GLOBAL JOURNAL OF GEOLOGICAL SCIENCES VOL. 3, NO. 2, 2005: 133 - 142
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BOTTOM-HOLE TEMPERATURE CORRECTION-THE CHAD BASIN, N. E., NIGERIA CASE STUDY

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(Received 1 December 2004; Revision accepted 3 June, 2005)

ABSTRACT

Correction of the effects of drilling on bottom-hole temperatures, BHTs, measured in drilled wells require multiple measurements in the same well at the same depth but at different elapse times in order to predict true formation temperatures, TFTs. The relaxation of the same-depth requirement for depths differing by less than 100 m allowed the application of two such methods to a qualifying pair of single BHTs from where estimates of Horner plot slope and thermal diffusivity, κ were obtained. By assuming both the slope and κ to be typical of the basin, several correction methods were employed to estimate TFTs from a dataset collected from the log-headers of wells drilled for oil and gas exploration in the Chad basin, N.E., Nigeria. Although the different TFT estimates did not agree, sensitivity of the methods to variations of either the slope or κ enabled the results to be used to define the range within which the actual TFTs lie. TFT estimates obtained using empirical temperature correction methods were observed to fall within the defined range, and suggest that the data are amenable to empirical correction. Based on significant correlations, empirical equations relating correction and drilled well parameters were therefore derived.

KEYWORDS: Bottom-hole temperature (BHT), True Formation Temperature (TFT), Horner plot slope, thermal diffusivity, same-depth relaxation.

INTRODUCTION

Records of temperature taken soon after the drilling of oil and gas wells constitute the bulk of temperature observations that are being used by geoscientists with increasing frequency for the purpose of geothermal studies. The circulation of fluid during and soon after drilling disturbs the thermal state of the formation. The temperature recorded by the sonde lowered into the drilled hole, called the 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. Properly recorded BHT gradually approaches the TFT as the time after circulation of the drilling fluid increases. After sufficient time lapse, the two temperatures become equal, and the well is said to have completely equilibrated. Because sufficient time is never allowed for a well to completely equilibrate before BHTs readings are taken, the records have to be corrected. A plethora of schemes have been devised for correcting the effect of the circulation of drilling fluid on BHTs and by which TFTs may be estimated. The purpose of this paper is to review the correction schemes with the view to determining the most appropriate, including devising new schemes, to be used for a dataset from the Chad basin, NE, Nigeria.

TEMPERATURE CORRECTION SCHEMES

The relationship between BHTs and TFT is affected by many factors, a lot of which are unknown. In an attempt to simplify this complex relationship, many correction schemes have been proposed. These correction schemes may however be grouped into two broad types - those based on the model of temperature buildup in drilled wells, and the empirical methods.

Methods Based on Model of Temperature Buildup in Wells

The method of Horner plot is the oldest BHT correction method in this group as well as the most commonly employed. It was first derived by Bullard (1947) and Lachenbruch and Brewer (1959), and owes its name to the fact that the equation on which it is based is identical to an equation developed by Horner (1951) for the prediction of the recovery of pressure in drilled petroleum reservoir rocks. The temperature disturbance caused by both drilling and fluid circulation is modelled as a line heat sink in a homogeneous medium. In the approximate solution of the full line source equation, Bullard (1947) showed that the TFT is dependent only on three parameters- the BHT recorded, the duration of circulation of the drilling fluid, called the circulation time, t_c, and the time elapse, t_e. In order to apply this correction, two or more sets of time-temperature observations, measured in the same well, at the same depth but at difference elapse times are required. Although not the most accurate, the Horner plot method of BHT correction is found to be more precise than most other methods (Hermanrud et al., 1990). The method has certain drawbacks, principal among which is the availability of multiple BHTs measured in the same well, at the same depth, but at different elapse times. Another drawback is that the accuracy of the method depends on the accuracy and reliability of the three parameters, t_e, t_c, and BHT. Speece et al. (1985) have reported on many of the practices contributing to the lack of accuracy and reliability of the parameters, and hence of the method. The times at the end of drilling fluid circulation and logger at bottom of hole are commonly recorded on log headers, and t_e, is obtained as the difference between the two. Where t_e is unknown, the BHT cannot be corrected by the method. The least reported Horner plot parameters is t_c, and where this is unavailable, Chapman et al. (1984), Reiter and Jessop (1985), Willet and Chapman (1988), Deming and Chapman (1989), Correia et al. (1990) and Hermanrud et al. (1990) have devised various ways of obtaining it.

The model upon which the Horner plot method is based involves simplifying assumptions concerning the geometry of the borehole and the rate of heat exchanged between the wall rock and the drilling fluid. Even when suitable set of data is available, the indiscriminate application of the method has been discouraged (Lachenbruch and Brewer, 1959; Dowdle and Cobb, 1975; Luheshi, 1983; Drury, 1984; and Shen and Beck, 1986). In general, the accuracy of the method increases as the ratio of t_c to t_e decreases. In particular, the method is known not to accurately approximate the actual rise of temperature in the well until t_e is at least the duration of the t_c (Shen and Beck, 1986). Deming and Chapman (1988a and b)

