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APPLICATION OF BOTTOM-HOLE TEMPERATURE CORRECTIONS IN GEOTHERMAL STUDIES

DAVID DEMING

Department of Geology and Geophysics, Louisiana State University, Baton Rouge, Louisiana 70803, *U.S.A.*

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Abstract—Bottom-hole temperature (BHT) data measured in oil and gas wells constitute a large, low-quality set of temperature observations commonly used in geothermal studies. Raw BHT data are, on the average, cooler than true formation temperatures. To estimate true formation temperatures, corrections must be applied. Empirical BHT corrections may be applied to BHT data for which only depths of measurement are known, but may not be valid outside of the area for which they are calibrated. If multiple BHT measurements from successive logging runs are available, the Horner plot correction procedure can be used. The accuracy of the Horner plot is limited by simplifying assumptions made in its derivation, and by the common lack of information on parameters such as duration of mud circulation. More detailed and complete treatments provide insight into the borehole equilibration process, but their application is similarly limited by a common lack of data regarding borehole thermal properties. A new type of empirical correction procedure may be derived in some areas and allows a correction to be made for BHTs for which only a depth and time of measurement are known. Noise is invariably present in the BHT data found on well log headers from oil and gas wells, and the consequence of noise in these data should be considered when choosing and applying a correction. Although the average nature and magnitude of error in raw BHT data may be approximately known, application of all BHT correction procedures to the typical data available from oil and gas well log headers usually involves an unknown amount of error. Reliable estimates of average geothermal conditions can be made only from suites of BHT data, and are condemned to be imprecise at best.

INTRODUCTION

Bottom-hole temperature data constitute a large set of temperature observations that are being used with increasing frequency for various types of geothermal studies. Estimates of terrestrial heat flow have been made from BHT data for sedimentary basins in Brazil (Carvalho and Vacquier, 1977), Indonesia (Carvalho *et al.*, 1980; Vacquier, 1984), the North Sea (Andrews-Speed *et al.*, 1984), Western Canada (Majorowicz and Jessop, 1981), the Western United States (Chapman *et al.*, 1984; Eggleston and Reiter, 1984; Reiter *et al.*, 1986; Deming and Chapman, 1988a, b), Mexico (Reiter and Tovar, 1982) and Eastern Canada (Reiter and Jessop, 1985). BHT data have also recently been used for geothermal reconnaissance studies in the Michigan Basin (Speece *et al.*, 1985), Alberta (Lam and Jones, 1986), and Tunisia (Ben Dhia, 1988), and for inferring regional groundwater circulation patterns (Bodner and Sharp, 1988; Willet and Chapman, 1987a, b, c).

Although the use of BHT data is becoming more common, the data themselves are of notoriously poor quality. If a BHT has been properly measured and recorded, it represents a measurement of the temperature of the drilling fluid in a borehole, which is generally cooler than the true undisturbed formation temperature in the bottom of the well. For this reason, a plethora of BHT correction schemes exist by which true formation temperature may be estimated. However, there is a considerable gap between theory and practice. Many correction procedures have been proposed recently (Middleton, 1979; Leblanc *et al.*, 1981; Lee, 1982; Luheshi, 1983; Shen and Beck, 1986; Cao *et al.*, 1988), but none of these correction procedures have been applied in the geothermal studies cited above. Many of the BHT data analyzed in these studies were corrected using either simple empirical methods, or a correction procedure (Horner plot) that was originally derived by Bullard (1947).

The primary purpose of this paper is to review correction procedures in a critical manner. The practical aspects of applying different corrections are considered, and the possible influence of noise in the data is discussed. Practical recommendations are made, and a new type of correction procedure is discussed. This correction may be derived in some areas and is suitable for application to the type of BHT data which is usually available.

TEMPERATURE CORRECTIONS

Temperature corrections may be divided into those which are based upon some mathematical model of the temperature buildup in a well, and empirical corrections. Perhaps best known of the empirical corrections is the correction proposed and used by the American Association of Petroleum Geologists (AAPG). The correction arose as an outgrowth of the AAPG geothermal survey of North America in the early 1970s. The AAPG correction is based upon a comparison between BHTs and equilibrium temperatures measured in 602 wells in the states of Louisiana and West Texas, and has been used in geothermal studies by Speece *et al.* (1985) and Bodner and Sharp (1988). The data were subdivided into two sets (Louisiana and West Texas), and the temperature difference between a BHT and equilibrium temperature was used to derive a geothermal gradient difference for that depth (Kehle, 1972). A third-order polynomial was then fitted to these differences by least-squares, yielding an average geothermal gradient correction as a function of depth. This gradient correction may be multiplied by depth to yield a temperature correction as a function of depth.

$$\Delta T = az = bz^2 + cz^3 = dz^4$$

where ΔT is the temperature correction in degrees Celsius, and z is depth in kilometers. Since the correction coefficients are not generally available, they are given in Table 1.

