

## Effects of Near-Surface Air Temperature on Sub-Surface Geothermal Gradient and Heat Flow in Bornu-Chad Basin, Nigeria

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### Abstract

A study of the effect of near-surface temperature on fields of subsurface geothermal gradient and heat flow has been carried out in the Bornu-Chad Basin, Nigeria, using corrected Bottom-Hole Temperatures (BHTc) lithologic-log data from 9 oil wells. The geothermal gradient using only BHTs ranges from  $15.9^{\circ}\text{Ckm}^{-1}$  to  $38.2^{\circ}\text{Ckm}^{-1}$  with an average of  $26.9\pm 3.5^{\circ}\text{Ckm}^{-1}$ , while that computed with mean annual temperature and BHTs ranges from  $28.2^{\circ}\text{Ckm}^{-1}$  to  $51.5^{\circ}\text{Ckm}^{-1}$  with an average of  $37.5\pm 2.5^{\circ}\text{Ckm}^{-1}$ . The geothermal gradient using the mean annual temperature and BHTs in the Bornu-Chad is higher than using only BHTs by  $7.0^{\circ}\text{Ckm}^{-1}$ . Heatflow ranges from a minimum of  $61\text{ mWm}^{-2}$  to a maximum of  $114\text{ mWm}^{-2}$  with an average of  $68\pm 5.89\text{ mWm}^{-2}$ . The isotherm maps exhibit an increasing SW-NE trend. An average heat flow of  $68\pm 5.9\text{ mWm}^{-2}$  deduced from Bornu-Chad basin is normal for a continental passive margin with age of about 100My. Geothermal gradient results show a distinct and direct relationship with near-surface conditions. There are indications that surface heat flow is controlled by lithology, geothermal gradient and near-surface solar radiation conditions in the Bornu-Chad basin. Consequently, it is recommended that the mean surface temperature be used in geothermal gradients and heatflows estimations. The knowledge of geothermal properties is very important in the search for geothermal energy in the area of study.

### Keywords

Geothermal gradient,  
Heat flow,  
Boton-hole-temperature,  
Bornu-Chad basin,  
Nigeria.

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## 1. Introduction

Geothermal gradient is the rate of temperature change with respect to increasing depth in Earth's interior. Generally, the temperature of the crust is rising with depth due to the heat flow from the mantle. Away from tectonic plate boundaries, temperature rises at the rate of about  $25\text{--}30^{\circ}\text{C/km}$  of depth near the surface, in most of the world (Fridleifsson *et al.*, 2008). Geothermal gradients are important parameters in different fields of oil and gas study. Geothermal gradient is the rate of increase in temperature per unit depth in the earth due to the outflow of heat from deeper levels (Lowrie, 1997; Anomohanran, 2011). Geothermal gradients may be measured through a borehole section using a probe on which a number of close-spaced thermistor probes are mounted (Kearey *et al.*, 2002). The temperature so measured at lower levels of the borehole are called Bottom-Hole Temperature, BHT, when recorded properly, is necessarily a value between the True Formation Temperature, TFT, which is unknown, and the temperature of the drilling fluid (Ali *et al.*, 2005). The BHT

and TFT become equilibrated as the time after circulation of the drilling fluid increases.

Several authors have studied the geothermal state of the Bornu-Chad basin (Kwaya *et al.*, 2016; Nwankwo *et al.*, 2009; Umar, 1999; Nwankwo and Ekine, 2010; Nwazeapu, 1990; Askira and Schoeneich, 1987; Olugbeniro and Ligous, 1999; Lawal *et al.*, 2018). In this basin, different but close values are reported by different authors. Nwankwo *et al.* (2009) reported  $30.0$  to  $44.0^{\circ}\text{C/km}$  using annual mean temperature assumed to be  $27^{\circ}\text{C}$ . Kwaya (2016) obtained values ranging from  $28.2^{\circ}\text{Ckm}^{-1}$  to  $58.8^{\circ}\text{Ckm}^{-1}$  using annual mean surface temperature for the region to be  $28^{\circ}\text{C}$ . Nwankwo and Ekine (2010) presented a regional geothermal gradient of  $34.0^{\circ}\text{Ckm}^{-1}$  using annual mean air temperature assumed to be  $27^{\circ}\text{C}$ . Nwazeapu (1990) presented an average geothermal gradient of  $33.1^{\circ}\text{Ckm}^{-1}$  from corrected BHTs. Terrestrial heat flow varies in the area from low to moderately high,  $45$  to  $90\text{ mWm}^{-2}$  (Kwaya *et al.*, 2016).

