Appendix D: Colorado Oil and Gas Well Bottomhole Temperatures

D.1 Introduction

Bottomhole temperatures (BHTs) are temperatures measured close to the bottom of wells during geophysical logging of boreholes drilled for oil and gas exploration and production. BHTs have a variety of different uses including correction of other geophysical logs that are temperature sensitive (e.g. electrical logs), geothermal studies, and studies of hydrocarbon maturation. When wells are drilled, the circulation of the drilling mud (or other drilling fluid) disturbs the temperature in the well. Well logging runs are typically made before these temperature disturbances have dissipated, and therefore BHTs generally do not represent undisturbed rock temperatures. A correction is therefore necessary if a reasonable estimate of the undisturbed rock temperature is required. A section on drilling corrections is included in this report.

After correction for circulation of drilling fluid, the BHT of any single well depends on the vertical heat flow through the rocks in which the well was drilled and the thermal conductivities of those rocks. Assuming one-dimensional heat flow, vertically upward, the temperature at any depth, z is given by Fourier's Law of Heat Transfer:

$$q =- K(z)\frac{\partial T}{\partial z} \qquad (1)$$

where q is the heat flow, positive upward, K(z) is the vertical component of the thermal conductivity of rocks as a function of depth, z, increasing downward, and $\frac{\partial T}{\partial z}$ is the rate of change of temperature with depth, or the geothermal gradient. Equation can be rewritten as:

$$T_z = T_S + \frac{q\,(\partial z)}{K(z)} \qquad (2)$$

If the section penetrated by the well comprises n layers with thicknesses z_1, z_2, ... z_n, where z_n is the thickness of the *n*th layer to the BHT depth measurement, the thermal conductivities of the layers are K_1, K_2, ... K_n, and the temperatures at the top of the layers are T_1, T_2, ... T_n ($T_1 = T_S$), then the BHT is given by:

$$BHT = \sum_{i=1}^{n} T_i + \frac{q\,z_i}{K_i} \qquad (3)$$

Equations 2 and 3 illustrate that BHTs do not increase linearly with depth but are also controlled by the thermal conductivities of the rocks. Thermal conductivities may change by as much as a factor of two in Colorado basins, for example between low conductivity shales and higher conductivity sandstones and limestones. This results in a high thermal gradient in shales and relatively low thermal gradient in sandstones and limestones. Thus, to understand and interpret BHT data, variations in vertical thermal conductivity must be taken into account.

D.2 Drilling Corrections

BHT data are primarily temperatures recorded on well-log headers from measurements recorded during routine logging operations of hydrocarbon wells. Temperature measurements are generally made with electrical thermometers in logging tools or with maximum-recording thermometers in pressure tubes (to prevent pressure from increasing the apparent temperature) that are fixed at the top of, or just above, the logging tool. BHT measurement may be repeated during a sequence of logging runs in a borehole. BHT data are not reported on all log headers, nor for all wells. The primary use for recording temperature data with well logs is in correcting for the temperature coefficient of electrical resistance in resistivity logs: the temperature data are therefore of secondary importance to the loggers. However, large quantities of BHT data may be obtained for only the expense of extracting the data from well-log headers, which makes them a useful regional reconnaissance tool for geothermal exploration, even if individual accuracy of the data may be low.

Initial geophysical logs are generally run in hydrocarbon wells within a day of the end of drilling and completed within a few days of the completion of drilling. During drilling, a fluid is circulated down through the drill rods, through the bit, and back up the borehole in the annulus between the drill rods and the borehole or casing. The purpose of this fluid is to cool the bit and remove rock fragments produced during drilling. Rarely is this fluid at the same temperature as the rock that is being drilled, and consequently the circulating fluid is either heated or cooled by the formation. As the drilling progresses to depth the rock is generally hotter than the fluid and in response to the cooler fluid the rock is cooled. The cooling effect is increased if the fluid penetrates into the rock. Drilling fluid is generally circulated in a well after the completion of drilling for several hours to clean out and stabilize the borehole before logging, so even the bottom of a borehole has a significant period of cooling before logging. In addition, BHT measurements are not made at the bottom of the hole, but at the depth of the temperature measurement device, a few meters above maximum depth penetrated by the logging tool. Thus, at the depth at which the BHT is measured there may have been several hours of drilling fluid circulation and cooling of the rock. The change in temperature of the rock caused by the fluid circulation is called the "drilling disturbance." A correction for the drilling disturbance is necessary to estimate the undisturbed rock temperatures before drilling.