Table 1 lists three sets of correction coefficients. One set derived from wells in Louisiana, one set derived from wells in West Texas, and an average of the two. The average correction is zero at zero depth, increases in a nearly linear manner to a maximum of 14.1°C at 4574 m depth, and then decreases to 9°C at 6 km depth. One possible reason for the correction to decrease at great depths is that it takes the logging tool longer to reach the bottom of deeper holes, allowing the borehole a longer time to equilibrate. The average correction was used to correct BHT data used in the creation of the AAPG geothermal gradient map of North America (AAPG, 1976). Speece *et al.* (1985) also applied the average correction in their study of the Michigan Basin. The existence of two sets of correction coefficients suggests that the correction procedure is not statistically reliable outside of the area within which it is calibrated. Therefore, application of the correction to data from areas other than the calibration areas involves an unknown amount of error. It is also not apparent how the equilibrium temperatures used to calibrate the correction were determined. Kehle (1971, p. 6) simply says that the equilibrium temperature

Table 1. AAPG correction coefficients

Area	a	b	c	d
West Texas	-1.169×10^{-3}	-4.689×10^{-7}	6.609×10^{-10}	-8.312×10^{-14}
Louisiana	4.926×10^{-3}	2.164×10^{-6}	-7.628×10^{-10}	4.950×10^{-14}
Average	1.878×10^{-3}	8.476×10^{-7}	-5.091×10^{-11}	-1.681×10^{-14}

measurements were "made under controlled engineering conditions by engineers of the operating company."

Ben Dhia (1988) corrected BHTs from Tunisia by comparing BHTs with temperatures measured during drill stem tests (DST). A comparison between 55 BHTs and DSTs measured at the same depth in the same wells yielded an average correction as a function of depth. The correction is between 0 and 10°C for depths between 200 and 1000 m, 10 and 13°C for depths between 1000 and 2000 m, and 13 and 15°C between 2000 and 3000 m (Ben Dhia, 1988, p. 1482). Like the AAPG correction, the validity of this correction is unknown outside of the area for which it is calibrated. Implicit in the correction scheme is the assumption that DST temperatures are, at least on the average, the same as true formation temperatures. However, as Ben Dhia (1988, p. 1480) points out, the relationship between true formation temperature and DST temperature is unknown for any single temperature measurement.

Andrews-Speed *et al.* (1984) in a study of terrestrial heat flow in the North Sea applied an arbitrary linear correction to BHT data. The correction is

$$T_\infty = 1.15(\mathrm{BHT} - T_0)$$

where T_∞ is equilibrium temperature, and T_0 is temperature at zero depth. For an average geothermal gradient of 25°C/km, this correction is nearly identical to the average AAPG correction at depths shallower than about 4 km. At greater depths, the arbitrary linear correction continues to increase while the AAPG correction decreases. If the AAPG curves are valid, it is possible that application of an arbitrary linear correction to BHT data measured in very deep holes may lead to substantial errors.

The oldest of methods based upon mathematical models of the temperature buildup in the bottom of the well is the so-called Horner plot, which was derived by Bullard (1947) and Lachenbruch and Brewer (1959). The Horner plot owes its name to the fact that it is identical to an equation developed by Horner (1951) to predict reservoir pressure recovery. The temperature disturbance caused by the circulating mud is modeled as a line heat-sink in a homogeneous medium. The solution reduces to (Bullard, 1947)

$$T_\infty = \mathrm{BHT} + A \log_e \left[\frac{t + t_{\mathrm{circ}}}{t}\right]$$

where t_{circ} is the duration of mud circulation, t is the shut-in time, or time elapsed between the end of mud circulation and BHT measurement, T_∞ is the equilibrium temperature in the borehole, and A, the slope of the Horner line, is an unknown constant. This simple expression is an approximation to the full line source solution given by Bullard (1947). In order to apply the correction, it is necessary to have a time–temperature set of two or more BHTs, measured in the same well, at the same depth, but at different shut-in times.

The Horner plot has been applied to BHT data from oil and gas wells by Carvalho *et al.* (1980), Blanchard and Tailleur (1982), Vacquier (1984), Reiter *et al.* (1986), Reiter and Jessop (1985), Chapman *et al.* (1984), Willet and Chapman (1987a, b, c), and Deming and Chapman (1988a, b). The Horner method has also been used by Lachenbruch and Brewer (1959), Lachenbruch and Sass (1988) and Sass *et al.* (1988) to estimate equilibrium temperature profiles from high-precision temperature logs. In practice, there are two drawbacks to application of the Horner plot: it cannot be applied to single BHTs, and although shut-in time is usually found on log headers, information on the duration of circulation times is often not found. The more serious of these problems is that time–temperature sets are frequently not available for most wells. Chapman *et al.* (1984) estimate that only 5% of log headers from the Uinta Basin have multiple BHTs, measured in the same well, at the same depth, but at different shut-in times.