The aim of this present study is to investigate the effects of near-surface atmospheric temperature on subsurface geothermal gradients in the Bornu-Chad Basin, Nigeria.

Knowledge of sub-surface temperature distribution and heat flow are useful in understanding the mechanism of basin formation and geological processes such as rifting, and the development of volcanic fields (Reiter and Jessop, 1985). The geothermal gradient is also very useful for the analysis of reservoir fluid properties, in the understanding of regional and sub-regional tectonics and in the assessment of geothermal resource potentials of the study area.

## 2. Geologic Setting of Study Area within the Bornu-Chad Basin

The Nigerian Bornu-Chad Basin with an area of about 2,500,000km<sup>2</sup> (Oteze and Fayose, 1988) occupies a vast area with altitudes between 200m and 500m above sea level (Cratchley *et al.*, 1984; Kwaya and Kurowka, 2018). The Bornu Basin which represents the Chad Basin in Nigeria is one-tenth of the total area of the Chad Basin which extends to the Niger, Chad and Cameroon Republics (Okosun, 1995). It is a part of the western Central African Rift System (WCAS) that was formed in response to the mechanical separation of the African crustal blocks in the cretaceous (Genik, 1992; Avbovbo *et al.*, 1986; Okosun, 1995; Nwachukwu and Ekine, 2010). This basin lies between latitudes 10°N to 14°N and longitudes 12°E to 15°E in North-Eastern Nigeria (Kwaya *et al.*, 2016), as indicated in the map of Figures 1. The study area is limited between latitudes 12°30' and 12°00'E and longitudes 12°00' and 13°30'N.

The Borno-Chad basin Nigeria is a broad sediment-filled depression spanning north-eastern Nigeria and adjoining parts of the Republic of Chad. The stratigraphy of Borno-Chad basin has been reported by several authors (Avbovbo *et al.*, 1986; Obaje, 2009; Nwachukwu and Ekine, 2009), Figure 3. The stratigraphic units represented in Bornu Basin range in age from Albian to recent (Okosun, 1995; Whiteman, 1982; Petters, 1981). Deposition took place under varying conditions with each deposit representing one complete cycle of transgression and regression. It has been divided into six formations based on the nature of sedimentary deposits within the depression. The divisions are named Bima, Gongila, Fika, Gombe, Kerri-Kerri and Chad formations as shown in Figure 2 (Okosun, 1995; Avbovbo *et al.*, 1986; Carter *et al.*, 1963).

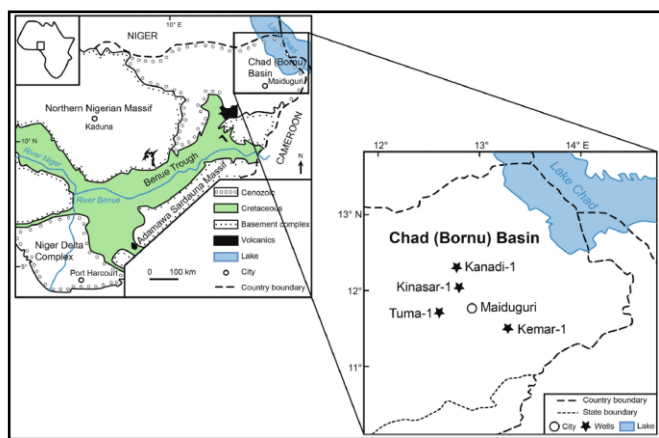


Figure 1 - Map of Nigeria showing Bornu-Chad Basin (Ola-Buraimo and Abdulganiyu, 2017).

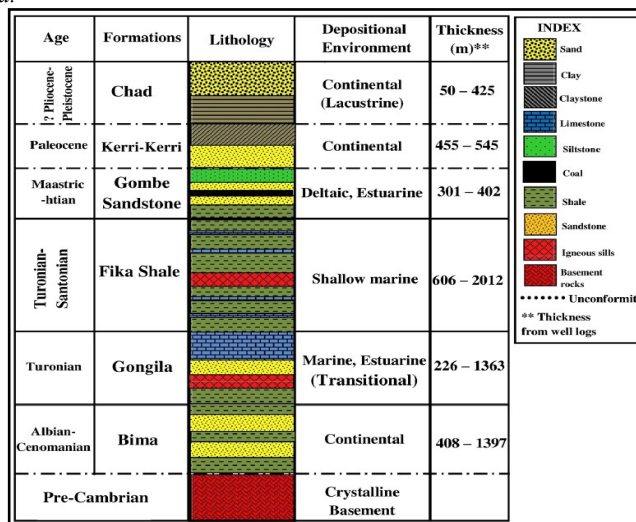


Figure 2 - The Stratigraphy of the Bornu-Chad Basin (Okosun 1995; Avbovbo *et al.*, 1986; Carter *et al.*, 1963).