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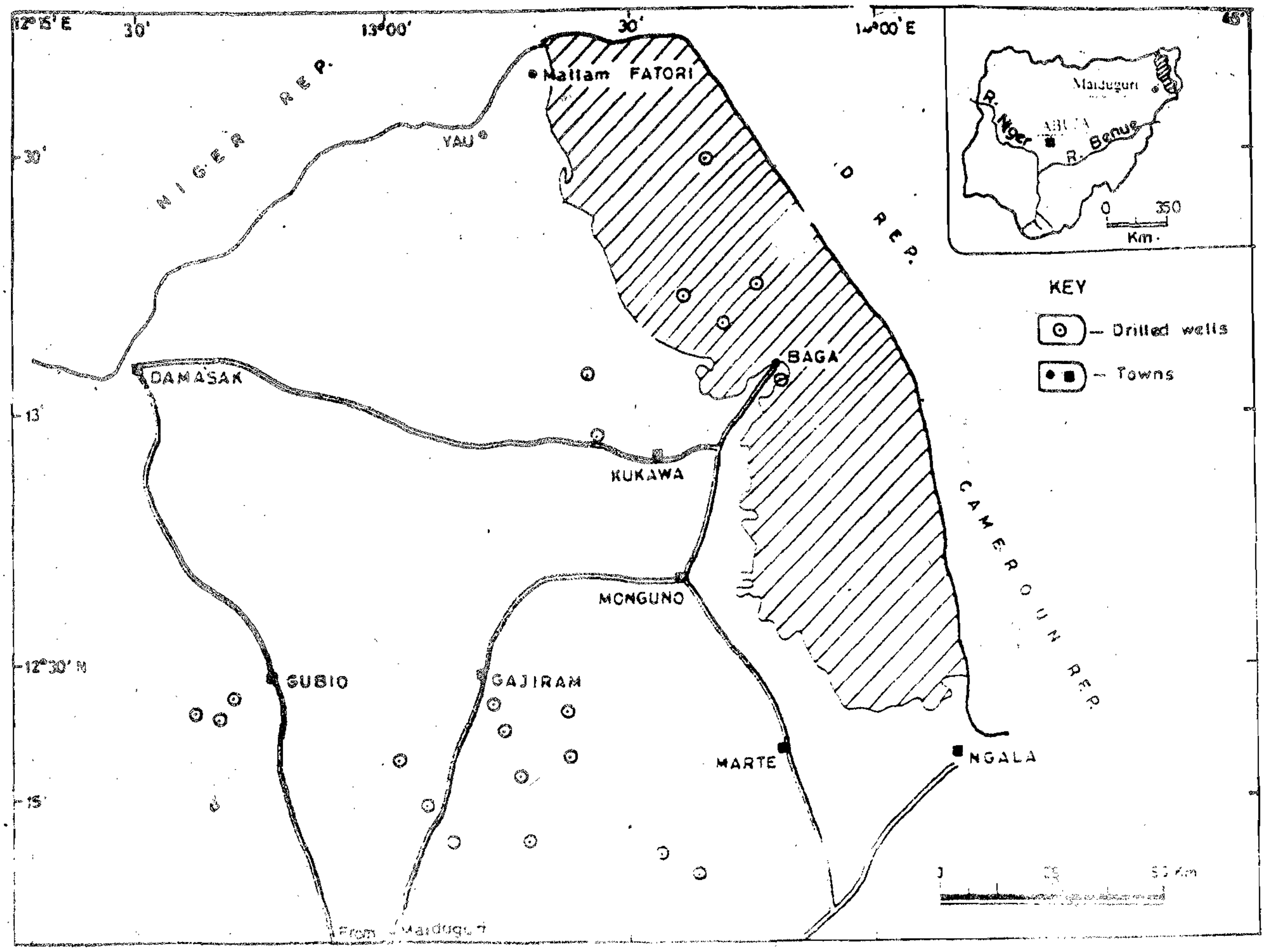
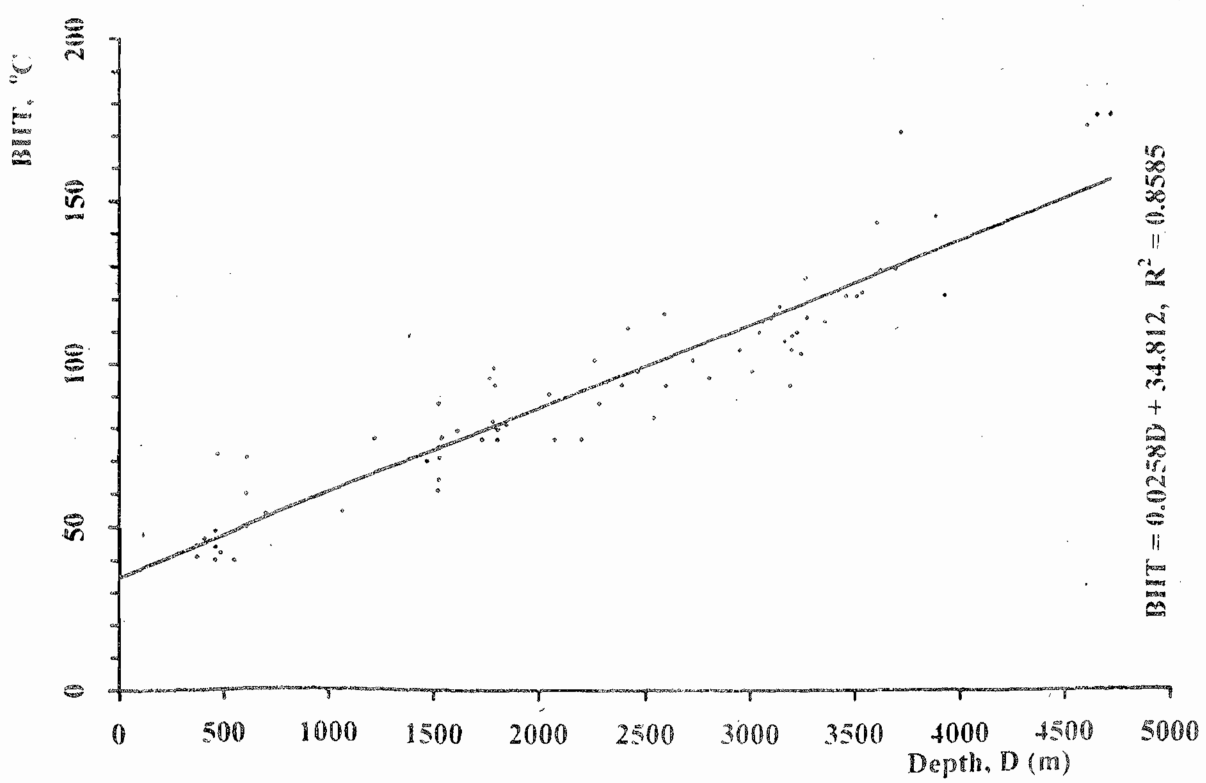
rejected elapse times shorter than 4 or 5 hours as being unsuitable for the application of the Horner plot corrections, while Drury (1984) and Roux et al., (1982) recommended the use of the method only when t_e is twice or more, and three times t_c respectively. The assumption of a line source as basis for the Horner plot method is known to get progressively worse as the borehole diameter gets bigger (Luheshi, 1983). The method is also known to be bias towards under estimating TFT for values of $t_c/t_e > 1/3$ (Dowdle and Cobb, 1975), and Roux et al. (1982) has developed a procedure to compensate for the theoretical bias of the method for the occasions when $t_c/t_e > 1/3$. Beardsmore and Cull (2001) have however observed that the Roux et al. (1982) *correction* is sensitive to data quality, and argued that where the extra parameters needed for the correction exist and are of sufficient quality then the Cooper and Jones (1959) method of BHT correction is recommended over the Horner plot method.

The Cooper and Jones (1959) *method* of BHT correction, adjudged to be the most accurate of many others (Hermanrud et al., 1990), is similar in some respect to those of Middleton (1979) and Leblanc et al. (1981). The method modelled the thermal conditions within the drilled hole by assigning different thermal properties for the drilling fluid and the wall rock while the latter two methods assumed a thermally homogeneous medium, like the method of the Horner plot. In contrast to the Horner plot method, however, all three methods assumed a hole of finite dimension drilled and filled with a cooler fluid but ignored the effects of its circulation. The models have three unknowns, namely, TFT, drilling fluid temperature, T_f, and the thermal diffusivity of the wall rock, κ. A time-temperature set of data observed at the same depth at three different times would therefore be needed to estimate TFT. Because such data are hard to come by, the methods are difficult to apply in these forms. By assuming an average value for κ, the number of unknowns is reduced to two, and the methods may be applied to time-temperature data set consisting of only two BHT observations (Leblanc et al., 1981). This step has been likened to the use of an average circulation time in the application of the Horner plot method (Deming, 1989). In addition, if T_f is recorded, or a value is assigned to it, the methods may be applied to single BHT observations that constitute the bulk of BHT data. It is not known whether the TFT estimated using the three methods with either one or both *simplifications* are better or worse than similar estimate made by the Horner plot method in spite of the differences in their background models. Ekine (1989), however, applied the Leblanc et al. (1981) method with both simplifications to BHTs from the Anambra Basin, SE, Nigeria, and obtained *corrections whose* range appear similar to that obtained by Correia et al. (1990) who corrected BHTs from the Jeanne D'Arc Basin, Atlantic offshore, Canada, using the Horner plot method.

