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STATISTICAL ANALYSIS ON CORRECTED WELL-LOG DERIVED TEMPERATURES IN SOUTH-EASTERN NIGER DELTA

O.I. HORSFALL, E. D. UKO & D. H. DAVIES

Department of Physics, Rivers State University of Science and Technology, Port Harcourt Nigeria

ABSTRACT

Analysis of bottomhole temperature (BHT) data from 10 exploration wells in X-Field of south eastern Niger Delta has been carried out in order to determine appropriate correction method and correction factor which can be used to correct the measured bottom hole temperatures, estimate geothermal gradient, true formation temperatures using the corrected BHT and to ascertain the accuracy of the corrected BHT data using statistical tool. Horner and Waple's methods were used to correct the bottomhole temperatures. The study shows that the geothermal gradient of a formation can be effectively determined by first correcting the measured bottom-hole temperatures. Geothermal gradients computed from the various wells indicated that these gradient varies from well to well. These variations may be attributed to changes in thermal conductivity of the rocks within the formation groundwater flow etc. The geothermal gradients ranges from 0.014ºC/m to 0.030ºC/m. A regional average vertical geothermal gradient of 0.023ºC/m or 23ºC/Km was obtained from the study area. The accuracy associated with the corrected bottom-hole temperatures (BHTs) was achieved using the student's t distribution at the desired level. At 95% and 99% confidence interval (CI) and computed corrected BHTs for Well AMK-1 is 113.27 ±8.02 and 113.27 ± 19.14 Similarly for Well AMK-2 is110.43 ± 6.20 and 110.43 ± 27.15. It was observed that the 95% confidence level is more reliable than the 99% since the lower limits of the confidence intervals will be very far from the uncorrected bottom-hole temperatures, in principle the lower confidence interval limit should be equal to or greater than the uncorrected bottom-hole temperatures. The deviations of the uncorrected bottom-hole temperatures (BHTs) from the corrected (BHTs) using both Horner and Waple's methods for wells AMK-1 and AMK-2 are σ_h = 3.30, σ_w =3.82 for AMK-1 and σ_h = 0.26, σ_w =0.81 for AMK-2. Our investigations also show that there is a high degree of closeness between the corrected bottom-hole temperatures (BHTs) values of Horner and Waple's method.

KEYWORDS: Statistical Analysis on Corrected Well-Log Derived Temperatures in South-Eastern Niger Delta

INTRODUCTION

The understanding and strong dependence of temperature study has led to the renewed interest in using thermal data in exploration for hydrocarbons, detection of zones of over pressure, basin analysis, stratigraphic modeling of thermal migration of organic matter, and the study of earth's evolution etc.

Temperature which is the quantitative measure of the tendency of heat to flow in a given direction. is one of the primary factors controlling hydrocarbon generation, sediment diagenesis and migration of hydrocarbons and other fluids (Nwankwo, 2007).

Subsurface temperature increases with depth due to the outflow of heat from radioactive isotopes from the centre of the earth (Lowrie, 1997). The rate of temperature increase with depth is known as geothermal gradient. Geothermal gradient can be used in the study of regional and sub-regional tectonics, assessment of geothermal resource potential, indicator of subsurface temperature distribution, Identification of prospective areas for oil and gas exploration etc.

Borehole temperature is the temperature measured inside the borehole during drilling or when drilling has stopped. Borehole temperature measurement is important in several areas of underground resource investigation and management (Ochuko, 2011). In mineral exploration, it aids the detection of massive mineral exploration. In hydrogeology, temperature variations can be a key element in the understanding of underground water flow.

Bottom hole temperature is the maximum recorded temperature from a wellbore few hours after drilling has stopped. Most bottom hole temperature measurements only provide two or three temperature data; this makes it unreliable in generating borehole temperature profile, also during drilling, most times temperature data are obtained after the perturbing (mainly cooling) effects have subsided hence correction needed to be applied using circulation time, and time since circulation has stopped for correcting the original temperature of the logging suit. Provided several logging runs have been made and data obtained are subjected to corrections, then the true formation temperature can be obtained.

Records show that bottom hole temperatures has been used by various authors in the Niger Delta area for temperature studies (Akpabio and Ejedawe, 2011) used the linear extrapolation between ambient and bottom hole temperatures to develop a geothermal gradient map of the Niger delta. (Bayram et al., 2011) showed in their study that approximate temperature at various depths in different parts of an area can be estimated from temperature gradient map. (Nwankwo and Ekine, 2009) used bottom hole temperature study to show that differences in geothermal gradients may reflect changes in thermal conductivity of rocks, groundwater movement and endothermic reactions during digenesis. (Uko et al., 2002) working on the Northern Niger Delta calculated geothermal gradient to vary between 15.26ºC/Km to 27.27ºC/Km. (Uko et al.,2002) also observed that lithology controls geothermal gradient of a formation. (Nwachukwu, 1976) stated that the geothermal gradient map could be used in the application of the hydrocarbon concept for oil exploration.

GENERAL GEOLOGIC SETTING

The Niger Delta Basin which is one of the world’s most prolific petroleum producing tertiary deltas and accounts for about 5% of the world’s oil and gas reserves is located on the continental margin of the Gulf of Guinea in equatorial West Africa and lies between latitude 4º and 7ºN longitude and 3º and 9ºE(Whiteman, 1982). Three lithostratigraphic units have been identified in the subsurface Niger Delta (Short and Stauble, 1967; Frankl and Cordy, 1967, Avbovbo 1978). These stratigraphic units are from the oldest to the youngest, the Akata, Agbada, and Benin formataions. The Akata formation (Eocene –Recent) is a marine sedimentary succession that is laid in front of the advancing delta. It is mainly uniform under compacted shale with colours consisting of dark grey, sandy, silty shale with plant remains at the top. The shales are rich in planktonic and benthonic foraminifera and were deposited in shallow to deep marine environment.