Deming and Chapman (1988a, b) found that about 50% of wells in north-central Utah for which BHT data were available had time–temperature sets. However Ben Dhia (1988) in a survey of available geothermal data from well logs in Tunisia found only 25 time–temperature sets suitable for application of the Horner plot from a total of 1154 BHTs collected from the entire country. The type and quality of BHT data available vary widely and may be affected by age of logging, locality, logging practices, and local government regulations regarding disclosure of log data.

When multiple time–temperature data are available, the chief practical difficulty in applying the Horner plot correction is that information on the duration of circulation time is almost always unavailable. In practice, various investigators have circumvented this difficulty by using a standard circulation time for all corrections. Chapman *et al.* (1984) and Reiter and Jessop (1985) used 4 hours, Deming and Chapman (1988a, b) used 5 hours. The apparent justification for this practice is that it may be easily shown that an equilibrium temperature predicted by application of the Horner plot varies little as the assumed circulation time varies. This is not quite the same thing as showing that the accuracy of the Horner plot does not suffer when an incorrect circulation time is used; however, Luheshi (1983) has shown that the temperature build-up in a well is relatively insensitive to the duration of the circulation time. A study by Scott (1982) of 301 Canadian wells for which circulation times were given found a mean circulation time of 8 hours, a median of 3 hours and a standard deviation of 13 hours, indicating that although a standard circulation time of 4 or 5 hours is probably a reasonable choice, situations in which the actual circulation time are as great as 30 or 40 hours may not be uncommon.

Because the Horner plot is based upon a mathematical model that incorporates simplifying assumptions concerning the geometry of the borehole and the rate at which heat is extracted, it should not be applied indiscriminately A number of authors, including Lachenbruch and Brewer (1959), Dowdle and Cobb (1975), Luheshi (1983), Drury (1984), and Shen and Beck (1986) have pointed out that accuracy of the Horner model increases as the ratio of shut-in time to circulation time increases. In particular, Shen and Beck (1986) have shown that the Horner plot does not begin to accurately approximate the actual rise of temperature in the well until the well has been shut-in at least as long as the duration of the mud circulation. Deming and Chapman (1988a, b) note that in practice they reject BHTs measured at times shorter than 4 or 5 hours as being unsuitable for Horner plot corrections. Luheshi (1983) also points out that the line source assumption on which the Horner plot is based becomes progressively worse as the borehole diameter becomes larger.

Middleton (1979) and Leblanc *et al.* (1981) introduced simple analytical models of the borehole thermal regime that are alternatives to the Horner plot. Like the Horner plot, these models assume a medium with homogeneous thermal properties; however, they incorporate a geometry (cylindrical or square borehole) that is more realistic than the line source assumption of the Horner plot. Unfortunately, in order to arrive at a relatively simple expression for temperature equilibration, they assume zero circulation time. These models also have three unknowns: the temperature of the circulating mud, the equilibrium temperature, and the thermal diffusivity of the homogeneous medium, and thus require a time–temperature set consisting of a minimum of three BHTs for equilibrium temperature estimation. Leblanc *et al.* (1982) compare their method to the Horner plot and suggest that use of an average thermal diffusivity, somewhat similar to the use of an average circulation time in application of the Horner plot, would make the method tractable for application to time–temperature sets of two BHTs, which are generally much more available than sets of three or more. It is not clear that the application of the models of Middleton (1979) and Leblanc *et al.* (1981) results in estimates of true formation temperature that are any better or worse than those obtained from the Horner plot. Although these models incorporate a more realistic assumption concerning the geometry of the borehole, the Horner method more realistically allows the incorporation of a finite circulation time.

The models of Lee (1982), Luheshi (1983) and Shen and Beck (1986) are more realistic approximations to the borehole equilibration problem. Typically, these models explicitly include a finite borehole radius, finite circulation time, and different thermal properties for the drilling mud and wallrock. Lee (1982) uses the finite-element method, Luheshi (1983) models the borehole thermal state with a finite-difference technique, and Shen and Beck (1986) derive analytical solutions using Laplace transforms. Both Luheshi (1983) and Shen and Beck (1986) also discuss the thermal influence of fluid flow into and out of the well during circulation time.

These models (Lee, 1982; Luheshi, 1983; Shen and Beck, 1986) provide insight into the nature of the temperature buildup in a well during shut-in. Luheshi (1983) studied the sensitivity of the temperature build-up in the borehole to the thermal diffusivity and conductivity of the mud and wallrock, the duration of the circulation time, the borehole diameter, and fluid flow into and out of the well. Luheshi (1983) also concluded that the effect of vertical temperature gradients on borehole equilibration was negligible for distances greater than about 1 m from the bottom of the hole, and that the effect of free convection in the borehole is usually not important. Shen and Beck (1986) compared and contrasted the accuracy of different correction schemes by generating and inverting a series of synthetic BHT data. They concluded that the choice of a correction is much more critical when working with BHTs measured at comparatively short shut-in times, and that the Horner plot is likely to systematically underestimate equilibrium temperatures, particularly for BHT data measured at comparatively early shut-in times.

