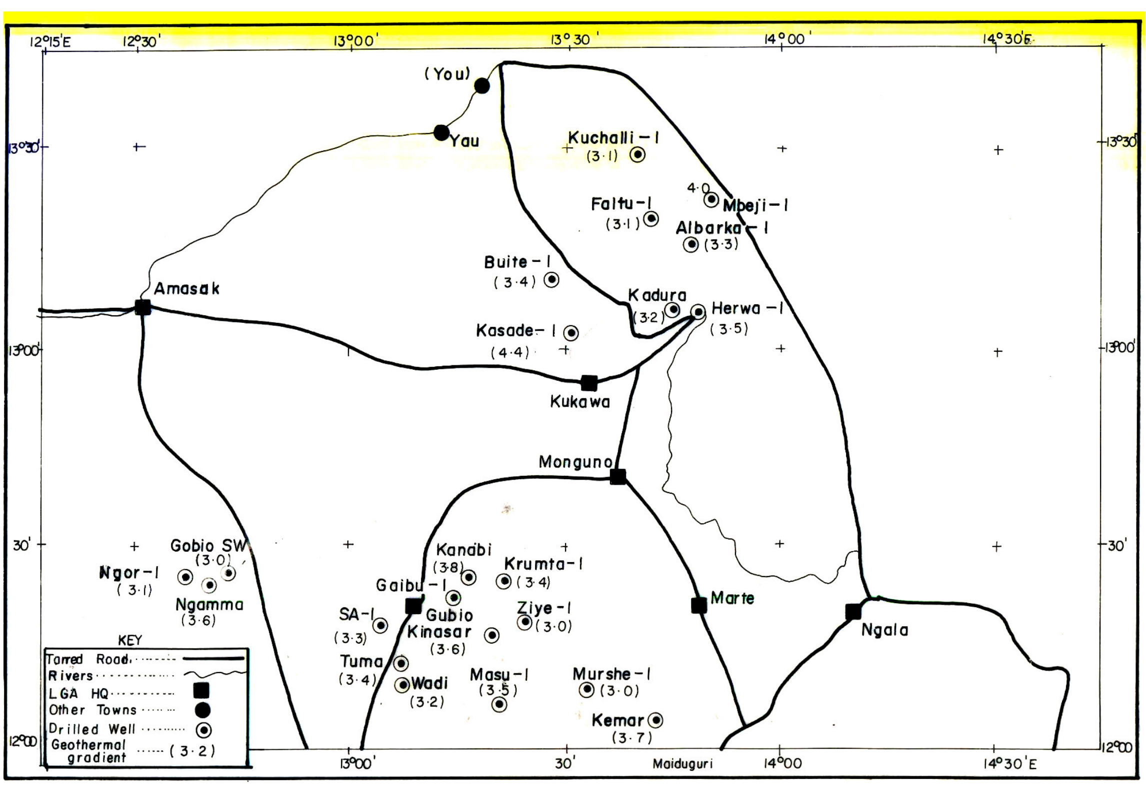

Figure 2. Geothermal gradient map of the wells in Chad Basin Nigeria.