The Agbada Formation (Eocene-Recent) is characterized by paralic interbedded sandstone and Shale with a thickness of over 3,049m (Reijers, 1996). The top of Agbada Formation is defined as the first occurrence of shale with marine fauna that coincides with the base of the continental-transitional lithofacies. The base is a significant sandstone body that coincides with the top of the Akata Formation (Short and Stauble, 1967). Some shales of the Agbada Formation were thought to be the source rocks, however; Ejedawe et al., (1984) deduced that the main source rocks of the Niger Delta are the shales of the Akata Formation.

The Benin Formation is the youngest lithostratigraphic unit in the Niger Delta. It is Miocene – Recent in age with a minimum thickness of more than 6,000 ft (1,829m) and made up of continental Sands and sandstones (>90%) with few shale intercalations. The sands and sandstones are coarse-grained, sub angular to well rounded and are very poorly sorted. Planktonic foramin

METHODOLOGY

Bottom Hole Temperature Correction Methods

It is evident that measured subsurface temperature from a borehole is always lower than the static formation temperature; this is because when the borehole is being drilled a large quantity of the drilling mud is circulated in the borehole to facilitate the drilling, evacuate the cuttings and stabilize the hole. The adverse effects of this circulation and other drilling influence like thermal properties of the drilling fluids, nature of heat exchange between borehole and the well, duration of drilling, non-equilibrium temperature at the time of measurement etc, on the formation were the reasons why bottom hole temperature data was rarely used in geophysical studies. Hence correction of the measured bottom hole temperature is of utmost importance.

Several methods to correct bottom hole temperatures have been proposed by many authors, such as the correction made (Davies et al., 2007); Henrikson and Chapman, 2002; Onuoha and Ekine, 1999 etc.

In this study the Bottom Hole Temperatures from 10 exploratory wells were collected for correction to true or static formation temperature.

The bottom Hole drilling effects were corrected by using two different methods; The Horner Plot and Waple's methods.

The Horner's Plot method is a concept of a straight line relationship between the measured bottom hole temperatures and circulation times, while Waples method allows corrections to be made on individual recorded bottom hole temperatures.

The Horner's Method

The Horner's Plot is a method that relies on a concept of straight line relationship between BHT and the log of $\Delta t / (\Delta t+T)$. On extrapolation of this straight line to cut across the abscissa at 1, yields the true static formation temperature.

$$\text{BHT's versus } \Delta t / (\Delta t+T) = 1 \quad (1)$$

A plot of BHT versus $\Delta t / (\Delta t+T)$ on semi log paper is a straight line.

Because Lim $\Delta t / (\Delta t+T) = 1$ corresponds to T_f.

D. W Waples et al., Method

Waple*et al* all extrapolated that for individual temperatures, the correction factor f_s, which is applied to the difference between the measured temperatures and the surface temperature is given as below

$$BHT_K = T_S + f_S(T_M - T_S) – 0.0001391(Z – 4498) \text{(Waples and Ramly, 2001)} \quad (2)$$

$$f_S = 1.3433e^{-0.0059(TSC)} \quad (3)$$

Where,

BHT_k = Corrected BHT

f_S = Correction factor

T_S = Surface Temperature (°C)

T_M = Measured Temperature (°C)

Z = Depth (m)

TSC = Time Since Ciculation has Stopped(Hrs)

After the measured bottom hole temperatures were corrected using the various methods statistical analysis was carried out to investigate the level of confidence associated with those corrected temperatures in each wells.

Student's t distribution was used to compute the confidence levels for the mean corrected bottom hole temperature at the desired levels and the Chi-Square for the standard deviation. (Edward and Srivastava 1989; Morris 1975)

Using coefficient of variation and confidence interval. The desired level used for this study is 95% and 99% intervals. (Murray et al., 1975)

The Student's t Distribution

$$BHT_K \pm tc(S/V) \tag{4}$$

$$V = N - K \tag{5}$$

$$BHT_K \pm t_c\left(\frac{S}{\sqrt{N-1}}\right) \tag{6}$$

BHT_K = Corrected Bottom Hole Temperature

t = Critical values or confidence coefficients, which depends on the desired level of confidence and the sample size

S = Standard Deviation

V = Degree of freedom

N = Sample population.

RESULTS AND DISCUSSIONS

Using the Horner plot and Waple's methods to correct for the drilling effects on bottom-hole temperatures (BHT), results were obtained which are presented in the various tables and figures below. The Horner's plot assumes a linear relationship between BHT at a given depth from each of several logging runs against the log of (Δt/Δt + t) which is a dimensionless time. The extrapolation of this straight line cuts the absisca at 1 and yields the true static formation temperature. i.e. BHT_K. While the Waple's method approach allows correction to be made on individual recorded BHT data.

Table 1 shows the bottom-hole temperatures (BHT) obtained from the ten different wells and its correction using the Horner's plot method. The table is showing the depths, uncorrected bottom-hole temperature (BHT) values, the corrected bottom-hole temperature (BHT_h) values, the time since circulation has stopped (T), and the length of time that the borehole was subjected to the cooling effect of the fluid (Δt). The effect of this correction is to raise the uncorrected bottom-hole temperatures to the static formation temperature or very close to the formation temperature of the formation under consideration.