The practical application of the models of Lee (1982), Luheshi (1983), and Shen and Beck (1986) to estimating formation temperature is usually hampered by a lack of data. The lack of simplifying assumptions inherent in simpler models results in a larger number of unknown variables. In particular, information regarding the thermal conductivity and diffusivity of the wallrock and drilling mud is seldom available. In practice, it may be necessary to fill in the required parameters by guesswork (Luheshi, 1983, p. 758). Parameters such as the thermal diffusivity of rock do not vary much for most earth materials (see, for example, data in Kappelmeyer and Haenel, 1974; or Roy *et al.*, 1981). However little is known about the thermal properties of drilling muds, particularly with respect to how these parameters may change with increasing temperature and pressure (Luheshi, 1983, p. 764).

Somewhat different from the approach of Lee (1982), Luheshi (1983) and Shen and Beck (1986) is the model of Cao *et al.* (1988). The model is similar in that it attempts to accurately model the thermal stabilization of a borehole by not compromising the complexity of the problem. Cao *et al.* (1988, p. 979) list five unknown factors: (1) true formation temperature, (2) temperature of the circulation mud, (3) thermal invasion distance of the mud into the formation, (4) formation thermal conductivity, and (5) an "efficiency factor" for heating the mud in the borehole after the end of circulation. Cao *et al.* (1988, p. 980) argue that a virtue of their model is that it is a true inverse procedure that uses BHTs to infer the previous five unknown factors, one of which is the true formation temperature. They furthermore argue that because some of the unknown variables enter their model in a non-linear manner, it is possible to estimate all five variables from only three BHTs. However they demonstrate that in the presence of only 1°C noise in the data the method may yield estimates of equilibrium temperature that are in error by as much as 50°C (Cao *et al.*, 1988, p. 984). Interestingly enough, Cao *et al.* (1988, p. 984) also demonstrate that the Horner plot yields much better results in every one of 7 cases in which their synthetic test temperatures are closely spaced in time, and yields estimates of equilibrium formation temperature that are nearly identical to their model when the test temperatures are widely spaced in time.

With the exception of the study of Cao *et al.* (1988) and recommendations made by Luheshi (1983, p. 763), noise in BHT data is a problem that has otherwise received little consideration in studies concerned with BHT corrections. Yet noise is almost invariably present in typical BHT data from oil and gas well log headers. This noise can result from a legion of sources. For example, thermometers may not be properly calibrated and the depth of measurement may not be (and usually is not) the true bottom of the hole (Speece *et al.*, 1985, p. 1319). The depth of measurement may vary between logging runs owing to infill of the hole and different thermometer locations relative to the bottom of the logging tool. Data may be fabricated. Investigators should be wary of circumstances such as three separate logs showing 180, 190, and 200°F (82, 88, 93°C). Even if the true BHT is measured, the measurement or time of measurement may not be properly recorded. Since the borehole is in a transient thermal state, any error in recording the measurement time is equivalent to an incorrect temperature measurement. Probably more serious than actual measurement error is model error. For example, even when highly detailed models of the temperature build-up in a well, such as those proposed by Lee (1982), Luheshi (1983), Shen and Beck (1986), and Cao *et al.* (1988) are used, the theoretical model is always an approximation to the actual physical state of the borehole. Borehole geometry is never perfectly cylindrical and there is always likely to be some finite amount of fluid flow out of, or into, the borehole during equilibration. Furthermore, unknown periods of mud circulation between logging runs may be common, and the thermal diffusivity of the mud and wallrock are not constant during equilibration, but are functions of temperature. Human error in the collection of BHT data is an additional problem. It has been my experience, from examining hundreds of log headers, that it is not uncommon to find information that appears to be physically implausible. Frequently, multiple logging runs contain the same BHT as the first. The usual interpretation of these data is that a BHT was measured on the first logging run and then written on headers for subsequent logs. Other types of unusual situations, such as a measurement time before the end of circulation, or temperature that appears to go up and then down on successive logging runs, may be found. The existence of these problems suggests that original well log headers should be scrutinized whenever possible to screen raw BHT data before correction and analysis.

DEPTH-TIME CORRECTION

As an alternative to known correction procedures, it may be possible to derive a new type of correction in some areas, one that allows the correction of single BHTs for which only a depth and time of measurement is known. The correction was first suggested and applied by Deming and Chapman (1988b) and is based on an empirical correlation between the slope of the Horner line and depth. Figure 1 shows Horner slopes as a function of depth determined by applying Horner plot corrections to data from the (a) Pineview, (b) Anschutz Ranch–Cave Creek and (c) Anschutz Ranch East oil and gas fields in the Utah–Wyoming thrust belt in the western United States. The slopes were calculated using an assumed circulation time of 5 hours in all cases. The points show very large scatter and may result from several sources. For example, the outlying points representing high (negative) slopes in Fig. 1b may represent fluid flow into the well during equilibration. Attempts to decrease the scatter by assuming, for example, that slopes determined from 4 points are better than those determined from 2, yield marginal improvements. Attempts to understand the scatter by categorizing the data, by borehole radius, for example, are similarly fruitless. The depth correlation is weak, but present. The correlation is best seen in Fig. 1a. The data in Fig. 1c are restricted to such a narrow depth range (2 km) that no correlation can be observed.