The deficiency of the last methods was addressed by the methods of Lee (1982), Luheshi (1983), and Shen and Beck (1986) whose models also incorporated finite borehole radius. In contrast to the Middleton (1979) and Leblanc et al. (1981) models however, these models incorporated finite circulation time and different thermal properties for the drilling fluid and the wall rock. *Without the over simplification of the* previous methods, the three methods modelled temperature buildup in





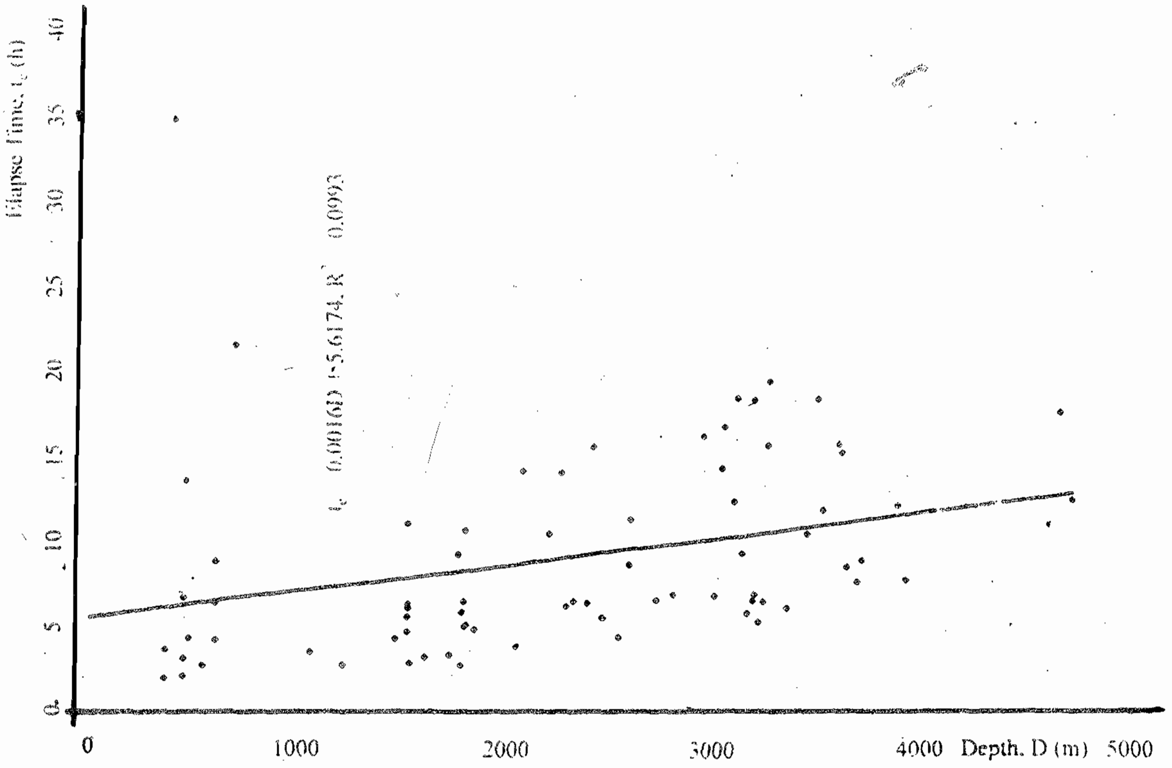
drilled wells during shut-in, Lee (1982) by finite element method; Luheshi (1983) by finite difference method; and Shen and Beck (1986) by using Laplace transforms. This lack of simplifying assumptions, however, translates to the need for large number of unknown variables or variables that are known only by guess. In particular, Luheshi (1983) investigated the sensitivity of TFTs to variations of κ, conductivities of the drilling fluid and wall rock, the duration of drilling fluid circulation, size of the well bore and fluid flow into and out of the well, and concluded that temperature variations affect borehole equilibration only for distances less than one metre from the bottom of the hole, while free convection is unimportant, although Ribeiro and Hamza (1986) showed that additional heat transport by formation fluids into the well results in shorter recovery time. This suggests that models ignoring formation fluid invasion of the well are likely to under estimate TFTs. Shen and Beck (1986) compared and contrasted the accuracy of different correction schemes and concluded that the choice of a scheme is more critical when working with BHTs measured at short t_e in comparison to t_c, and that in such situations the Horner plot method is likely to systematically underestimate TFTs.

The models of Lee (1982), Luheshi (1983) and Shen and Beck (1986) are similar to the model of Cao et al. (1988) in that they all accurately modeled temperature buildup in drilled wells without compromising the complexity of the problem. Cao et al. (1988) listed five parameters of the temperature buildup problem. These parameters are the TFT, κ, T_f, the thermal invasion distance and heating efficiency factor, and argued that because the last three enter their equation in a non-linear manner, only a dataset with three BHTs measured in the same well at the same depth but at different elapse times are needed to estimate all five parameters. They however showed that a 1 °C noise in the data would, by their method, result in TFT estimate that is in error by as much as 50 °C, and that the Horner plot method yields better results when the elapse times are closely spaces, and yields nearly identical results when the elapse times are widely spaced.

Empirical Correction Schemes

The knowledge that BHTs are lower than the TFTs has made researchers believed that any form of correction, no matter how flimsy its justification, is better than none (Speece et al., 1985). In devising empirical BHT correction schemes, sample BHTs are usually corrected using some reliable method and a relationship between a correction parameter and any parameter of the drilled well is then established. This relationship is thereafter assumed to be applicable to the correction of other BHTs in the same region. To make the correction statistically reliable, the number of sampled BHTs is made as large as possible.