The oldest sediments are Albian to Cenomanian and comprise continental, sparsely fossiliferous, poorly sorted, thickly bedded, cross-stratified fine to coarse-grained feldspathic sandstones of the Bima formation, which rest unconformably on basement (Okosun, 1995). The early Turonian Gongila formation, which consists of thin to moderately thick bedded, grey to dark grey calcareous shales, silty sandstones and sandstones, conformably overlies the Bima formation and represents a transitional sequence between the underlying continental Bima formation and the overlying marine Fika formation. Volcanic intrusives which occur as diorite sills are present at several horizons within the Gongila formation (Okosun, 1995). The Fika formation comprises blue-black, ammonite-rich, and open marine shale which are occasional gypsiferous and with intercalations of thin limestone beds. There is also an occurrence of volcanic intrusives which occur as diorite sills at numerous horizons the formation. The formation is diachronous, and it has been dated Turonian-Santonian. The estuarine/deltaic Gombe formation rests unconformably on the Fika formation and occurs only in some parts of the basin. It comprises sandstone and siltstone with minor interbeds of claystone, ironstone and shale with thin coal beds. The formation was deposited simultaneously with the deformation episode of the Maastrichtian, which resulted in a widespread uplift, along the long axis of the basin. Overlying the Gombe 'Sandstone' formation is the continental (lacustrine and fluvial) Kerri-Kerri formation of Paleocene age. The youngest stratigraphic unit in the basin is the continental (lacustrine and fluvial) Chad formation, which is made-up of Quaternary sedimentary sequence of fine to coarse-grained sand and clay. The sand is uncemented with angular and subangular quartz grains of variable colour from yellow, brown, white to grey, while the clay is massive and locally gritty in texture due to the presence of angular to subangular quartz grains (Okosun, 1995). Chad formation is dated Pleistocene (Carter *et al.*, 1963).

Thin bands of clay and siltstone occur as intercalations with the sandstone and vary in colour from red to grey or brown. The Bima Formation is the basal unit (Figure 2). The deposition of this sequence consists of sandstones, mudstones and occasional shales of variable lithology, texture, colour and structure (Matheis, 1976; Petters, 1981; Okosun, 1995).

### 3. Materials and Methodology

#### 3.1. Data Collection and Well-Logs Conditioning

The temperature data for the research was provided by the Nigerian National Petroleum Corporation (NNPC). The data consisted of 29 bottom-temperature (BHTs) and lithologic data from 9 oil wells. The locations of selected wells are indicated in Figure 3. The well logs were carefully edited prior to their use. This means great care was taken to correctly edit the log data describing locations of shale strata, across drilling breaks, casing points, and washouts. In all cases the log data were edited, normalized, and interpreted before they were used. All the available logs in the field were validated in terms of depth-matching. Logs with multiple runs were spliced. The logs used were generally of good quality and logged to different depths, allowing the calculation of required parameters. The BHTs were corrected for thermal perturbations arising from drilling fluid circulation, using standard procedures (Dowdle and Cobb, 1975; Lachenbrush and Brewer, 1959).

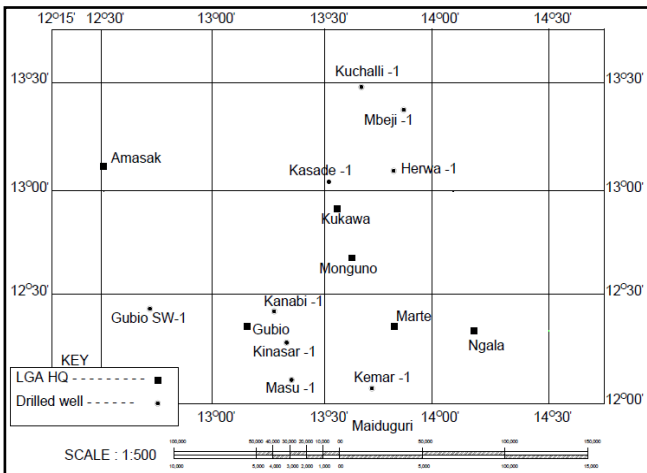


Figure 3 - Map of study area in the Bornu Basin, indicating locations of oil wells.

#### 3.2. Mean Surface Temperature

The mean annual near-surface air temperature for the Bornu-Chad Basin used in this study was obtained from Akinsanola and Ogunjobi (2014), who collected surface temperature for 30 continuous years and used them to compute the average near-surface atmospheric temperature of 28°C for the region. His analysis took into consideration effects of seasonal, climatic, solar radiation, rainfall, evaporation and altitude variations.