Table 2. shows the corrected bottom-hole temperatures using the Horner's method. These corrected values give the formation temperatures of the various wells. The corrected values obtained indicates that in all the wells under study there is the possibility of hydrocarbon formation since the corrected temperatures falls within the range of temperatures where maturation occurs(60º - 120º).

Table 3 also shows the bottom-hole temperatures (BHT) obtained from the ten different wells and its correction using the Waple's method. The table is showing the depths, uncorrected bottom-hole temperature (BHT) values, the corrected bottom-hole temperature (BHT_w) values, and the number of runs. Similarly the effect of this correction is to raise the uncorrected bottom-hole temperatures to the static formation temperature or very close to the formation temperature of the formation under consideration.

Table 4 shows the corrected bottom-hole temperatures using the Waple's method. These corrected values also give the formation temperatures of the various wells. The corrected values obtained indicates that in wells AMK-1 – AMK-8, and AMK-10 under study there is the possibility of hydrocarbon formation since the corrected temperatures falls within the range of temperatures where maturation occurs(60º - 120º). AMK-9 has temperature below the range of maturation and subsequent formation of hydrocarbon.

Table 5 shows the comparison of the corrected bottom-hole temperature values (BHT's) using both Horner and Waple's methods. Careful observation indicates that the difference in the corrected bottom-hole temperature values from the two methods are very close.

Table 6 shows the geothermal gradients computed from the various wells, these gradients vary from well to well. The geothermal gradients range from 0.014ºC/m to 0.030ºC/m. A regional average geothermal gradient of 0.023ºC/m was obtained from the study area.

Table 7 is a statistical table showing the confidence levels of the corrected bottom-hole temperature values using Waple's method the desired confidence levels used are 95% and 99% respectively. The statistical analysis indicated that at 95% confidence level the corrected bottom hole temperature values are reliable. This is evident in the range of values presented in table 7. The assurance of the corrected bottom-hole temperature values is that, the lower limit of the confidence level should always be equal to or higher than the average uncorrected bottom-hole temperature in the particular well under consideration as evident in wells AMK-2, AMK-5, AMK-9 and AMK-10 where the lower limit values of the confidence level is higher than the uncorrected bottom-hole temperature values. In essence if the lower limit temperature value is lower than the average uncorrected bottom-hole temperature values, then it is advisable to only work with the upper limit bottom-hole temperature values. Using 99% confidence level the lower limit exhibited bottom-hole temperature values that are very far from the average uncorrected bottom-hole temperature values.

Table 8 shows the deviations of the uncorrected bottom-hole temperatures from the corrected bottom-hole temperatures for both methods, the values obtained showed that deviations of uncorrected bottom-hole temperatures from the corrected values for both methods are not too far from each method in the various methods.

Table.9 shows the coefficient of variations in percentage using both methods.

Figures1. AMK-1 - AMK-10 presented below shows the variation of the uncorrected bottom-hole temperature and corrected bottom-hole temperature with depth with. The temperatures increases with an increasing depth. The red line indicates the corrected bottom-hole temperature while the blue represents the uncorrected bottom-hole temperatures. From the plots it was observed that the corrected temperature values is higher than the uncorrected temperature as evident in the red and blue lines. Figures 11 – 20 is showing the Horner's plot for wells AMK-1 - AMK-10. The general knowledge of the Horner's extrapolation is to substitute X=1 in the linear equation displayed on the plots to give the static formation temperatures of various wells.

Figure 21 is plot showing corrected bottom-hole temperatures with depth to give the regional geothermal gradient within the study area.

Table 1: Bottom-Hole Temperature Correction Values Using Horner's Method

Δt (Hrs)	T(Hrs)	Δt+T(Hrs)	(Δt/Δt+T)	BHT(°C)	BHT$_h$(°C)
7.00	6.00	13.00	0.5385	104	114.35
11.50	6.00	17.50	0.6571	107	
19.50	6.00	25.50	0.7647	109	
7.00	6.00	13.00	0.5385	100	116.67
11.50	6.00	17.50	0.6571	105	
19.50	6.00	25.50	0.7641	108	
8.25	3.00	11.25	0.7333	116	115.86
11.00	3.00	14.00	0.7857	125	
13.50	3.00	16.50	0.8182	128	
1.50	6.00	7.50	0.2000	102	112.54
6.00	6.00	12.00	0.5000	106	
11.50	6.00	17.50	0.6571	108	
7.25	4.00	11.25	0.6440	100	157.51
10.00	4.00	14.00	0.7143	109	
12.50	4.00	16.50	0.7576	119	
7.00	6.00	13.00	0.5385	90	100.35
11.50	6.00	17.50	0.6571	93	
19.50	6.00	25.50	0.7647	95	
7.00	6.00	13.00	0.5385	91	101.35
11.50	6.00	17.50	0.6571	94	
19.50	6.00	25.50	0.7647	96	
1.50	6.00	7.50	0.2000	67	81.54
6.00	6.00	12.00	0.5000	71	
11.50	6.00	17.50	0.6571	73	
8.25	4.00	12.25	0.6735	50	76.02
11.00	4.00	15.00	0.7333	54	
13.50	4.00	17.50	0.7714	58	
7.25	5.00	12.50	0.5800	60	90.08
10.00	5.00	15.50	0.6667	65	
12.50	5.00	17.50	0.7143	70	

Table 2: Corrected Bottom-Hole Temperature Values Using Horner's Method

Wells	BHT$_h$(°C)
AMK-1	114.35
AMK-2	116.67
AMK-3	115.86
AMK-4	112.54
AMK-5	157.51
AMK-6	100.35
AMK-7	101.35
AMK-8	81.54
AMK-9	76.02
AMK-10	90.08