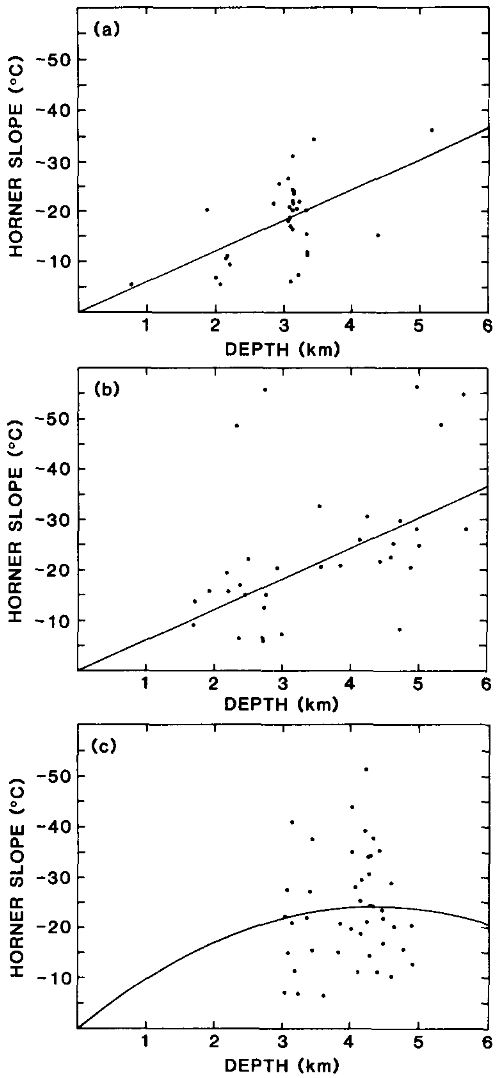

Fig 1. Horner slope A as a function of depth for (a) Pineview, (b) Anschutz Ranch–Cave Creek and (c) Anschutz Ranch East oil and gas fields. The slopes shown were calculated by using an assumed circulation time of 5 hours.

The idea behind the depth–time correction scheme is to derive an average Horner slope as a function of depth by fitting a function to the points shown in Fig. 1. The function chosen should be constrained to yield a slope of zero at zero depth, as the temperature of the drilling mud at the bottom of extremely shallow holes should be approximately the same as the temperature of the ground surface. The slope of the Horner line must then increase with depth as the cooler drilling mud encounters progressively hotter temperatures at the bottom of deeper holes. In this instance I use a quadratic function, $A = az + bz^2$ where A is Horner slope in degrees Celsius and z is depth in kilometers. A least-squares regression on the points shown yields $a = -6.03$, -7.41, and -11.1, and $b = -1.03 \times 10^{-2}$, 1.91×10^{-2}, and 1.27, for Figs 1a, 1b, and 1c, respectively.

Figure 2 shows the temperature corrections predicted from Fig. 1 as a function of depth and

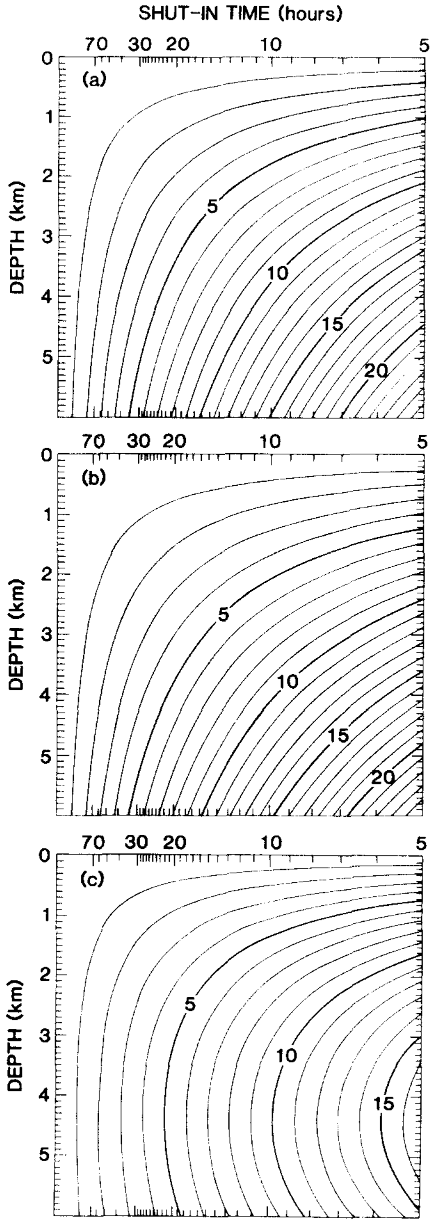

Fig. 2. Depth–time correction (°C) calibrated for (a) Pineview, (b) Anschutz Ranch–Cave Creek and (c) Anschutz Ranch East oil and gas fields.