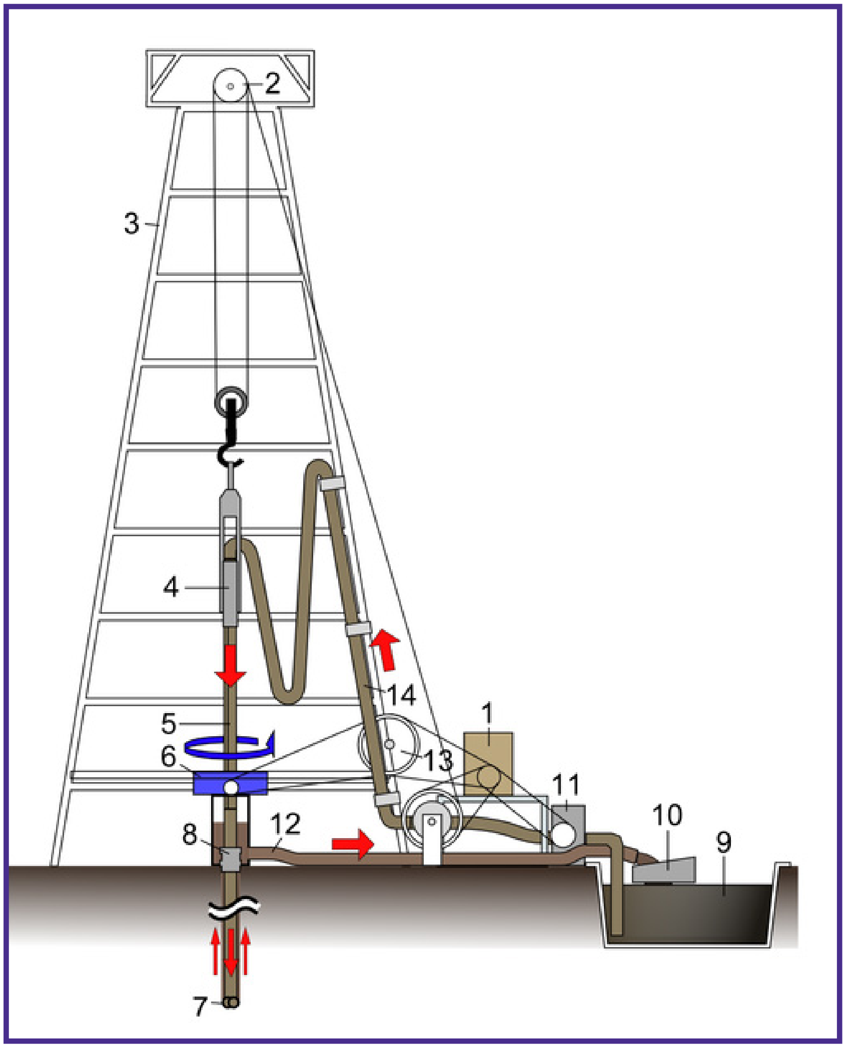

***Figure D.1: Diagram of oil drilling rig basic components**. Path of drilling fluid circulation is shown by red arrows from mud pit (9) through mud pump (11) up stand pipe (14) through Kelley hose into draw works (4) down in drill pipe (5), through the drill bit (7), into the casing head (8), through the flow line (12), into the shale shaker (10), and back into the mud pit (9). Samples of the rock formations being drilled are recovered from the shale shaker (10). The drilling fluid may range from heavy mud to water, to an air/water mist.*[1]

Guyod (1) discussed a number of factors associated with drilling that result in non-thermal equilibrium conditions in a well. Figure 1 shows the typical surface system for circulating and recycling drilling fluid in a drilling operation. One of the first, if not the first, attempts to calculate the drilling disturbance associated with drilling was by Bullard (2). Bullard used an approximate analytical solution to estimate the time necessary for the drilling disturbance to decay. He concluded that the time could be as long as months for temperatures along the length of the borehole, but as short as a day for the temperature at the bottom of the hole.

1 Drilling rig diagram: Tosaka, http://commons.wikimedia.org/wiki/File:Oil_Rig_NT.PNG. Image use courtesy of Creative Commons Attribution 3.0 Unported license.