#### 3.3. Determination of Geothermal Gradient

- (i) The geothermal gradient using only BHTs (from the working interval) is represented as:

$$G_{wi} = \frac{dT}{dx} \quad (1)$$

where the subscript “wi” refers to the working interval, i.e. line of best fit joined through only the BHTs.

- (ii) The geothermal gradient based on BHTs and surface temperature of 28°C is represented as:

$$G_{si} = \frac{dT}{dx} \quad (2)$$

where the subscript “si” refers to the interval between surface and bottom-hole temperatures, i.e. line of best fit constrained to pass through the BHTs and the mean annual near-surface air temperature of 28°C.

### 4. Results and Discussion

The vertical distributions of BHTs of wells and their respective depth values are presented in Figures 4 – 12. The estimation of the geothermal gradients was obtained from the slopes of the linear best fit. The geothermal gradient estimation (using the Surface temperature and BHTc) for the Chad Basin ranges from 28.24°Ckm<sup>-1</sup> to 51.51°Ckm<sup>-1</sup> with an average of 37.48+/-2.5°Ckm<sup>-1</sup>, while the geothermal gradient estimation (BHTs) for the Chad Basin ranges from 16.92°Ckm<sup>-1</sup> to 38.16°Ckm<sup>-1</sup> with an average value of 26.96+/-3.5°Ckm<sup>-1</sup> using only BHTs.

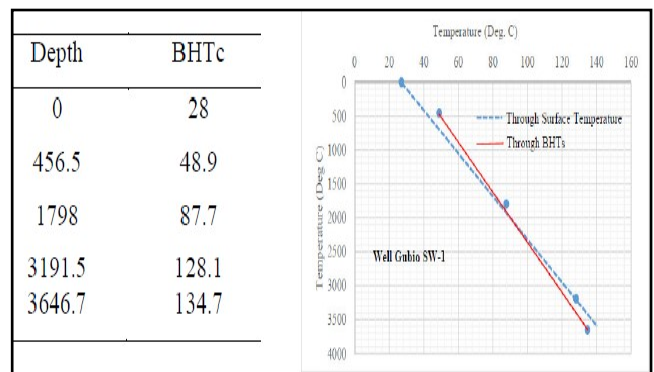


Figure 4 - Geothermal Gradient Profile for Well-1: Gubio SW-1.

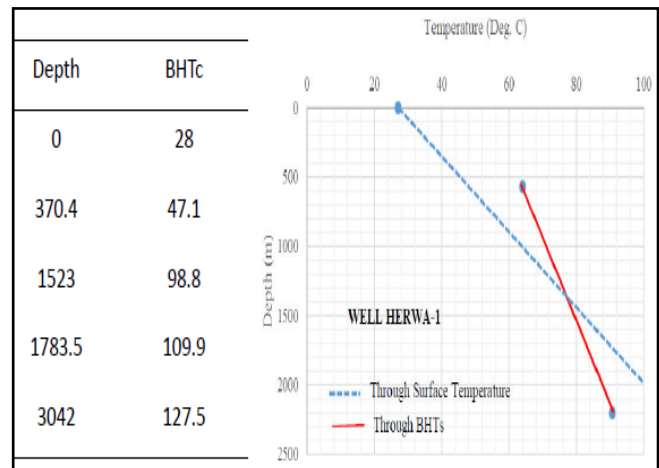


Figure 5 - Geothermal Gradient Profile for Well-2: Herwa-1.

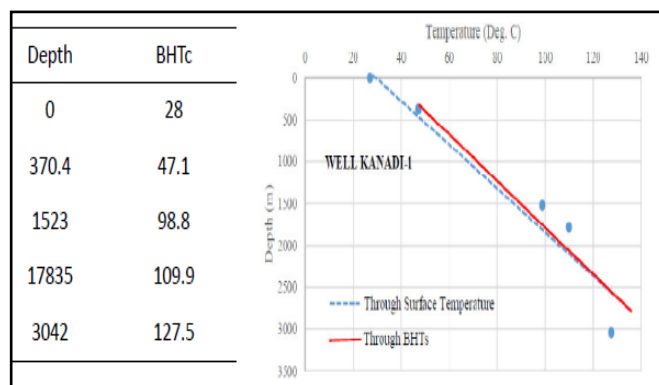


Figure 6 - Geothermal Gradient Profile for Well-3: Kanadi-1.