time. The corrections shown were calculated using an assumed circulation time of 5 hours. Corrections derived from the Pineview and Anschutz Ranch–Cave Creek fields (Fig. 2a, b) are nearly identical. The largest difference is about 1.6°C at a depth of 3.5 km and a shut-in time of 5 hours. Larger differences may be found by comparing the correction derived from Anschutz Ranch East (Fig. 2c) with the Pineview and Anschutz Ranch–Cave Creek corrections (Fig. 2a, b). At a depth of 5 km and shut-in time of 5 hours, Fig. 2a and 2c differ by about 5°C, Fig. 2b and 2c differ by 6°C. These differences increase to about 11°C at a depth of 6 km. It should be noted however, that it is inappropriate to apply the Anschutz Ranch East correction to depths greater than 5 km, because the data set used to calibrate it contains no data from greater than 5 km.

If enough time–temperature data are available for calibration of this method, there are two possible advantages to using the procedure as an alternative to other types of empirical corrections. First, the correction is calibrated for the area to which it is applied. Second, by using information on shut-in time, the correction may be more precise than empirical corrections which rely on depth only.

DISCUSSION

The true error in raw BHT data is really unknown. There is no rigorous study that compares true equilibrium temperatures to BHTs derived from the logging of oil/gas wells. Studies such as Jam *et al.* (1969), Kehle (1971, 1972), or Gosnold *et al.* (1982) come close, but are lacking in some respect. For example, the methodology used to determine equilibrium temperature in Jam *et al.* (1969) and Kehle (1971, 1972) is not sufficiently documented. Gosnold *et al.* (1982) compared precision equilibrium temperature logs with nearby (within 10 km) BHT data, but the precision logs were not measured in the same holes.

However, all empirical and theoretical studies yield a consistent picture of the approximate nature and magnitude of the "average" BHT correction. That is (1) BHT data are generally cooler than true formation temperatures by an amount that, on the average, may be about 10–15°C, but probably varies from area to area, (2) the amount of correction needed increases with depth, but this increase may not be linear, and the correction may even decrease at great depths, (3) the amount of correction needed decreases with increasing shut-in time, and (4) any single BHT may be spurious.

Accurate BHT correction is not difficult; it is, in fact impossible. It is impossible in the sense that the data needed to make accurate corrections are not available. The temperature of the circulating mud, the duration of the circulation time, the thermal properties of the mud and wallrock, possible fluid flow into and out of the borehole—all of these factors are generally unknown. Therefore what is needed is not more complex or better correction schemes, what is really needed is better data. For example, studies using synthetic temperature data show that if shut-in time is large enough compared to circulation time, equilibrium temperature predictions made from different models tend to converge (Shen and Beck, 1986).

Since higher-quality data are not available now, some practical guidelines are required. In the absence of any information but depth, an empirical correction such as the AAPG correction, or the correction suggested by Ben Dhia (1988) may be applied. These empirical corrections may not be valid outside of the area for which they are calibrated. If time–temperature sets of BHTs are available, any number of other correction schemes may be applied. Even if circulation time is unknown, the Horner plot may be judiciously applied by using an average circulation time if its limitations are kept in mind. These limitations are that the accuracy of the Horner method increases with increasing shut-in time, but decreases with increasing borehole radius. If high-quality data are available, it is best to use only temperatures measured at later times to estimate equilibrium temperature (see temperature data in Lachenbruch and Brewer, 1959; Lachenbruch and Sass, 1988; and Sass *et al.*, 1988). For the typical data available from oil and gas well logging runs, it may be better to use all of the available data to average random errors. If a suitable suite of data exists, an average depth–time correction may be derived and applied, calibrated by the set of time–temperature data to which Horner plot corrections have been applied.

Some of the limitations inherent in the Horner plot may be alleviated by using Bullard's (1947) full line source solution (Luheshi, 1983; Drury, 1984). Although use of the full line source solution necessitates knowledge of the thermal diffusivity of the (hypothetical) homogeneous medium, Luheshi (1983) suggests that good results can be obtained by using a value of 5×10^{-2} m^2/s. The models of Middleton (1979) and Leblanc *et al.* (1981) also offer practical alternatives to the Horner plot. Compared to the Horner plot, the models have the theoretical advantage of incorporating a more realistic borehole geometry, but the disadvantage of assuming a zero circulation time.

The methods of Lee (1982), Luheshi (1983) and Shen and Beck (1986) require more work to implement than the empirical and simpler analytical methods discussed above. Unless data on the thermal properties of the drilling mud and wallrock are available, however, it is not clear that the application of these models results in more accurate predictions of borehole temperature. It is well known that the simplifying assumptions made in the derivation of models such as the Horner plot may lead to inaccurate results. However, models that are more accurate theoretical approximations to the borehole thermal state may be just as inaccurate in practical application if assumptions must be made regarding thermal properties. Different assumptions lead to different errors. For example, Luheshi (1983, p. 758) reports that for oil exploration data, his finite-difference method, the Horner plot, and the full Bullard line source solution were in good agreement for boreholes with diameters less than about 8.5 inches.