Table 3: Bottom-Hole Temperature Correction Values Using Waple's Method

Wells	Run No	Depth(m)	BHT(°C)	BHT$_w$(°C)
AMK-1	1	1350	104	105.32
	2	2650	107	115.30
	3	3048	109	119.20
AMK-2	1	700	100	105.12
	2	2200	105	112.10
	3	3200	108	114.08
AMK-3	1	2100	116	120.00
	2	3100	125	129.97
	3	3700	128	133.90
AMK-4	1	600	102	104.49
	2	2300	106	109.46
	3	3658	108	111.44
AMK-5	1	1500	100	105.72
	2	2500	109	115.66
	3	3300	119	125.60
AMK-6	1	1700	90	95.72
	2	3000	93	99.69
	3	3574	95	102.56
AMK-7	1	2500	91	93.00
	2	3200	94	96.00
	3	3650	96	98.55
AMK-8	1	600	67	72.58
	2	2100	71	76.55
	3	3100	73	78.53
AMK-9	1	800	50	54.14
	2	1500	54	59.12
	3	2861	58	63.09
AMK-10	1	1200	60	64.47
	2	2800	65	69.44
	3	3300	70	74.40

Table 4: Average Corrected Bottom-Hole Temperature Values Using Waple's Method

Wells	BHT$_w$(°C)
AMK-1	113.27
AMK-2	110.43
AMK-3	128.00
AMK-4	108.46
AMK-5	115.66
AMK-6	99.32

Table 4: Contd.,

AMK-7	95.85
AMK-8	75.87
AMK-9	58.78
AMK-10	69.44

Table 5: Comparison between Corrected BHTS Using Horner and Waple’s Methods

Well No	Horner’s Method	Waple’s Method
AMK-1	114.35	113.27
AMK-2	116.67	110.43
AMK-3	154.86	128.00
AMK-4	112.54	108.46
AMK-5	157.51	115.66
AMK-6	100.35	99.32
AMK-7	101.35	95.85
AMK-8	81.54	75.87
AMK-9	76.02	58.78
AMK-10	90.08	69.44

Table 6: Geothermal Gradients in the Various Wells

Well No.		Geothermal Gradients °C/m
AMK-1		0.030
AMK-2		0.027
AMK-3		0.028
AMK-4		0.023
AMK-5		0.030
AMK-6		0.020
AMK-7		0.020
AMK-8		0.016
AMK-9		0.013
AMK-10		0.014

Table 8: Deviations of the Uncorrected BHTS from the Corrected BHTS for Both Horner and Waple’s Methods

Wells	$\bar{X}_W$	σ_w	$\bar{X}_h$	σ_h
AMK-1	6.61	3.82	6.68	3.30
AMK-2	6.10	0.81	12.34	0.26
AMK-3	4.96	0.71	11.07	0.46
AMK-4	3.13	0.45	7.21	0.20
AMK-5	6.33	0.43	8.75	0.62
AMK-6	6.33	0.75	7.68	0.16
AMK-7	2.18	0.25	7.49	0.16
AMK-8	5.55	0.21	11.21	0.20
AMK-9	4.78	0.46	22.02	0.26
AMK-10	4.45	0.01	5.33	0.33

Table 9: Coefficient of Variation (CoV) for Both Horner and Waple’s Methods

Well	$(CoV)_h$%	$(CoV)_w$%
AMK-1	49.00	57.70
AMK-2	2.00	13.00
AMK-3	4.00	14.00
AMK-4	3.00	14.00
AMK-5	7.00	7.00
AMK-6	2.00	12.00