There are many techniques for estimating the drilling disturbance. These techniques cover a wide range of modeling assumptions including treating the drilling-fluid circulation as a line heat-source, modeling the drilling mud and wall-rock separately, finite-difference and finite-element models, two-dimensional, three-dimensional, fitting the disturbed data to equilibrium temperature data, and other techniques and variables. Some of these techniques and the modeling assumptions that they use are given in Table D.1 together with the number of parameters that are required to apply the techniques. Some of the techniques, such as Horner (3), are designed to require no parameters, but they require a series of temperature measurements through time from which the equilibrium temperature is extrapolated; in fact, Horner (3) describes a technique to recover equilibrium pressures from non-equilibrium pressure data, but the technique has been adapted for temperature data. In practice, there is no ideal or universally accepted method for estimating the drilling disturbance because drilling practices vary and the data recorded on log headers are not always the same. BHTs are not recorded in all wells, and if they are recorded, they are not always repeated in multiple logging runs. Having multiple temperature measurements that form a smooth time series converging on an equilibrium temperature gives confidence in a technique to estimate the drilling disturbance (i.e. 1,2). However, if only one BHT is available, techniques requiring multiple temperature values cannot be applied.

Model Parameters																											
Reference Number	4	5	6	2	7	8	9	10	11	1	12	3	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
# Required Parameters	0	0	3	3	0	0	0	5	3	0	2	0	5	2	3	7	6	6	7	5	0	0	1	5	5	6	2
Fit to equilibrium Temperatures									X		X																X
Cylindrical Coordinates	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X		X	X	X	X		X	X	X
Cartesian Coordinates																											
3 Dimensional													X														
2 Dimensional		X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X			X	X	X	X
Graphical		X	X						X		X						X				X						X
Finite Element																	X										
Finite Difference													X					X			X						
Analytical	X			X	X	X	X	X		X		X		X	X	X			X	X		X	X	X	X	X	
Inversion of Parameters	X					X	X															X	X				
Lateral Fluid Flow																								X		X	
Radial Fluid Flow						X				X								X								X	
Zero Circulation Time		X						X					X			X			X	X	X			X			
Two Media						X	X	X					X				X	X		X				X		X	
Single Medium	X	X	X	X	X				X			X		X	X	X			X		X	X	X		X		X
Exponential Decay	X								X													X	X				
Line Source				X	X							X			X												X

Table D.1: Examples of publications for techniques for estimating the drilling disturbance with the assumptions used in the techniques. References are in alphabetical order.

D.2.1 Drilling Disturbance Corrections in Colorado

Examination of headers from logs from several thousand hydrocarbon wells in Colorado indicates that BHT measurements are rarely repeated during multiple logging runs in a well. Temperatures may be recorded as derived from different logging runs, but these temperatures are almost always the same temperature as recorded for the first log, and most likely the first log BHT has been copied on subsequent log headers. This lack of information prevents the extrapolation of equilibrium rock temperatures from multiple temperature-time readings.

In addition, drilling and circulation times relative to logging time, the exact depth of the BHT measurement, and drilling fluid temperature are not recorded on Colorado log headers. Without this information, an analytical or numerical model of the drilling disturbance cannot be generated. For some wells, there are temperatures obtained from drill-stem tests (DSTs), i.e., tests in which a section of the well is isolated and fluid is produced from the rock formation in the isolated section. Temperatures of this fluid are commonly assumed to be good estimates of the undisturbed rock temperatures because they measure the temperature of the rock fluid (i.e., 28 p. 59). However, if there is a component of expanding gas, gas adiabatic expansion causes cooling and thus the DST temperatures will be lower than undisturbed rock temperatures. The amount of cooling depends on the amount of gas associated with each DST. In addition, bond logs are run to ensure that the bottom of the well is securely cemented, and some of these logs are run several weeks after the cessation of drilling. As temperatures at the bottom of the drill hole relax to their undisturbed temperatures more rapidly than shallower intervals where temperatures are disturbed for longer periods, cement bond log BHTs taken several weeks after drilling were examined as a test of their approximation to virgin rock temperatures.

Corrections were derived for each basin based on DSTs, and where these were not available, corrections were based on suitable cement bond log temperatures. These were used in the first CGS release of the Colorado BHT data. However, during preparation of this report, three precision temperature logs were made available to CGS, two in the Denver Basin and one in the Raton Basin, and the corrected BHTs were found to be undercorrected (Figures D.2 and D.3). A new search for methods to correct the BHTs for the drilling disturbance was therefore made.