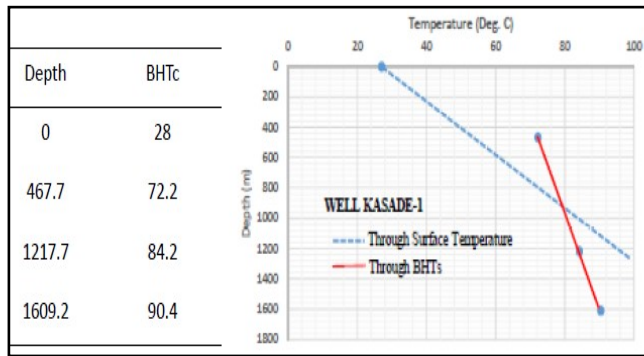


Figure 7 - Geothermal Gradient Profile for Well-4: Kasade-1.

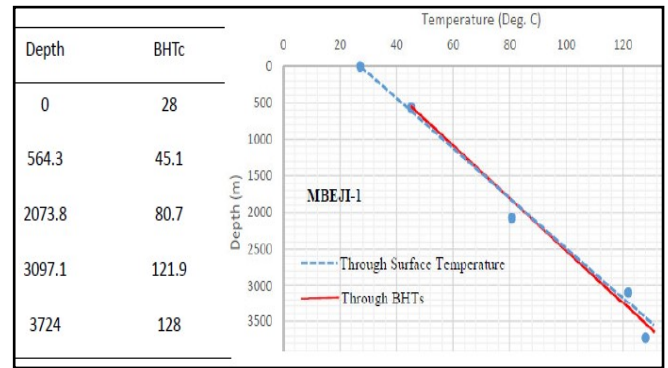


Figure 12 - Geothermal Gradient Profile for Well-9: Mbeji-1.

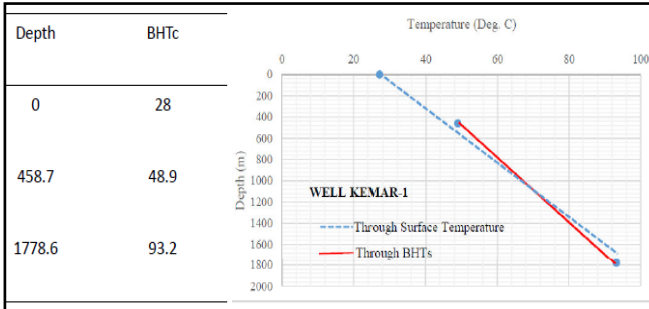


Figure 8 - Geothermal Gradient Profile for Well-5: Kamar-1.

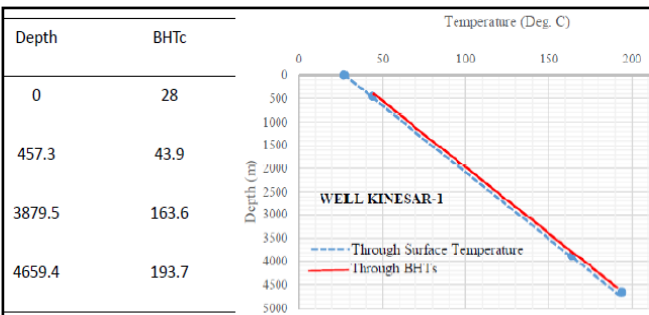


Figure 9 - Geothermal Gradient Profile for Well-6: Kinesar-1.

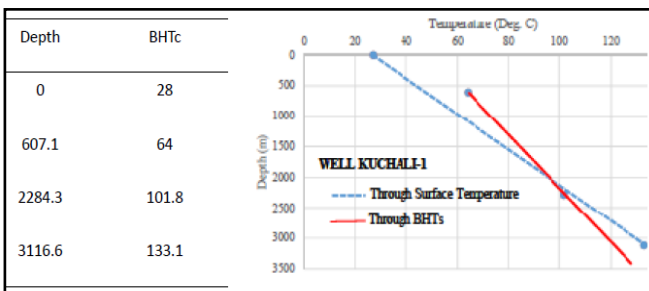


Figure 10 - Geothermal Gradient Profile for Well-7: Kuchalli-1.

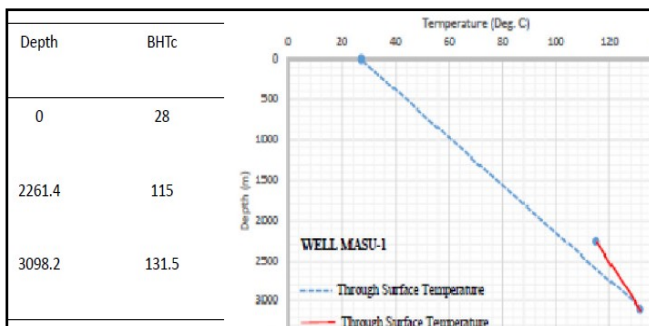


Figure 11 - Geothermal Gradient Profile for Well-8: Masu-1.