Table 9: Contd.,

AMK-7	2.00	11.00
AMK-8	2.00	4.00
AMK-9	1.00	10.00
AMK-10	0.20	6.00

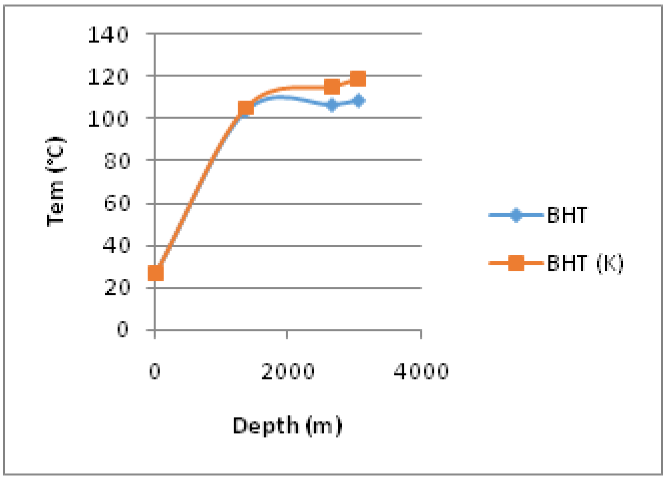

Figure 1: BHT Variation with Depth for AMK-1

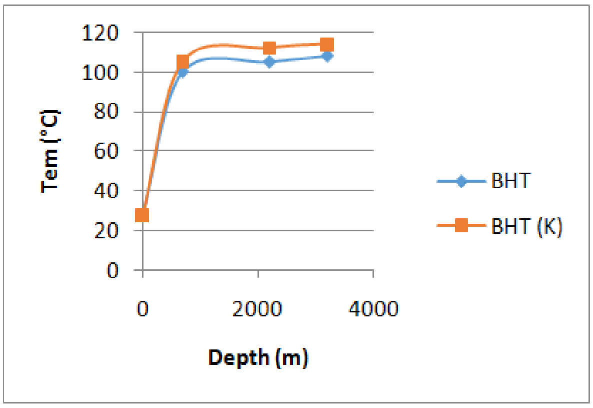

Figure 2: BHT Variation with Depth for AMK-2

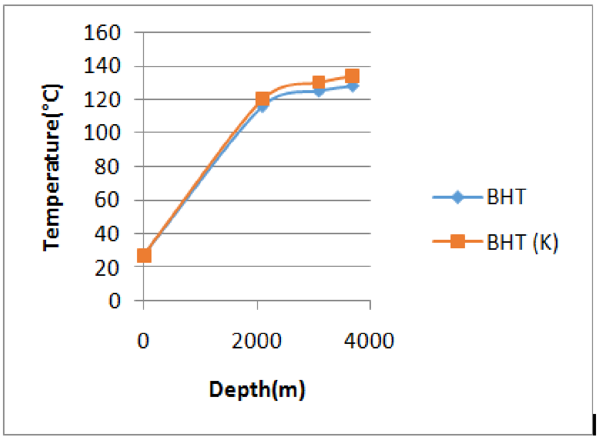

Figure 3: BHT variation with Depth for AMK-3

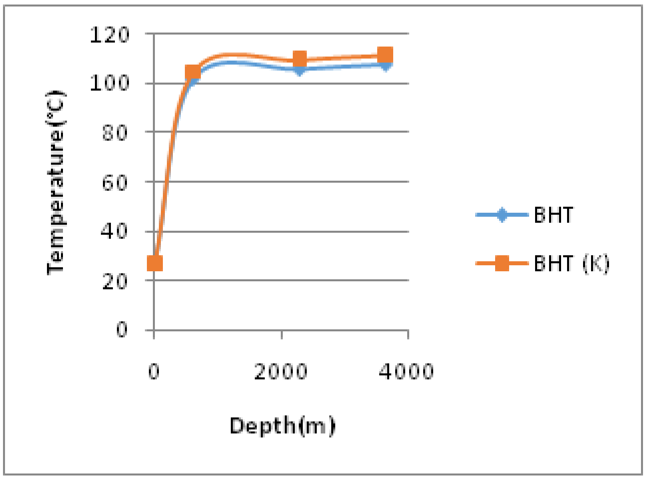

Figure 4: BHT Variation with Depth for AMK-4

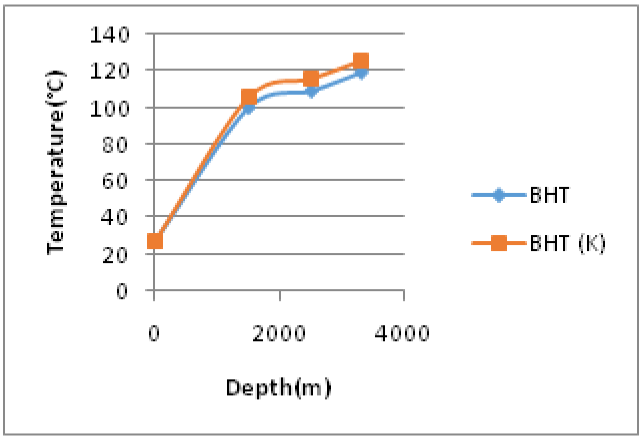

Figure 5: BHT Variation with Depth for AMK-5

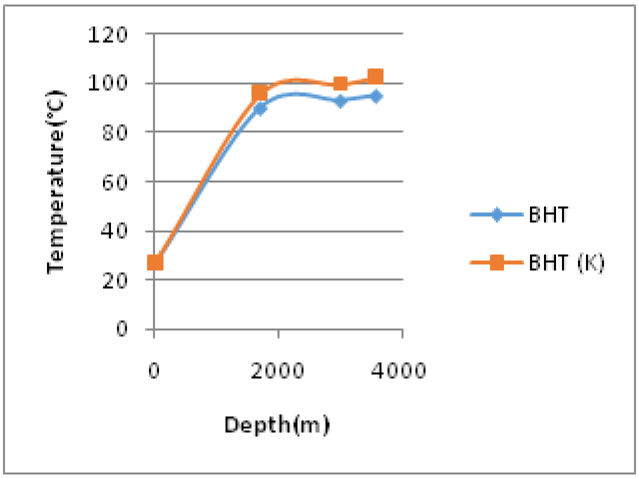

Figure 6: BHT Variation with Depth for AMK-6

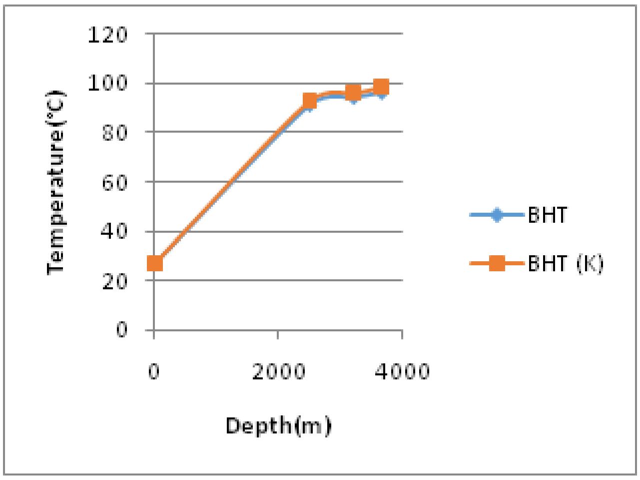

Figure 7: BHT Variation with Depth for AMK-7

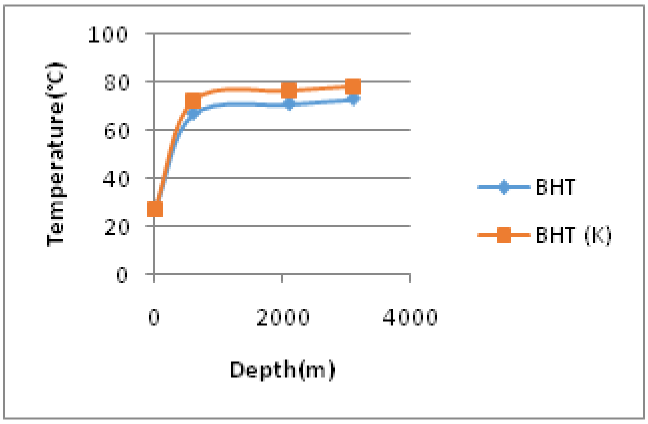

Figure 8: BHT Variation with Depth for AMK-8

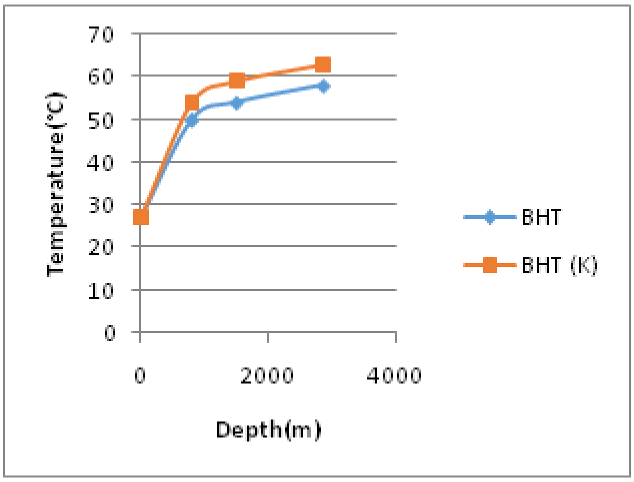

Figure 8: BHT Variation with Depth for AMK-9

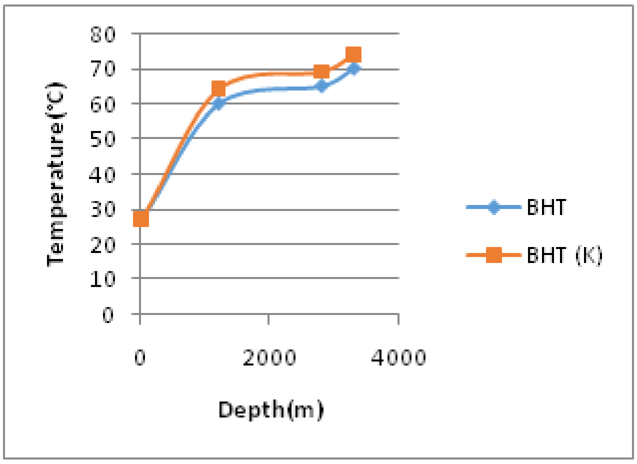

Figure 9: BHT Variation with Depth for AMK-10