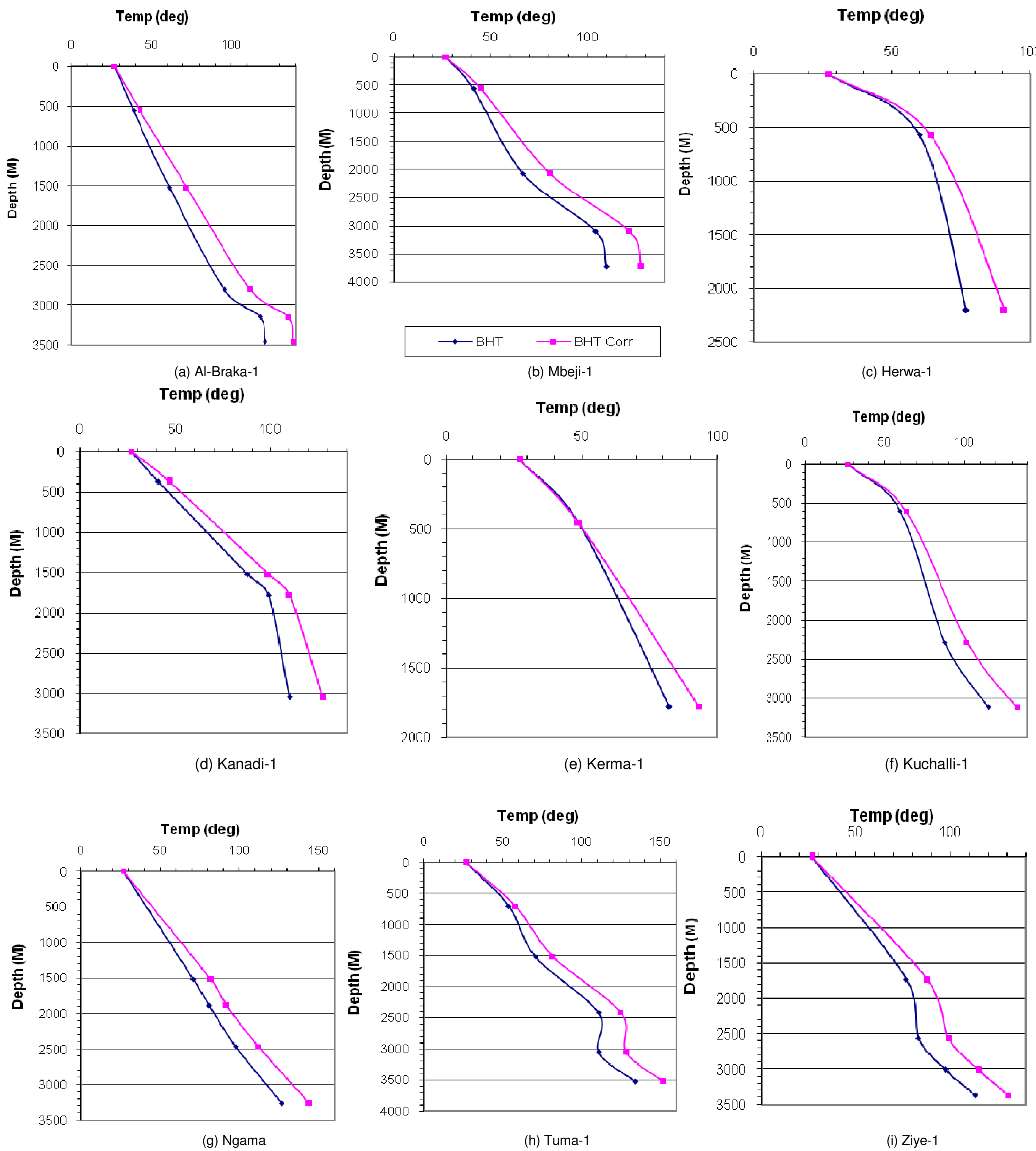

Figure 3. Bottom hole temperature variation with depth for representative wells in the Chad basin.

deep subsurface levels, making the oil window to be quite broad. Above the oil window any potential source rock will not have begun generating liquid hydrocarbon and below the oil window, liquid hydrocarbons would have been converted to gaseous hydrocarbons. In general, the oil formation process is more in young source rocks where

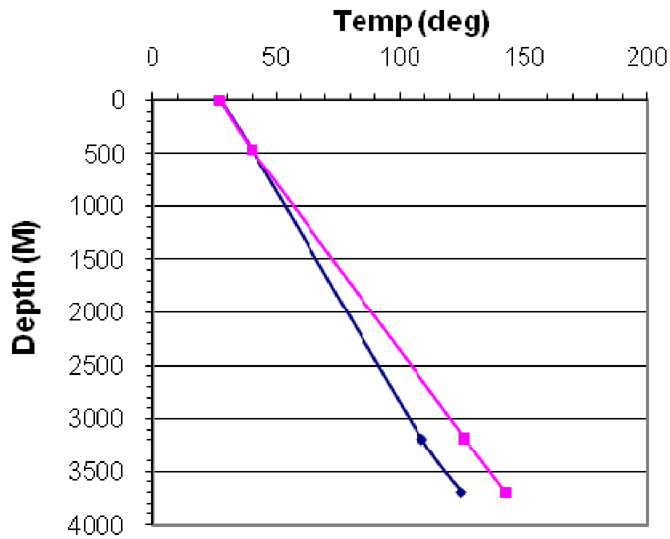

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Figure 3. Contd.