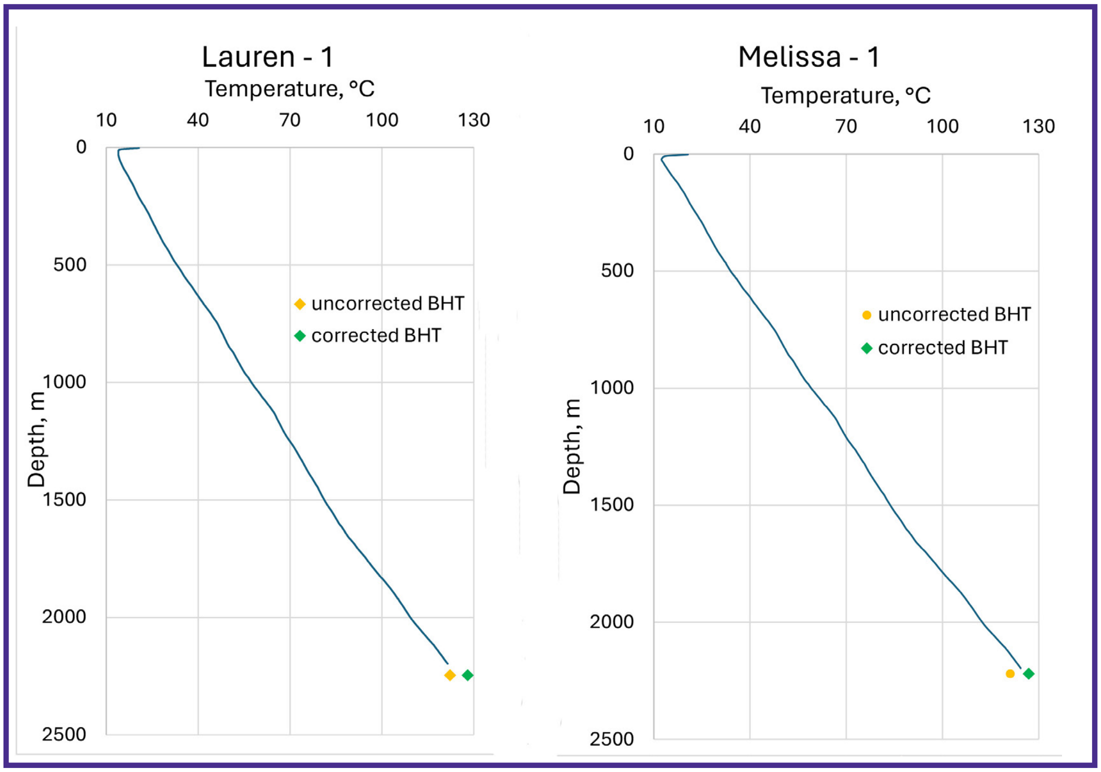

Figure D.2: Temperature vs. depth plots for Lauren-1 and Melissa-1 oil wells in the Denver Basin.[2] BHTs are from well scout cards with old correction and new correction.

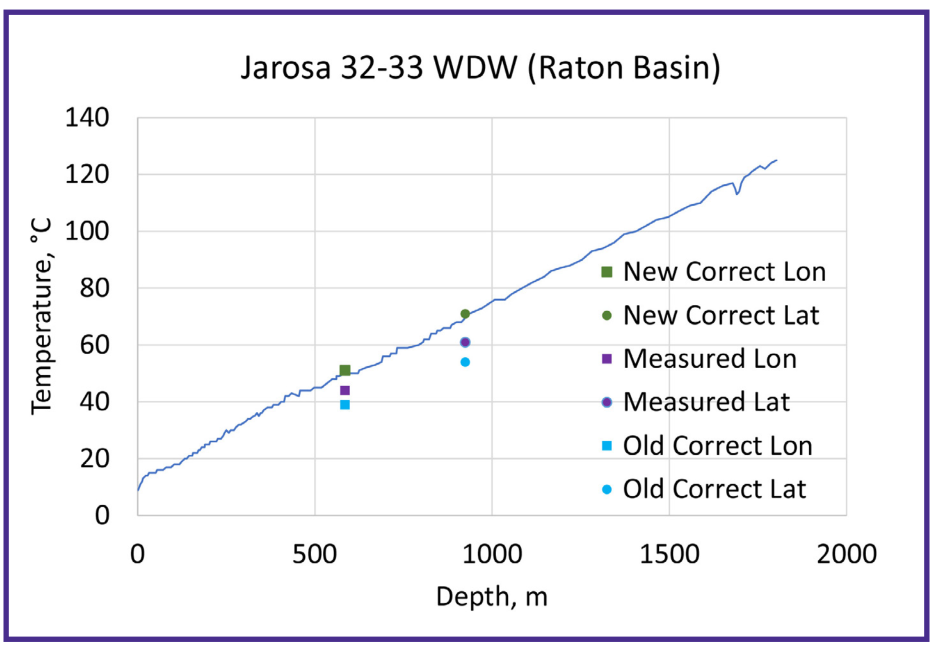

Figure D.3: Temperature vs. depth plots for Jarosa 32-33 water disposal well in the Denver Basin.[3] No BHT was measured in this well so BHTs were taken from the closest coalbed methane wells in longitude and latitude and plotted with the old and new corrections.