Noise is invariably present in BHT data, and the effect of noise in the data should be considered when choosing and applying a BHT correction. If a time–temperature set of several BHTs is available, the application of a correction scheme which requires a minimum of several BHTs may yield much worse results than a method which requires only 2. The method which requires only 2 BHTs may be able to take advantage of redundancy in the data by averaging errors.

In summary, although the average and approximate nature of error in BHT data may be well known, the application of all BHT correction schemes to the typical data available from oil and gas wells involves an unknown amount of error. There are a large number of corrections available; different corrections may be suitable for different sets of data. The correction procedure most widely used in geothermal studies, the Horner plot, is likely to be as accurate as any correction scheme if it is applied judiciously. An average depth–time correction may be derived and applied in some areas; its precision and accuracy are largely unknown. Any single estimated equilibrium temperature is suspect; reliable (but imprecise) estimates of geothermal conditions can only be made from sets of BHT data.

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REFERENCES

American Association of Petroleum Geologists (AAPG) (1976) Basic data file from AAPG geothermal survey of North America. University of Oklahoma, Norman, Oklahoma.

Andrews-Speed, C. P., Oxburgh, E. R. and Cooper, B. A (1984) Temperatures and depth-dependent heat flow in western North Sea. *Bull. Am. Ass. Petrol. Geol.* **68**, 1764–1781.

Ben Dhia, H. (1988) Tunisian geothermal data from oil wells. *Geophysics* **53**, 1479–1487.

Bodner, D. P and Sharp, J. M. Jr. (1988) Temperature variations in South Texas subsurface. *Bull. Am. Ass. Petrol. Geol.* **72**, 21–32.

Blanchard, D. C. and Tailleur, I. L. (1982) Temperatures and interval geothermal-gradient determinations from wells in National Petroleum Reserve in Alaska. USGS Open File Report, pp.82–391.

Bullard, E. C. (1947) The time necessary for a borehole to attain temperature equilibrium. *Mon. Not. R. astr. Soc.* **5**, 127–130.

Cao, S., Lerche, I and Hermanrud, C. (1988) Formation temperature estimation by inversion of borehole measurements. *Geophysics* **53**, 979–988.

Carvalho, H. D. S. and Vacquier, V. (1977) Method for determining terrestrial heat flow in oil fields. *Geophysics* **42**, 584–593.