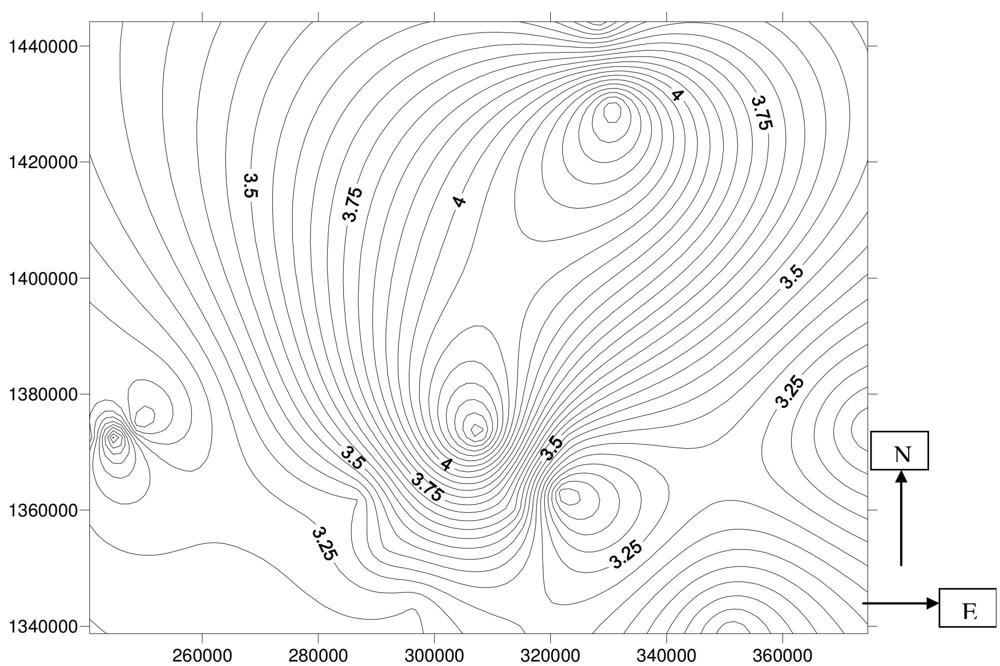

Figure 4. Geothermal Gradient Contour Map of the Chad Basin.

there is a high geothermal gradient and oil can form early at shallow depths. Low burial rates, also arising from the high geothermal gradients implies that compaction of sediments in the basin should be efficient. However, the fact that no meaningful oil or gas discovery has been made in the basin despite the results obtained in this study and the interpretations thereof, which suggest favourable conditions for hydrocarbon accumulation and maturation, the need for more geological and geophysical investigations of the area becomes more demanding. Thus, other geophysical and geological studies could be tied with the well logs in order to know the sill or intrusive subsurface that can give rise to high heat flow and hide the geothermal information of the generative rock. Also the deeper areas of the basin should be the target for further drilling, which should take cognizance of the presence of the intrusives within the basin.

Conclusion

Regional geothermal gradients vary clearly from well to well and with depths. This variation is related to facies change of rock types, changes in thermal conductivity of the intervening rocks samples or subsurface water movements. Average geothermal gradients are lowest ($3.0^{o}C/100$ m) at the Southwest axis towards the Benue Trough and in the Northeast. A maximum gradient value of $4.4^{o}C/100$ m was recorded at the centre of the basin. The geothermal gradients in the Chad basin suggests that sediments in the region are thermally mature for hydrocarbon generation. The average depth to oil floor in the basin is 3626 m, suggesting that wells to be drilled in the region should be drilled up to a total depth of 3626 m and beyond.

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