The AAPG (1976) gradient correction scheme is perhaps the most prominent of the empirical BHT correction methods. The correction is based on the comparison of recorded BHTs in 602 wells from the States of Louisiana and Texas, USA with equilibrium temperatures measured under controlled engineering conditions. The correction to geothermal gradient is expressed as a third degree polynomial in depth. Deming (1989) has multiplied the gradient correction with depth to obtain the temperature correction, the magnitude of which varies from 0 °C at zero depth to a maximum of 14.1 °C at the depth of 4574 m. Thereafter, the correction decreases to 9 °C at 6000 m, possibly because the logging tools take longer time to reach the bottom of the deeper holes, allowing the borehole to equilibrate. The provision of two sets of constants for the AAPG (1976) correction suggests that the correction procedure is not statistically reliable outside the areas within which it was calibrated, although Speece et al. (1985) has applied the average correction to data from Michigan basin, arguing that temperature gradient in the control areas and the Michigan Basin do not differ greatly. Willet and Chapman (1988), not satisfied with the application of the AAPG (1976) correction to data from the Uinta Basin, Utah, USA, used a dimensionless time variable to modify it. We are unaware of any attempt to compare corrections by this method with those from other methods, particularly the AAPG (1976) method, which it is attempting to improve upon. Majorowicz et al. (1990), also not satisfied with the AAPG (1976) method for the



data from the Mackenzie Delta Basin, Northern Canada, as well as with the modification of Willet and Chapman (1988), proposed a scheme that expresses percentage correction, obtained using the Horner plot method, as a second-degree polynomial in t_e. Variations as large as 30 % or greater (Majorowicz et al., 1990), suggests that the accuracy of the method may be low.

Bhen Dhia (1988) corrected BHTs records from wells drilled in Tunisia by comparing them with drill stem test (DST) temperature records, with the underlying assumption that TFT are the same as their corresponding DST temperatures. In reality, however, the relationship between TFT and DST temperatures is unknown. Other drawbacks for the method include lack of records of DST temperatures for the correction method to be applied as well as the reliability of the application of DST-calibrated TFT in one well to another. In general, the results obtained compared favourably well with those obtained using the Horner plot method. An arbitrary linear correction to BHT has also been proposed and used for the data from the North Sea (Andrews-Speed et al., 1984). For an average geothermal gradient of 25 °C/km, Deming (1989) observed the correction is identical to the average AAPG (1976) correction at depths shallower than 4.0 km, while at greater depths, this correction continue to increase while the latter decreases. If the AAPG (1976) corrections are valid, then the linear correction is likely to lead to substantial errors at larger depths. Similar situation may also occur for data from areas outside the North Sea.

Deming and Chapman (1989) have also proposed an empirical correction scheme that allows the correction of single BHTs from the correction of multiple BHTs obtained using the Horner plot method. The method is based on a weak trend observed between the slopes of Horner plots and depths. A quadratic function that constrains the slope to be 0 °C at zero depth was fitted to the slope–depth data, the reason being that the temperature of the drilling fluid is approximately the same as that of the surface prior to its circulation. The temperature correction was then directly read off a map of the function for various depths and elapse-times. A drawback for the method is that it can only be applied when sufficient multiple BHT data are available that a statistically reliable relationship between slopes of Horner plots and depths can be established. The method also gives spread of up to 20 °C in TFT at any particular depth.

CHAD BASIN CASE STUDY

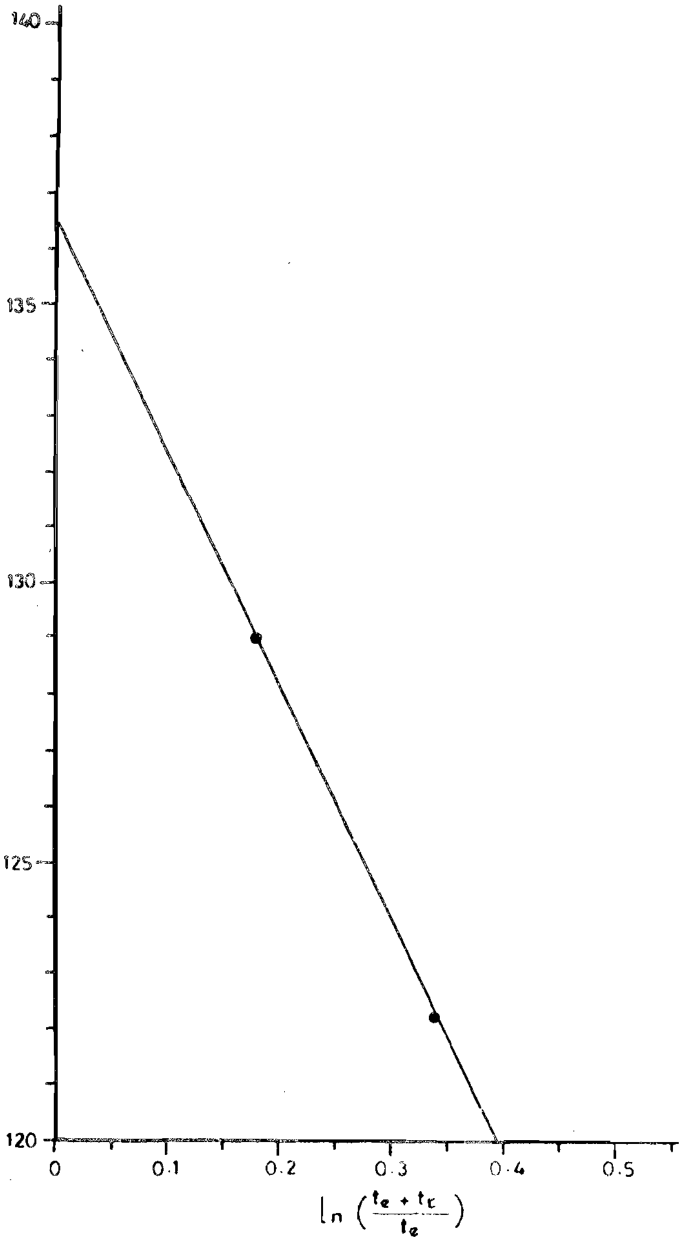
The records of BHTs used in this study were measured as part of the Chad Basin petroleum exploration-drilling program of the Nigerian National Petroleum Corporation, NNPC. Fig. 1 shows the well locations. Beside the preliminary information, other data collected from the log headers of drilled wells include depth driller, depth logger, bit size, drilling fluid density, times of end of drilling fluid circulation and logger at bottom as well as the maximum temperature for each run.

In all, 76 BHT records were collected from the log headers of 21 wells. These were obtained as single BHTs recorded in two to six runs per well. One BHT record was rejected for lack of the record of the time of end of fluid circulation. Two BHTs, both recorded as run number 5 for the same well, and taken 17 days apart, were adjudged to represent separate runs numbers 5 and 6. Unit of recorded BHTs were converted from degrees Fahrenheit to degrees Celsius, and elapse times, t_e, were calculated as the difference between the times of the end of fluid circulation and logger at bottom. No information on the time of end of drilling was contained on the log header, thus the duration of fluid circulation could not be calculated. Using information of depth of BHT measurement, however, the empirical method of Hermanrud et al. (1990) was employed to estimate the desires times. Although depth drillers are the true depths of the bottom of the drilled holes, depths logger were taken to be the corresponding depths of the recorded BHTs, presuming that the logging tool only reached thus far. Furthermore, the elevations of the reference level, the rotary table were subtracted from the depths driller in order to refer

BHT depths to the ground surface, that being the reference heat flow\surface. The densities of the drilling fluid, quoted in lb/g were, converted to the appropriate unit of kg m^{-3}. The temperature of the drilling fluid is assumed to be the same as that of the ground surface, which in turn is assumed to be 3 °C warmer than the mean annual air temperature, estimated to be 27 °C from meteorological records of air temperatures from nearby Maiduguri.