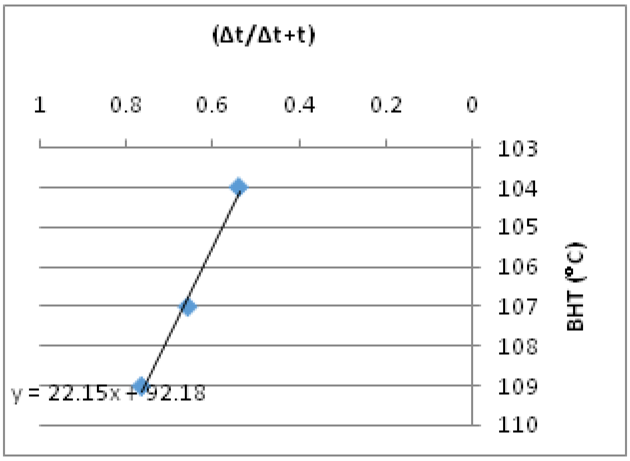

Figure 11: Horner's Plot AMK-1

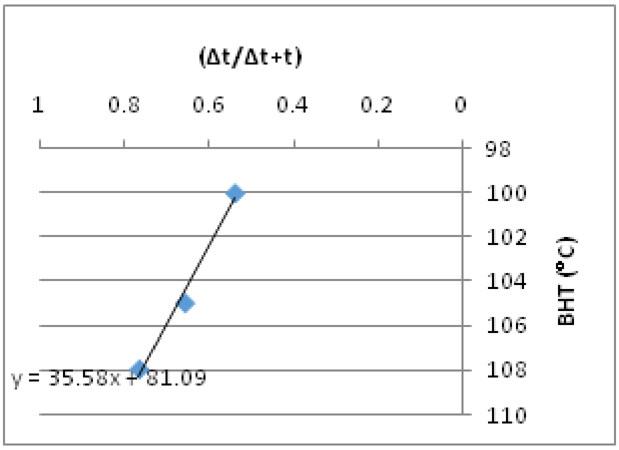

Figure 12: Horner's Plot AMK-2

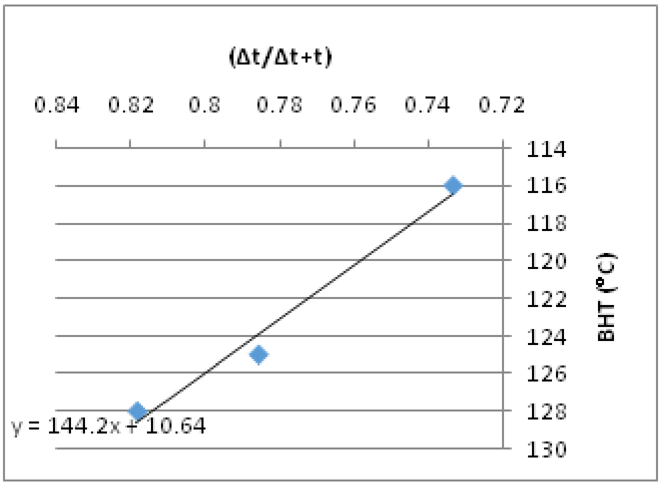

Figure 13: Horner's Plot AMK-3

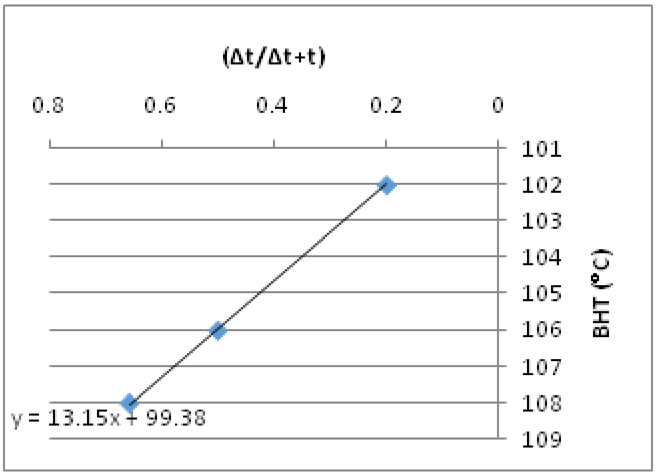

Figure 14: Horner's Plot AMK-4

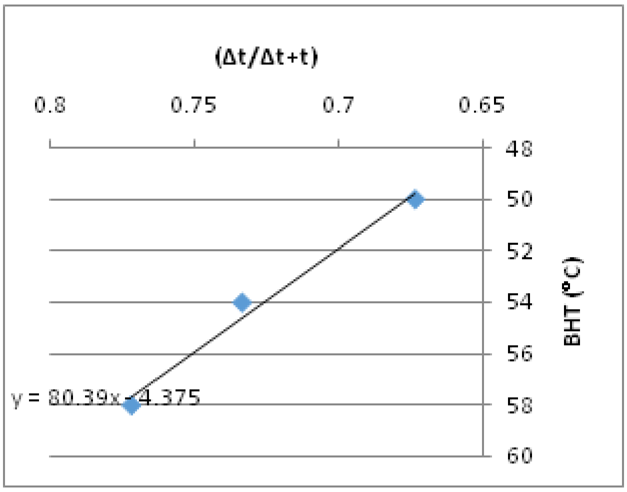

Figure 15: Horner's Plot AMK-5

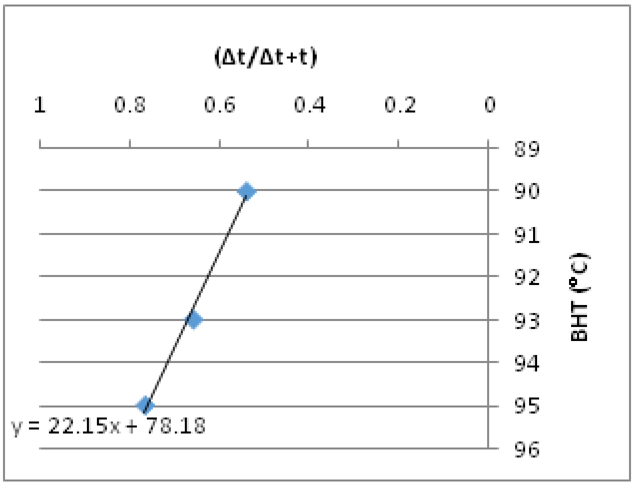

Figure 16: Horner's Plot AMK-6

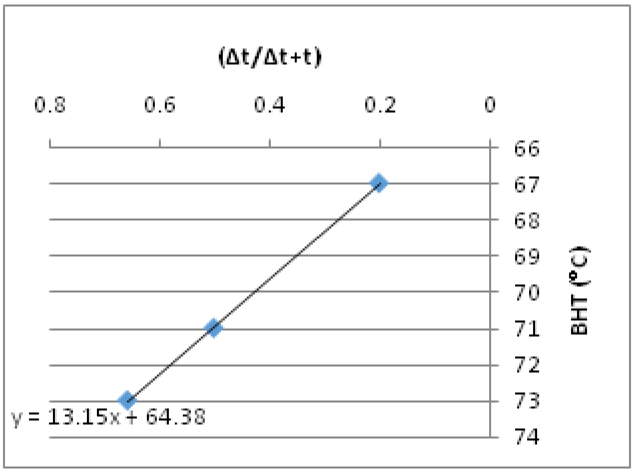

Figure 17: Horner's Plot AMK-7

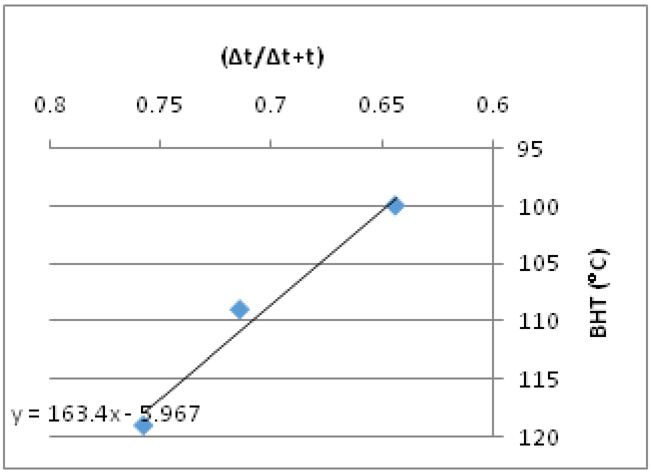

Figure 18: Horner's Plot AMK-8

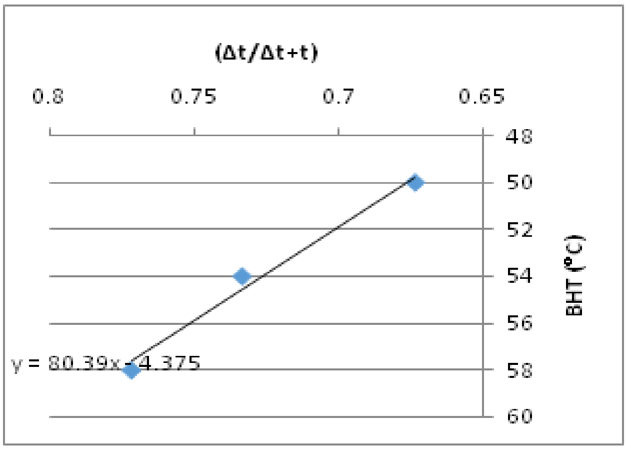

Figure 19: Horner's Plot AMK-9

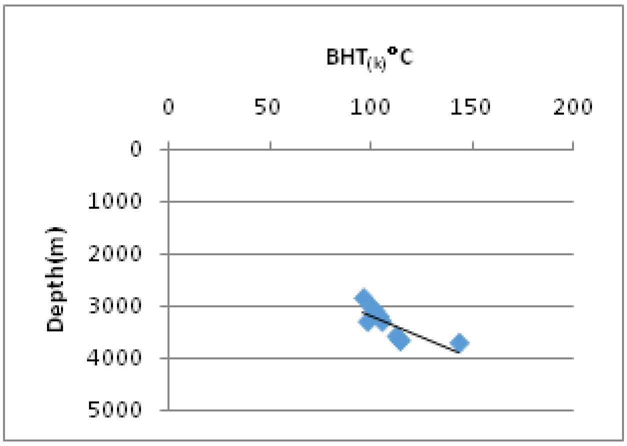

Figure 20: Horner's Plot AMK-10

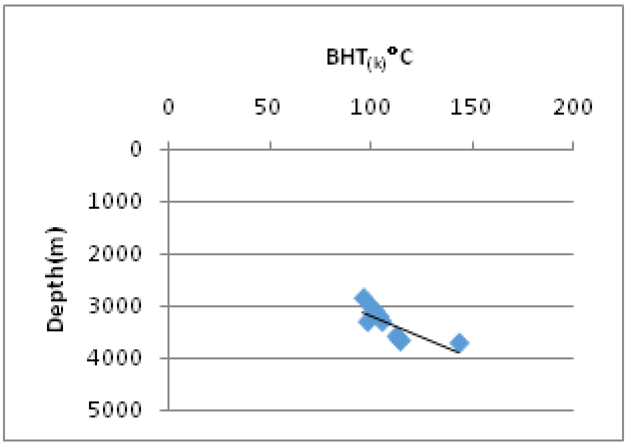

Figure 21: Plot of Corrected BHT versus Depth to Give the Geothermal Gradient of the Study Area

CONCLUSIONS

From the results of the bottom-hole temperature correction and the statistical analysis, the following observations were made and conclusions drawn.