A summary of the gradient values and depth intervals is presented in Table 1. The average geothermal gradient estimation gives a higher value using values for air surface and BHTs than using the working interval with a difference of 7.0 °C/km. Lovering and Goode (1963) observed that the temperature of any rock or soil at and near the surface of Earth results nearly from heating by the sun and cooling through radiation, evaporation, and diverse heat-absorbing processes. They further stated that at any particular surface location, the heat supplied from below the surface has near constant values. This difference can introduce significant errors when calculating geothermal gradient from discrete BHTs. The geothermal gradients obtained illustrate that the variation in the difference between the surface air temperature with BHTs and that obtained only BHTs is primarily due to incident solar radiation. It is reasonable to assume that the variation in incident solar radiation between locations or regions will account for a large proportion of the variations in differences of the mean annual temperature.

Table 1 - Geothermal gradient estimated in the Bornu-Chad Basin. See foot notes for details.

Well	G <sub>si</sub>	G <sub>wi</sub>	Ele.	Lat.	Lon.
1	32.00	33.55	318	12°44'	12°25'
2	38.18	16.92	282	13°50'	13°8'
3	47.41	38.16	306	13°17'	12°25'
4	51.51	15.94	298	13°30'	13°2'
5	37.11	33.56	172	13°14'	12°5'
6	35.50	35.50	301	13°21'	12°16'
7	33.83	22.86	288	13°40'	13°29'
8	33.55	18.82	304	13°24'	12°7'
9	28.24	27.37	286	13°51'	13°22'
Mean	37.48	26.96	284		

Foot Notes: Well numbers refer to following: 1 - GubioSW-1; 2 - Herwa-1; 3 - Kanadi-1; 4 - Kasade-1; 5 - Kamar-1; 6 - Kinaser-1; 7 - Kuchalli-1; 8 - Masu-1; 9 - Mbeji.

G<sub>si</sub> - geothermal using surface temperature and BHTs;  
G<sub>wi</sub> - geothermal gradient using only BHTs;

#### 4.1. Thermal Conductivity Estimation

In sedimentary basins, thermal conductivity of rock strata mainly depends on the mineral composition, porosity and the nature of the saturating fluid in the pore space. It also depends on rock structure (Sekiguchi, 1984). The bulk thermal conductivity of the porous rock, k<sub>s</sub>, can be expressed as a

function of the *in-situ* conductivity of the solid rock ( $k_m$ ), the *in-situ* conductivity of the saturating fluid in the pore space,  $k_f$ , and the *in-situ* porosity,  $\phi$ , (Sekiguchi, 1984).

For the Bornu-Chad Basin as in other sedimentary basins, overall thermal conductivity mainly depends on the respective values of each constituent of the rock and of the fluid which fills the pores. Thus, effective thermal conductivity of the rock (matrix),  $K_s$ , can be expressed as a function of the respective values of the solid phase ( $K_m$ ) and the pore-fluid ( $K_f$ ) as well as the porosity ( $\phi$ ) of the rock matrix (Sekiguchi, 1984; Brigaud et al. (1989):

$$K_s = K_f^\phi K_m^{(1-\phi)} \quad (1)$$

If the solid phase contains several components, the bulk thermal conductivity is calculated from geometrical model value applied to matrix conductivity:

$$K_m = K_1^{\phi_1} K_2^{\phi_2} K_3^{\phi_3} \dots K_n^{\phi_n} \quad (2)$$

where  $K_n$  represents the thermal conductivity of the principal constituents and  $\phi_n$  their volumetric proportion. Sonic and Density logs were used to determine porosity change with depth. Porosity,  $\phi$ , was computed using sonic log data. This approach makes use of the Wyllie time-average equation (Wyllie et al., 1956):

$$\phi = \frac{\Delta t_{\log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \quad (3)$$

where  $\Delta t_{\log}$  is the transit time on the sonic log ( $\mu\text{s/m}$ ),  $\Delta t_{ma}$  is the transit time of the matrix material (with assumed value of 182  $\mu\text{sec/m}$ ),  $\Delta t_f$  is the transit time of the pore fluid (with assumed value of 607  $\mu\text{sec/m}$ ). This approach was adopted in the absence of samples for experimental measurements. Similar procedures were also employed in determining the thermal conductivities from lithologic data and geophysical well logs by Brigaud et al. (1989), Jessop et al. (2005), Taylor et al. (1989), Dieokuma et al. (2013), Chapman and Pollack (1975), Chapman et al. (1984), Willet and Chapman (1987), Jones et al. (1990) and Majorowicz and Embry (1998). In the study area, the main lithologies are sandstone and shale. The representative thermal conductivity values for sandstone, shale and water were obtained from the results of Brigaud et al. (1989): 1.9 to 2.9  $\text{Wm}^{-1}\text{K}^{-1}$  for sandstone, 1.7 to 2.3  $\text{Wm}^{-1}\text{K}^{-1}$  for shale and 0.6  $\text{Wm}^{-1}\text{K}^{-1}$  for water. The sandstone-shale ratios were deduced from the gamma-ray (lithologic) log. A summary of values adopted in the present work are given in Table 2.