CORRECTION PROCEDURES AND RESULTS

The requirement of at least two BHT records measured in the same well at the same depth but at different elapse times inhibited the application of the Horner plot method for the correction of our dataset. Because the method requires multiple BHT measurements at the same depth, we investigated its sensitivity to depth variations. We noted from Bullard's (1947) approximate solution that TFT is independent of the depth, but on the BHT, t_e and t_c, and that these variables may be indirectly affected by the depth. An indication of the depth-dependence of BHT was given by a strong linear correlation coefficient of 0.8585, which increases to 0.8771 for the quadratic line for the correlation between BHT and depth (Fig. 2). By this correlation, a depth variation of 100 m would produce a BHT change of 0.1 °C, which in turn would produce an equivalent change in TFT. Next we note that t_c were estimated using the method of Hermanrud et al. (1990), by which a depth variation of 100 m would result in a circulation time change of 0.15 h. For an average BHT of 100 °C, a Horner slope of −30.00 °C, an elapse time of 6.0 h and circulation time of 5.0 h, a 0.15 h variation in t_c would produce a 0.4-°C change in TFT. Lastly, we also note that although it takes the sonde longer time to be lowered down the bottom of deeper drilled holes compared to shallower ones, a t_e - depths plot (Fig. 3) gives a weak linear correlation having a coefficient of 0.087 which increases to 0.122 for the third order regression line. A 100 m depth variation would therefore produce a negligible change in t_e, which in turn would produce a negligible change in the TFT. The sum of changes in TFT due to combined variations in the BHT, t_c and t_e produced by a depth change of 100 m would amount to about 0.5 °C or 0.9 °F. Such temperature change would hardly be detected by the ordinary thermometer lodged in the commercial sonde which records BHT to the nearest °F. For the purpose of the application of the correction methods requiring multiple BHT records at the same depth, in the same well but at different elapse times therefore, BHTs measured in the same well but at depths differing by not more than 100 m could be assumed as having been measured at the same depth. Only one pair of the single BHTs satisfied this condition, differing in depth by 92.20 m. The application of the Horner plot correction to this pair (Fig. 4) yielded a slope of −41.77 °C.



The Horner slope obtained was next assumed to be typical of the whole basin, and thereafter used to estimate the TFTs for the dataset. Column 4 of Table 1 gives the TFT estimates. The assumption of a common slope for the whole basin is similar to the adoption of a common κ for the formations in a basin. The minimum, maximum and average corrections and percentage corrections are calculated as 1.57, 27.34 and 15.18 °C, and 3.36, 46.82 and 17.97 % respectively. The sensitivity of the method was investigated by varying the slope between ± 10 % of its value. The amount of correction, ΔT, and percentage correction, ΔT %, appear to vary proportionally with slope, while TFT estimates varied by 3.56 % on the average. Graphs of ΔT and ΔT % were plotted on the same axis against BHTs, depths and t_e in order to investigate possible relationships. Only the plots of ΔT % against t_e (solid line, Fig. 5) gave significant correlations, the best of which has coefficient of 0.9371 for a power function of t_e.

The Leblanc et al. (1981) method, like the Horner plot method also requires multiple BHTs recorded at the same depth, in the same well but at different elapse times in order to estimate TFTs. The relaxation of the same depth requirement for depths differing by not more than 100 m enabled the use of the method to simultaneously estimate the temperature and κ of the formation rocks for the qualifying data. The method gave the rocks a TFT of 156.80 °C and $\kappa = 4.579 \times 10^{-7}$ m^2 s^{-1}. By assuming κ to be typical of the basin, we applied the method to correct the dataset. The amounts of correction, ΔT, varied between 0.11 and 4.78 °C but averaged 2.14 °C, while ΔT % averaged 2.38 %. Column 5 of Table 1 gives the TFT estimates. The sensitivity of the method was investigated by varying κ between ± 10 % of its value. The results revealed an inverse relation between the TFT estimates, ΔT and ΔT % and κ, with the variations averaging 0.56 % for the TFTs, and 15.0 % for both ΔT and ΔT %. Graphs of ΔT and ΔT % against BHTs, depths and t_e were plotted to investigate possible relationships. The plots gave insignificant correlations except those between ΔT % and t_e which gave significant correlations the best of which has a coefficient of 0.8320 for the exponential functions of the t_e (broken line, Fig. 5).

The Middleton (1979) method also requires multiple BHT records. The complexity of the error function, which the method employs to express the TFT, inhibited the application of similar same-depth relaxation. The method was however applied using an earlier value κ to correct our dataset. Column 6 of Table 1 give the TFT estimates. The amount of correction, ΔT, and ΔT % averaged at 35.90 °C and 38.53 % respectively. Similarly also, the value of κ was varied in order to investigate the sensitivity of the method. The TFT estimates, ΔT and ΔT % inversely changed with κ, with ΔT and ΔT % changing by as much as 90 %, while the TFT estimates changed by 6.32 % on the average. The graphs of ΔT, and ΔT % on the same axis against BHTs, depths and t_e, plotted to investigate possible relationships did not yield any significant correlation.

In addition to multiple BHTs, the Cooper and Jones (1959) method requires the thermal conductivity, specific heat capacity and density of the wall rock as well as the specific heat capacity and density of the drilling fluid in order to estimate the TFTs. The unavailability of this rather large number of unknowns as well as the lack of multiple BHT records inhibited the application of the method. With the earlier value of κ and the assumption of 750 J kg^{-1} K^{-1} and 2650 kg m^{-3} as specific heat capacity and density of the wall rocks, and 3000 J kg^{-1} K^{-1} as the specific heat capacity of the drilling fluid, the method was applied to correct our dataset. Column 7 of Table 1 gives the TFT estimates. The amount of correction, ΔT, and ΔT % averaged 124.32 °C and 115.28 % respectively. The sensitivity of the method to variation of κ was similarly investigated. On the average, the TFT estimates, ΔT and ΔT % all increased with κ, the TFT estimates by 17.96 % on the average. Graphs of ΔT and ΔT % were also plotted against BHT, depth and t_e to investigate possible relationships, and significant correlations were obtained for three plots, ΔT against BHT with coefficient of 0.8097 for the 6th degree polynomial function of the BHT; ΔT against depth with coefficient of 0.7123 also for the 6th degree polynomial function of the depth; and ΔT % against t_e with coefficient of 0.8195 for the exponential function of t_e.

Empirical correction methods were employed to correct our dataset. These include the AAPG (1976) method, employed with the average calibration coefficients, the Willet and Chapman (1988), the Majorowicz et al. (1990) and the Andrew-Speed et al. (1984) methods. The correction, ΔT, averaged 7.51, 2.91, 9.44 and −20.50 °C for the four methods respectively, while ΔT % averaged 7.37, 2.85, 10.44 and −27.19 %. Columns 8, 9, 10 and 11 of Table 1 respectively give the TFT estimates by the methods.