- Horner plot and Waple's method are effective method for the correction of measured bottom-hole temperatures

(BHTs) to static formation temperature of a formation.

- This study has confirmed that the geothermal gradient of a formation can be effectively determined by first correcting the measured bottom-hole temperatures. The geothermal gradients computed from the various wells indicated that these gradients varies from well to well. These variations may be attributed to changes in thermal conductivity of the rocks within the formation groundwater flow etc. The geothermal gradients ranges from 0.014ºC/m to 0.030ºC/m. A regional average vertical geothermal gradient of 0.023ºC/m or 23ºC/Km was obtained from the study area.
- The accuracy associated with the corrected bottom-hole temperatures (BHTs) was achieved using the student's t distribution at the desired level. At 95%CI and 99%CI and computed corrected BHTs for Well AMK-1 is 113.27 ±8.02 and 113.27 ± 19.14 Similarly for Well AMK-2 is110.43 ± 6.20 and 110.43 ± 27.15. It was observed that the 95% confidence level is more reliable than the 99% since the lower limits of the confidence intervals will be very far from the uncorrected bottom-hole temperatures, in principle the lower confidence interval limit should be equal to or greater than the uncorrected bottom-hole temperatures.
- The deviations of the uncorrected bottom-hole temperatures (BHTs) from the corrected (BHTs) using both Horner and Waple's methods for wells AMK-1 and AMK-2 are

  $\sigma_h = 3.30$, $\sigma_w = 3.82$ for AMK-1 and $\sigma_h = 0.26$, $\sigma_w = 0.81$ for AMK-2
- Our investigations also show that there is a high degree of closeness between the corrected bottom-hole temperatures (BHTs) values of Horner Plot and Waple's method. It is also found that there is good agreement between the various correction methods.

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