Table 2 - Estimated values of thermal conductivity (K) for the Bornu-Chad Basin. See foot notes for details.

Well	Lon.	Lat.	Lithotypes	K
1	12°25'	12°44'	sandstone, sandy-shale, shale	1.9
2	13°8'	13°50'	Sandstone, sandy-shale, shale	2.9
3	12°25'	13°17'	Sandstone, sandy-shale, shale	2.2
4	13°2'	13°30'	Sandstone, sandy-shale, shale	1.7
5	12°5'	13°14'	Sandstone, sandy-shale, shale	2.0
6	12°16'	13°21'	Sandstone, sandy-shale, shale	2.1
7	13°29'	13°40'	Sandstone, sandy-shale, shale	2.1
8	12°7'	13°24'	Sandstone, sandy-shale, shale	1.8
9	13°22'	13°51'	Sandstone, sandy-shale, shale	2.3
Mean				2.11

#### 4.1. Terrestrial Heat Flux

In heat flow studies, it is usually assumed that thermal energy flows by solid state conduction from the Earth's interior towards the surface. For regions with uniform strata for which thermal conductivity is isotropic and constant, heat flow  $Q_o$  may be computed using Fourier's one-dimensional equation:

$$Q_o = -K_s \frac{dT}{dZ} \quad (4)$$

$$Q_o = K_f^{\left(\frac{\Delta t_{\log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}\right)} \cdot \left(K_{sh}^{\phi_1} K_{st}^{\phi_2}\right)^{\left[1 - \left(\frac{\Delta t_{\log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}\right)\right]} \cdot \frac{dT}{dZ} \quad (5)$$

where  $dT/dZ$  is the thermal gradient constrained to pass through the BHTs and surface temperature and  $K_s$  the average thermal conductivity. In equation 5  $K_{sh}$  and  $K_{st}$  refer to thermal conductivity values of shale and sandstone lithologies, while  $\phi_1$  and  $\phi_2$  are their respective volumetric proportions. Values calculated for heat flow are given in Table 3.

Table 3 - Estimated values of thermal conductivity and heat flow for the Bornu-Chad Basin. See foot notes for details.

Well	Lon.	Lat.	Ele.	$Q_o$
1	12°25'	12°44'	318	63
2	13°8'	13°50'	282	114
3	12°25'	13°17'	306	105
4	13°2'	13°30'	298	88
5	12°5'	13°14'	172	74
6	12°16'	13°21'	301	76
7	13°29'	13°40'	288	71
8	12°7'	13°24'	304	61
9	13°22'	13°51'	286	64
Mean			284	68

Foot Notes: Ele. - Elevation (m); K - thermal conductivity in  $\text{W}/(\text{m K})$ ;  $Q_o$  - surface heat flow in  $\text{mWm}^{-2}$ .  
Lat - Latitude; Lon - Longitude

Elevation changes are illustrated in the map of Figure 13. The distribution of the gradients and heat flow does not necessarily follow any trend as can be seen in the contours of Figures 14 and 15. However, from a conceptual understanding it could be expected to be a complex interplay between a wide range of climatic and geographic factors that may influence the near-surface temperature both directly, i.e. solar radiation, rainfall, evaporation, altitude and indirectly which may include vegetation, topography, periodic cloud cover. Clouds are the main atmospheric factor which determines the amount of solar radiation that reaches the earth. Therefore, the nearly cloud-free Bornu-Chad desert climate receives more solar radiation than the cloudy Niger Delta rainforest climate. This would suggest that the actual mean annual temperature of a region should be an important variable affecting the geothermal gradient.

Surface heat flow map of the study area contoured from data for the fairly dispersed 9 wells is shown in Figure 15. This map shows a general of low heat flow at the north-western part. The iso-flux varies from a minimum of 61  $\text{mWm}^{-2}$  to a maximum of 114  $\text{mWm}^{-2}$ . An average of 68 $\pm$ 6  $\text{mWm}^{-2}$  obtained in the study area which is comparable to the average world heat flow value of 61  $\text{mWm}^{-2}$  (Chapman and Pollack, 1975) for all continents.