DISCUSSIONS

Even after the applications of the correction procedures, only estimates of the TFTs are known, the actual TFTs remain unknown. They remain unknown not because the correction procedures are incapable of accurately predicting them, but because the data needed for doing so are unavailable. The application of the correction procedures on the available dataset provided TFT estimates that may be used to define the range within which the actual TFTs lie. The narrower the range is, the closer it will be to knowing the actual TFT. For a start, this range may be defined as that between the lowest and highest TFT estimates, namely, by the estimates from the Leblanc et al. (1981) and the Cooper and Jones (1959) methods. For the 'A1' well for example, at the depth of 1524.0 m where the BHT recorded is 61.11 °C, the actual TFT range lies between 62.80 and 96.51 °C. Little, if any, meaningful analysis can be made from such a wide temperature range, and thus the need to narrow it. To do this, we examined the accuracy of each correction procedure with a view to eliminating those that contribute to the wide range. First we

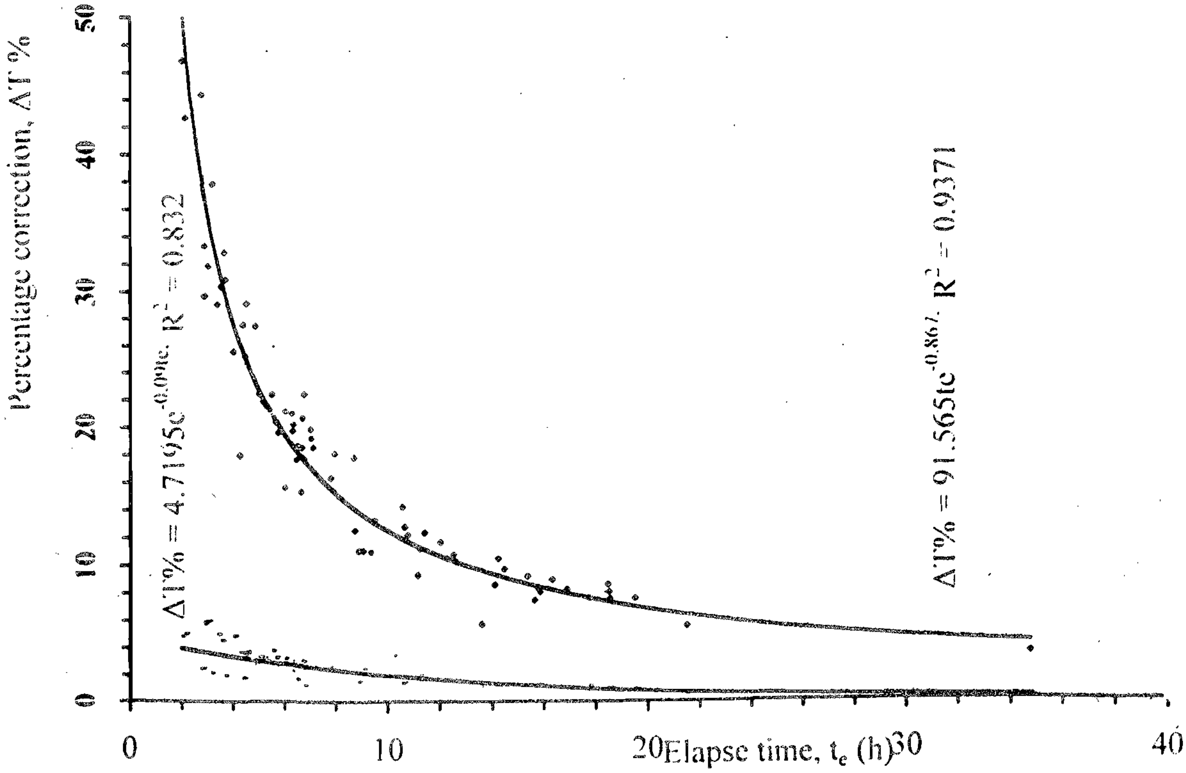


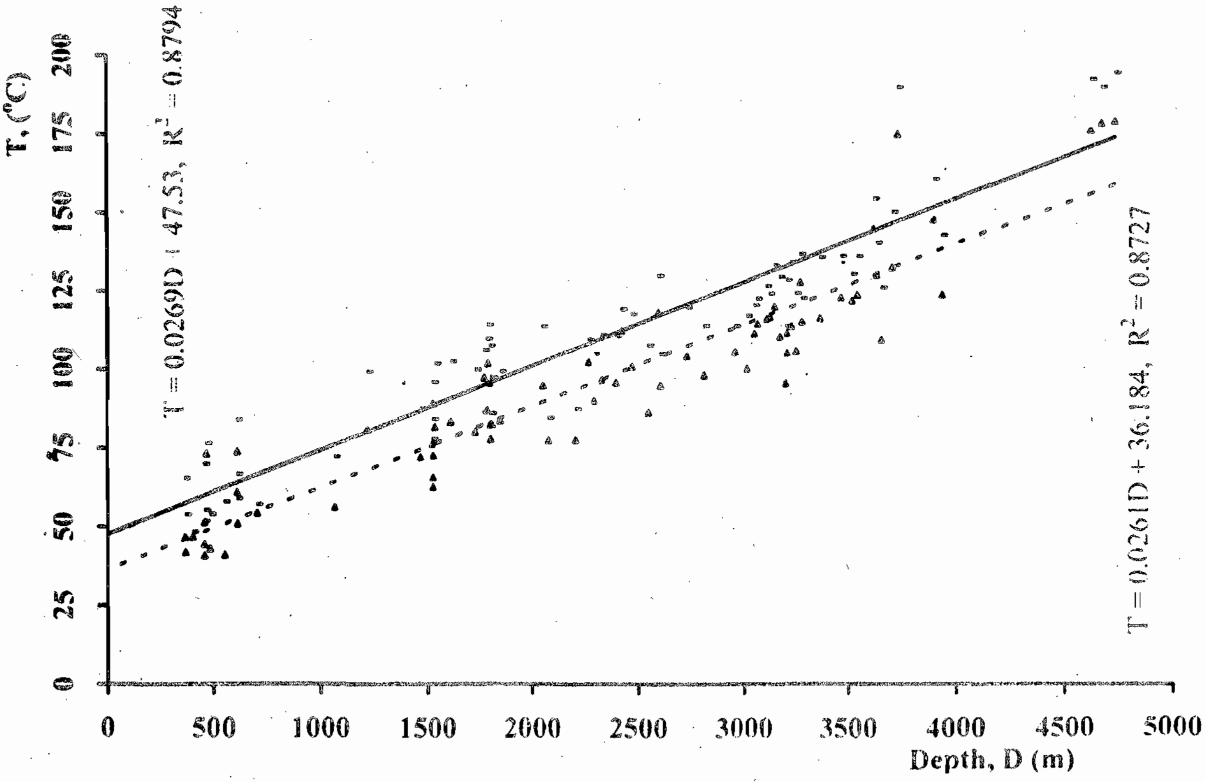
Table 1: Table of TFT estimates, T_∞ for (1) Horner plot, (2) Leblanc et al. (1981), (3) Middleton, (1979), (4) Cooper and Jones (1959), (5) AAPG (1976), (6) Willet ar Chapman (1988), (7) Andrew-Speed, (1984), and (8) Mojorowicz, et al., (1990) methods.