2 Graph created by Paul Morgan (CGS) with data courtesy of SMU Geothermal Lab.
3 Graph created by Paul Morgan (CGS) with data courtesy of Pioneer.

A new extensive literature search found a few publications that studied a large German BHT database in which most of the data were single BHT measurements. This database was the subject of study over at least three and a half decades to develop a BHT correction based on an empirical correlation (29–32). The empirical correlation allows drilling corrections for Colorado BHTs to be estimated where only single BHT measurements are available. The equilibrium formation temperature, T_∞, derived as Equation 5 of Agemar (31) and developed from the earlier reports, is:

$$T_\infty = \frac{BHT(t)\cdot 32a + T_0(e^{-a^2/4Kt} - 1)}{31a + (e^{-a^2/4Kt} - 1)} \tag{4}$$

where *BHT(t)* is the BHT measured at time *t* (time after cessation of circulation of drilling fluid), *a* is the radius of the hole, T_0 is the average ground surface temperature of the basin, and k is thermal diffusivity. In many of the German wells and most Colorado wells, *t* is not known. From a statistical analysis of the German BHT dataset, Bolotovskiy et al. (32) determined t as a function of the measurement depth, *z* in meters, as:

$$t = (3.612 + 0.001639 * z) * 3600 \text{ seconds} \tag{5}$$

In Bolotovskiy et al. (32), the suggestion was made that a constant radius of 0.08 m (6.25 in) gave the best results for the formula used in that report, but Agemar (30,31) reported that reliable results were obtained with the real radii of the wells. For the Denver Basin wells, not all well radii were given. When corrections were calculated for the Lauren-1 and Melissa-1 wells, one corrected BHT was too high and the other too low. When the well parameters were examined, the radii reported for these two wells were different by a factor of two. When the actual radii were replaced by 0.08 m, both corrected BHTs were close to the SMU measured log temperatures. With the lack of data and poor results with the Lauren-1 and Melissa-1 corrected BHTs, therefore, a radius of 0.08 m was used in Equation 4 for all Colorado wells.

Schulz and Werner (29) used a thermal diffusivity of 1.2 x 10^{-7} m^2/s but subsequent reports and Agemar (31) used a value of 1.5 x 10^{-7} m^2/s. The thermal diffusivity of liquid water ranges from 1.32 x 10^{-7} m^2/s at 0°C to 1.68 x 10^{-7} m^2/s at 100°C (33). Water is incompressible at this level of precision. Thermal diffusivity is a property of thermal conduction, whereas heat transfer between the drilling fluid and the rock surrounding the borehole is a combination of convection and conduction. Thermal diffusivity in this formula is a proxy term rather than a strict physical property. Thus, the term proxy diffusivity will be used in this context for this document. The best match to the SMU log temperatures for the Lauren-1 and Melissa-1 wells were given with a thermal diffusivity of 1.2 x 10-7 m2/s. Figure D.3 shows the SMU logs, the measured BHTs, the original corrected BHTs and the new corrected BHTs.

An equilibrium temperature log is available for a deep water disposal well in the Raton Basin, Jarosa 32-33 WDW, but a BHT was not available. BHTs were therefore taken from the most proximal coalbed methane wells, and these measured BHTs and their old and new corrected values are shown with the equilibrium log in Figure D.3. Air mist is used as the drilling fluid for coalbed methane wells in the Raton Basin rather than the "mud" utilized for gas and oil wells in other basins in Colorado. No reference was found for the proxy diffusivity for air mist drilling fluid, and therefore this was an unconstrained parameter. The diffusivity that gave the new corrections shown in Figure 2 was 1.6 x 10^{-7} m^2/s. Using a higher proxy diffusivity for air mist than for mud appears to contradict the conductive thermal properties of air mist and mud. However, air mist circulates in the well much faster than mud and therefore may transfer heat faster than slow-flowing mud.

D.3 References

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