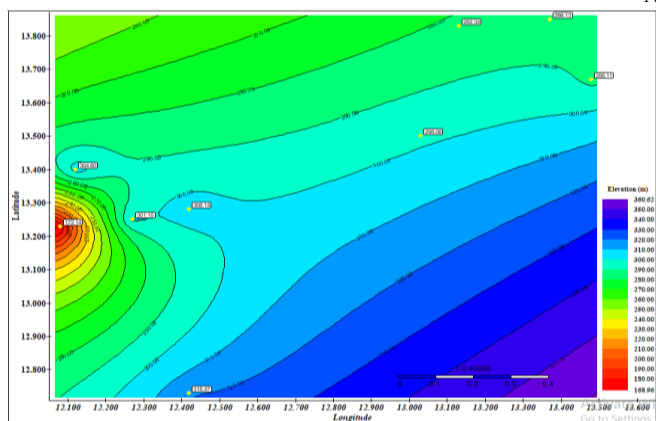


Figure 13 - Elevation Map of Study Area.

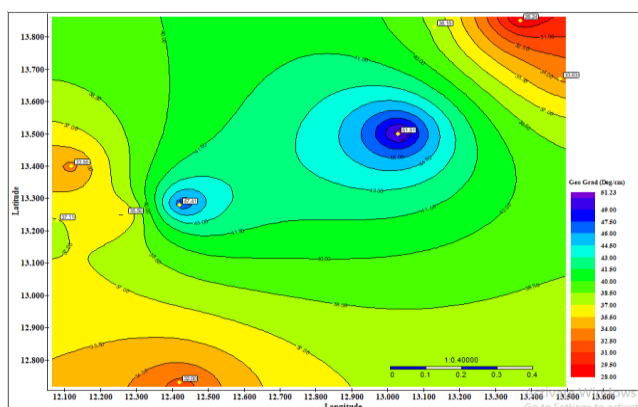


Figure 14 - Geothermal Gradient Map of Study Area.

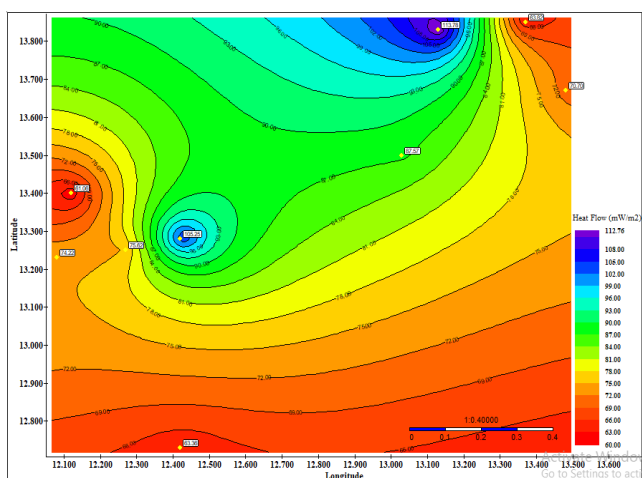


Figure 15 - Heat Flow Map of Study Area.

## 5. Conclusions

From the results, the following observations were made, and conclusions drawn.

- (i) The geothermal gradient using only BHTs ranges from  $15.9^{\circ}\text{Ckm}^{-1}$  to  $38.2^{\circ}\text{Ckm}^{-1}$  with an average of  $27.0^{\circ}\text{Ckm}^{-1}$ .
- (ii) The geothermal gradient using mean annual temperature of  $28^{\circ}\text{C}$  and BHTs ranges from  $28.2^{\circ}\text{Ckm}^{-1}$  to  $51.5^{\circ}\text{Ckm}^{-1}$  with an average of  $37.5^{\circ}\text{Ckm}^{-1}$ .
- (iii) The geothermal gradient using the mean annual temperature and BHTs in the Bornu-Chad is higher than using only BHTs by  $7.0^{\circ}\text{Ckm}^{-1}$ .
- (iv) Heatflow ranges from minimum of  $61\text{mWm}^{-2}$  to maximum of  $114\text{mWm}^{-2}$  with average of  $68\text{mWm}^{-2}$ .

- (v) Geothermal gradient results show a distinct and direct relationship with near-surface conditions. Geothermal gradient is therefore controlled by the near-surface conditions in the Bornu-Chad basin. Due to the effect of the near-surface conditions on sub-surface geothermal gradient estimation, it is recommended that the actual mean surface temperature of Basins be used in geothermal gradients and heatflows estimation.

## 6. Acknowledgements

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