Well Name	Depth (m)	BHT (°C)	T_∞ (°C)							
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
A1	1524.00	61.11	77.84	62.80	86.06	96.51	65.67	62.96	35.78	68.78
	2804.00	95.56	113.84	98.00	135.86	177.79	105.33	99.90	75.39	106.37
	3140.50	117.78	133.39	120.19	161.77	373.40	128.83	121.97	100.95	129.56
	3458.50	121.11	136.53	123.34	163.52	412.83	133.23	125.65	104.78	132.54
B1	483.00	42.22	53.80	42.96	52.82	56.02	43.32	42.53	14.05	47.64
	1066.00	54.44	72.27	56.23	78.91	77.87	57.32	55.69	28.11	61.67
	1466.00	70.00	87.59	72.38	104.22	114.01	74.34	71.85	46.00	78.95
F1	549.00	40.00	57.72	40.98	52.57	48.31	41.28	40.55	11.50	45.53
	1524.50	64.44	77.94	65.88	87.38	112.60	69.00	65.94	39.61	72.00
	2598.36	93.33	104.81	94.77	121.50	216.70	102.27	95.82	72.83	101.79
	3164.50	107.22	129.86	110.59	160.15	194.95	118.35	113.34	88.80	119.95
G1	610.00	71.11	83.81	73.67	107.53	117.28	72.56	71.56	47.28	80.29
	2589.50	115.56	129.96	118.11	160.93	242.60	124.47	118.67	98.39	127.58
	3609.00	143.33	154.72	145.18	184.24	444.66	155.90	146.81	130.33	153.53
	4609.50	173.33	192.62	176.65	237.71	459.74	187.42	179.93	164.83	189.19
G2	457.00	48.89	69.72	51.32	78.72	62.03	49.92	49.41	21.72	55.84
	1798.50	76.67	85.98	77.80	98.24	174.11	82.32	77.95	53.67	83.86
	3192.00	93.33	114.18	95.79	133.37	182.07	104.56	99.02	72.83	104.03
	3647.00	107.22	126.25	109.53	148.26	231.29	119.90	113.08	88.80	118.39
H1	2202.10	76.67	87.53	77.71	97.14	165.31	83.96	78.60	53.67	83.94
	3509.40	121.11	130.79	122.26	149.25	340.93	133.39	124.00	104.78	128.51
	4721.00	176.67	194.71	179.41	234.16	661.27	190.72	182.83	168.67	191.72
K1	370.70	41.11	53.76	41.90	51.95	51.84	41.92	41.36	12.78	46.56
	1523.00	87.78	95.89	89.09	113.46	199.94	92.34	88.68	66.45	95.84
	1783.50	98.89	114.24	101.84	145.49	179.63	104.48	100.97	79.22	110.64
	3042.00	110.00	120.60	111.40	140.18	271.66	120.68	112.75	92.00	118.46
K2	468.00	72.22	76.27	73.02	89.00	182.68	73.28	72.32	48.55	78.04
	1218.00	76.67	99.36	81.02	133.08	114.65	80.09	78.55	53.67	87.21
	1609.50	79.44	102.45	83.35	131.97	123.46	84.33	82.17	56.86	90.12
K3	459.00	48.89	NA	NA	NA	NA	49.92	NA	21.72	NA
	1778.90	82.22	109.56	87.00	144.37	117.97	87.79	85.92	60.05	93.52
K4	457.60	43.89	51.63	44.41	52.48	64.64	44.92	44.08	15.97	48.92
	1804.00	80.00	97.26	82.43	116.96	131.64	85.67	82.38	57.50	89.85
	3271.00	114.44	123.09	115.52	140.76	364.44	125.95	116.86	97.11	121.04
	3887.50	145.56	160.79	147.93	193.65	568.62	158.84	150.47	132.89	158.18
	4659.70	176.67	190.05	178.74	225.14	923.02	190.75	181.24	168.67	187.97
K5	403.20	46.67	48.24	46.78	50.27	143.78	47.56	46.70	19.17	47.87
	1790.80	93.33	107.50	95.65	131.81	180.84	98.95	95.26	72.83	104.10
	2323.00	94.44	111.21	96.80	133.59	178.27	102.25	97.62	74.11	105.34
	2950.00	104.44	113.72	105.53	129.63	283.59	114.78	106.77	85.61	111.69
K6	608.96	60.00	66.57	60.88	128.76	116.64	61.44	60.23	34.50	66.20
	2285.20	87.78	105.05	90.18	149.84	166.80	95.43	90.99	66.45	98.06
	3117.00	115.56	124.24	116.75	94.70	361.38	126.52	117.87	98.39	122.61
M1	2262.00	101.11	109.67	102.42	75.74	244.99	108.67	102.68	81.78	109.05
	3101.00	114.44	126.67	116.19	126.13	260.51	125.34	117.68	97.11	124.23
M2	2074.77	76.67	84.64	77.52	143.61	191.82	83.45	77.98	53.67	82.64
	3198.60	104.44	113.35	105.48	128.91	305.01	115.69	106.88	85.61	110.84
	3720.00	171.11	189.87	175.17	244.15	379.28	183.99	176.97	162.28	188.62
M3	1765.00	95.56	105.95	97.31	127.87	211.09	101.07	96.95	75.39	105.18
	3243.40	103.33	124.62	106.09	148.77	204.07	114.74	109.23	84.33	115.22
	3927.00	121.11	142.90	123.98	171.22	259.51	134.48	128.18	104.78	134.20
N1	1526.00	71.11	84.24	72.77	97.86	128.48	75.68	72.57	47.28	79.37
	1844.00	81.11	99.30	83.80	121.19	137.01	86.94	83.69	58.78	91.22
	2465.00	97.78	117.69	100.94	146.53	178.29	106.18	101.84	77.95	109.61
	3264.00	126.67	137.12	128.26	161.71	375.93	138.15	129.58	111.17	135.73
N2	457.80	40.00	55.11	40.85	51.22	48.52	41.03	40.38	11.50	45.43
	1797.30	80.00	97.49	82.56	118.37	136.48	85.64	82.40	57.50	89.90
	3199.30	108.89	128.96	111.80	157.05	219.42	120.15	114.38	90.72	121.16
	3696.20	129.44	150.43	132.77	186.34	278.63	142.25	135.97	114.36	143.54

Table 1 (Cont.)