Carvalho, H. D. S., Purwoko, Siswoyo, Thamrin, M. and Vacquier, V. (1980) Terrestrial heat flow in the Tertiary Basin of Central Sumatra. *Tectonophysics* **69**, 163–188.
Chapman, D. S., Keho, T. H., Bauer, M. S., and Picard, M. D. (1984) Heat flow in the Uinta Basin determined from bottom hole temperature (BHT) data. *Geophysics* **49**, 453–466.
Deming, D. and Chapman, D. S. (1988a) Inversion of bottom-hole temperature data: the Pineview field, Utah–Wyoming thrust belt. *Geophysics* **53**, 707–720.
Deming, D. and Chapman, D. S. (1988b) Heat flow in the Utah–Wyoming thrust belt from analysis of bottom-hole temperature data measured in oil and gas wells. *J. Geophys. Res.* **93**, 13657–13672.
Dowdle, W. L. and Cobb, W. M. (1975) Static formation temperature from well logs-an empirical approach. *J. Petrol. Technol.* **27**, 1326–1330.
Drury, M. J. (1984) On a possible source of error in extracting equilibrium formation temperatures from borehole BHT data. *Geothermics* **13**, 175–180.
Eggleston, R. E. and Reiter, M. (1984) Terrestrial heat flow estimates from petroleum bottom-hole temperature data in the Colorado Plateau and the eastern Basin and Range province. *Bull. geol. Soc. Am.* **95**, 1027–1034.
Gosnold, W. D., Jr., Eversoll, D. A. and Carlson, M. P. (1982) Three years of geothermal research in Nebraska. In *Geothermal direct heat program roundup technical conference proceedings* (Edited by Ruscetta, C. A.), Vol. 1, U.S. Dept. of Energy Report ID12079-79, pp. 142–157.
Horner, D. R. (1951) Pressure build-up in wells. *Proc. Third World Petroleum Congress*, The Hague, p. 503.
Jam, P. L., Dickey, P. A. and Tryggvason, E. (1969) Subsurface temperature in south Louisiana. *Bull. Am. Ass. Petrol. Geol.* **53**, 2141–2149.
Kappelmeyer, O and Haenel, R. (1974) *Geothermics with special reference to application*. Gebruder Borntraeger, Berlin.
Kehle, R. O. (1971) Geothermal survey of North America. Annual progress report. American Association of Petroleum Geologists, Tulsa, Oklahoma.
Kehle, R. O. (1972) Geothermal survey of North America. Annual progress report. American Association of Petroleum Geologists, Tulsa, Oklahoma.
Lachenbruch, A. H. and Brewer, M. C. (1959) Dissipation of the temperature effect of drilling a well in arctic Alaska. *U.S. Geol. Surv. Bull.* 1083C, Menlo Park, CA.
Lachenbruch, A. H. and Sass, J. H. (1988) The stress heat-flow paradox and thermal results from Cajon Pass. *Geophys. Res. Lett.* **15**, 981–984.
Lam, H. L. and Jones, F. W. (1986) An investigation of the potential for geothermal energy recovery in the Calgary area in southern Alberta, Canada, using petroleum exploration data. *Geophysics* **51**, 1661–1670.
Leblanc, Y., Pascoe, L. J. and Jones, F. W. (1981) The temperature stabilization of a borehole. *Geophysics* **46**, 1301–1303.
Leblanc, Y., Lam, H-L., Pascoe, L. J. and Jones, F. W. (1982) A comparison of two methods of estimating static formation temperature from well logs. *Geophys. Prospec.* **30**, 348–357.
Lee, T. C. (1982) Estimation of formation temperature and thermal property from dissipation of heat generated by drilling. *Geophysics* **47**, 1577–1584.
Luheshi, M. N. (1983) Estimation of formation temperatures from borehole measurements. *Geophys. J. R. astr. Soc.* **74**, 747–776.
Majorowicz, J. A. and Jessop, A. M. (1981) Regional heat flow patterns in the western Canadian sedimentary basin. *Tectonophysics* **74**, 209–238.
Middleton, M. F. (1979) A model for bottom-hole temperature stabilization. *Geophysics* **44**, 1458–1462.
Reiter, M. and Tovar, J. C. (1982) Estimates of terrestrial heat flow in northern Chihuahua, Mexico based upon petroleum bottom-hole temperatures. *Geol. Soc. Am. Bull.* **93**, 613–624.
Reiter, M. and Jessop, A. M. (1985) Estimates of terrestrial heat flow in offshore eastern Canada. *Can. J. Earth Sci*, **22**, 1503–1517.
Reiter, M., Eggleston, R. E., Broadwell, B. R. and Minier, J. (1986) Estimates of terrestrial heat flow from deep petroleum tests along the Rio Grande Rift in central and southern New Mexico. *J. Geophys. Res.* **91**, 6225–6245.
Roy, F. Jr., Beck, A. E. and Touloukian, Y. S. (1981) Thermophysical properties of rocks. In *Physical Properties of Rocks and Minerals, McGraw-Hill CINDAS Data Series on Material Properties* (Edited by Touloukian, Y. S., Judd, W. R. and Roy, R. F.), Vol II-2, pp. 409–502. McGraw-Hill, New York.
Sass, J. H., Priest, S. S., Duda, L. E., Carson, C. C., Hendricks, J. D. and Robison, L. C. (1988) Thermal regime of the State 2–14 well, Salton Sea scientific drilling project. *J. Geophys. Res.* **93**, 12995–13004.
Scott, G. N. (1982) Temperature equilibration in boreholes: a statistical approach. Unpublished M.Sc. thesis, University of Michigan.
Shen, P. Y. and Beck, A. E. (1986) Stabilization of bottom hole temperature with finite circulation time and fluid flow. *Geophys. J. R. astr. Soc.* **86**, 63–90.
Speece, M. A., Bowen, T. D., Folcik, J. L. and Pollack, H. N. (1985) Analysis of temperatures in sedimentary basins: the Michigan Basin. *Geophysics* **50**, 1318–1334.
Vacquier, V. (1984) Oil fields—a source of heat flow data. *Tectonophysics* **103**, 81–98.
Willett, S. D. and Chapman, D. S. (1987a) On the use of thermal data to resolve and delineate hydrologic flow systems in sedimentary basins: an example from the Uinta Basin, Utah. In *Proceedings, Third Canadian/American Conference on Hydrogeology, Hydrogeology of Sedimentary basins: Application to Exploration and Exploitation* (Edited by Hitchon, B., Bachu, S. and Seuveplane, C.), pp. 159–168. Dublin, Ohio.

Willett, S. D. and Chapman, D. S. (1987b) Analysis of temperatures and thermal processes in the Uinta basin. In *Sedimentary Basins and Basin-forming Mechanisms* (Edited by Beaumont, C. and Tankard, A. J.) *Can. Soc. Petrol. Geol.* Memoir 12, pp. 447–461.

Willett, S. D. and Chapman, D. S. (1987c) Temperatures, fluid flow, and the thermal history of the Uinta Basin. In *Migration of Hydrocarbons in Sedimentary Basins* (Edited by Doligez, B.), pp. 533–552. Editions Technip, Paris.