Well Name	Depth (m)	BHT (°C)	T∞ (°C)							
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
S1	609.30	50.00	58.79	50.79	62.86	79.30	51.45	50.31	23.00	55.82
	2390.10	93.33	110.69	95.83	133.82	171.88	101.42	96.74	72.83	104.16
T1	703.50	53.89	56.88	54.16	60.81	139.02	55.61	54.01	27.47	56.65
	1523.50	74.44	89.00	76.36	104.74	129.18	79.00	76.05	51.11	83.40
	2417.00	111.11	119.30	112.38	139.63	313.85	119.31	112.74	93.28	119.11
	3057.30	113.33	122.61	114.54	141.28	329.58	124.07	115.75	95.83	120.94
	3533.60	122.22	136.42	124.10	160.50	283.44	134.57	126.48	106.05	132.96
	3625.80	128.89	140.64	130.46	164.02	338.77	141.51	132.49	113.72	138.31
W1	365.80	44.44	65.25	46.58	70.18	54.12	45.24	44.84	16.61	50.79
	1535.20	77.22	101.75	81.77	135.79	113.11	81.82	79.96	54.30	87.77
	2046.00	90.58	113.65	94.91	150.04	145.57	97.24	94.31	69.67	102.41
	2721.90	101.11	119.76	104.11	148.79	190.94	110.55	105.39	81.78	112.75
	3222.00	110.00	134.58	114.11	171.65	198.23	121.34	116.77	92.00	123.39
Z1	1726.50	76.67	99.87	80.11	123.58	120.35	82.03	79.69	53.67	86.91
	2542,00	83.33	107.51	86.36	127.50	132.38	92.04	88.45	61.33	93.96
	3008.00	97.77	117.11	100.22	138.64	172.62	108.33	102.73	77.94	108.84
	3358.10	113.33	136.17	116.68	167.29	211.30	125.13	119.87	95.83	126.60

note that of the correction procedures employed, only the Horner plot and Leblanc et al. (1981) methods are independent, requiring no inputs from other methods. To apply the Middleton (1979) and the Cooper and Jones (1959) methods, use was made of κ estimate from the Leblanc et al. (1981) method. In addition, the latter method required the input of the heat capacity and density of the wall rock as well as heat capacity of the drilling fluid, all of which were not known to any degree of accuracy. Whatever error these inputs may contain would have been propagated into the TFT estimates of the two methods, thus rendering the estimates too large. Indeed, the average corrections for the methods are 35.90 and 124.32 °C, compared to 15.18 and 2.14 °C for the Horner plot and Leblanc et al. (1981) methods respectively. It is therefore argued that estimates from the Leblanc et al. (1981) and Horner plot methods respectively define the lower and upper limits of the range of actual TFTs. Plots of the TFT against depth from the two methods (Fig. 6) gave improved coefficient from its initial value of 0.8585 to 0.8794 and 0.8727 for the two methods respectively. The improvement in the correlation coefficient is interpreted as proof that the corrections have improved the internal



consistency of the data.

Both Horner plot slope and κ incorporate such factors as the thermal conductivity, density and heat capacity of the wall rock and drilling fluid. The conductivity especially, and the density to a lesser extend, are properties that do not appreciably change over many rocks (Kappelmeyer and Haenel, 1974; and Roy et al., 1981). TFTs are therefore expected not to appreciably change with variations of either the slope or κ. When they do, however, the TFT estimation method may be considered unstable and therefore unsuitable. For a 20 % (± 10 %) variation of κ, the TFT estimates from the Cooper and Jones (1959), Middleton (1979) and Leblanc et al. (1981) methods changed, on the average, by 17.96, 6.32 and 0.56 % respectively, while for a similar percentage changed in the slope, changes in the TFT estimates by the Horner plot method averaged 3.59 %. The rather large changes in the TFT estimates from the two former methods compared to those from the two latter ones suggests the instability and hence the unsuitability of the former methods. It also supports the earlier argument that the limits of the range within which the actual TFTs lie is defined the two latter methods.

The TFTs estimated using empirical methods were examined to ascertain whether they fall within the range of actual TFTs or not. The corrections by the Andrew-Speed et al. (1984) method fell outside the range and are also lower than the BHTs, thereby violating theories of temperature buildup in drilled-wells, and suggest the unsuitability of the calibration for the Chad basin compared to the North Sea. The corrections by the AAPG (1976), the Willet and Chapman (1988) and the Majorowicz et al. (1990) methods however fell within. This is interpreted as suggestive that the dataset is amenable to correction by empirical methods. Significant correlations between ΔT % and t_e (Fig. 5) suggested the forms of the empirical relationships for the Horner plot and Leblanc et al. (1981) methods respectively as:

$$\Delta T\ \% = 91.565 t_e^{-0.867} \quad \ldots (1)$$

$$\Delta T\ \% = 4.7195 e^{-0.07te} \quad \ldots (2)$$

Lack of significant correlation from any of the plots of correction parameters against well parameters for the Middleton (1979) method suggests the method is not amenable to being predicted by empirical method, while, significant correlations from the ΔT – BHT, ΔT – depth and ΔT % - t_e plots for the Cooper and Jones (1959) method suggests the opposite.

The intercepts of the TFT - depth plots for both the Horner plot and Leblanc et al. (1981) methods suggests that the ground surface temperature assumed to be 30 °C is much higher. While the uncorrected BHT - depth plot (Fig. 2) suggests that the value of the temperature is 34.81 °C, the TFT - depth plots (Fig. 6) suggest values of 36.18 and 47.53 °C.

CONCLUSIONS

The correction of BHT dataset from the Chad Basin, N.E. Nigeria by several correction methods was achieved only after the relaxation of the same depth requirement for BHTs measured in the same drilled well as well as the assumption that estimates of the Horner plot slope and thermal diffusivity, obtained from the relaxation as -41.77 °C and 4.579 x 10^{-7} m^2 s^{-1} respectively, are typical of the basin. Although the correction procedures gave widely varying TFT estimates for each BHT. the results were used to define a range within which the actual TFT lies. The lower limit of this range is defined by the TFT estimates from the Leblanc et al. (1981) method and the upper limit by those of the Horner plot method, with the TFT estimates by the Middleton (1979) and Cooper and Jones (1959) methods considered too large and outside the range. The Horner plot and the Leblanc et al. (1981) methods were also found to be stable with respect to the variation of the slope and the thermal diffusivity respectively, while the other methods were not. TFTs estimated using the AAPG (1976), Willet and Chapman (1988) and Majorowicz et al. (1990) empirical methods were found to fall within the range, while those from the Andrew-Speed et al. (1984) method did not. Derived empirical relationships between correction and drilled well parameters suggest that BHTs could be empirically corrected with high confidence.

ACKNOWLEDGEMENT

The authors are grateful to the Nigerian National Petroleum Corporation, NNPC, for providing the log of wells drilled in the Nigerian sector of the Chad basin from where the data for this study were extracted, and the Abubakar Tafawa Balewa University, Bauchi, Nigeria for providing the first-named author fellowship to undertake the study.

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