GEOLOGICAL SURVEY OF CANADA
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Well temperature data compilation, correction and quality assessment for the Beaufort-Mackenzie Basin

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2010

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Hu, K., Issler, D. R. and Jessop, A.M. 2010. Well temperature data compilation, correction and quality assessment for the Beaufort-Mackenzie Basin; Geological Survey of Canada, Open File 6057, 14 p. + 7 figures + 2 tables, 1 CD-ROM.

Open files are products that have not gone through the GSC formal publication process.

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SUMMARY

Subsurface temperature data have been compiled for 258 petroleum exploration wells drilled in the Beaufort-Mackenzie Basin between 1965 and 2007. The data are from two sources: log-based maximum bottomhole temperature (BHT) measurements (corrected for the cooling effects of mud circulation where possible) and maximum well fluid test temperatures (primarily from drillstem tests). This report contains 2236 quality-ranked temperature values for different depths within the study wells. Uncorrected, raw BHT data are included in a separate Excel spreadsheet along with depth, time, and other information needed for temperature correction and quality assessment.

In general, the quality of the temperature data set is better than for many sedimentary basins where information to correct BHTs using the Horner plot method is commonly unavailable. For BHT data with recorded mud circulation times, approximately 50% of the corrected BHTs have short circulation times (≤5 hours; median value is 5.3 hours) and 40% have long post-circulation shut-in times (≥5 times the duration of mud circulation). If circulation time was not available, Horner plot temperature corrections were made assuming a circulation time of 4 hours (quality-level "c" corrected BHT). Approximately 51% of the logged intervals have Horner plot temperature corrections of quality "a" (excellent), "b" (good) or "c" (fair), where quality levels are assigned on the basis of the numbers of observations, recorded circulation and shut-in times (including multiple circulation episodes), consistency or data scatter, and aspects of data recording. Plots of these corrected BHTs and DST temperatures versus depth show similar average geothermal gradients (BHT – 24.8°C/km; DST – 25.7°C/km) and variances, indicating that both data sets are of similar quality.

INTRODUCTION

Temperature controls organic maturation and petroleum generation and therefore it is a fundamental parameter for petroleum resource assessment. Also, it is a key variable for investigating nonconventional energy sources such as gas hydrate or geothermal energy. Subsurface temperature data have been compiled from National Energy Board well history reports as part of a multi-year, government-industry funded study of petroleum systems of the Beaufort-Mackenzie Basin. Figure 1 shows the location of 269 exploration wells, 258 of which contain temperature data used for this compilation (see Table 1).

TEMPERATURE DATA SOURCES

Well test data

Well tests are designed to extract formation fluids from a limited depth interval within a borehole in order to evaluate the nature of the pore fluid and the hydraulic properties of the formation containing the fluid. Well test data are available from wireline (Formation Tester (FT), Formation Interval Tester (FIT), Repeat Formation Tester (RFT), and Modular Formation Dynamics Tester (MDT)), drillstem test (DST) and production test measurements for the Beaufort-Mackenzie Basin. Almost all Beaufort-Mackenzie well test temperatures are from DSTs (177 wells); temperature data are also available from MDT measurements for five of the newer wells (Kumak I-25, Kurk M-15, Olivier H-01, Umiak N-10 and Unipkat M-45; Table 1) and from FIT measurements for one well (Adgo F-28; Table 1). Commonly, temperature is measured during the fluid flow and pressure build-up phases of a DST but only maximum temperatures were recorded for most wells drilled during the 1960s and 1970s. Newer wells may have continuous temperature recordings but the maximum temperature is still assumed as the closest approach to the true formation fluid temperature.

Log derived data

Bottomhole temperatures (BHTs) are measured by maximum-reading thermometers during routine logging operations. Typically, after the logging tool is lowered into the borehole, it is left near the bottom for a short period of time to allow the thermometer to adjust to the ambient temperature. Commonly, multiple temperature measurements are made at similar depths but at different time intervals corresponding to different logging runs. The bottom of the well is the most recently drilled portion and therefore it should be the least thermally disturbed. However, after drilling stops, it is common for mud circulation to continue for a period of time in order to clean and condition the hole. This results in BHT values lower than the true formation temperatures. Caving and settling of uphole rock fragments to the bottom of the well can further depress BHTs. If sufficient information is available, it may be possible to estimate the true formation temperature from a series of different BHT measurements (e.g., Dowdle and Cobb, 1975). The required information includes:

1. Maximum BHT (T_m) from multiple logging runs;
2. Depth of temperature measurement;
3. Mud circulation time (t_c, in hours), which is the time between when drilling stopped and when circulation stopped;
4. Shut-in time or elapsed time (Δt, in hours) which is the time between when circulation stopped and when the thermometer was at the bottom of the well.

Depth information is recorded on well log headers but terminology varies among different logging companies for different logging depths. The depth at which temperature was measured can be estimated using the position of the thermometer on the tool string (requiring knowledge of the tool and tool string configurations) and by comparing the depths recorded by the driller and logger, which may differ. In some cases, the logged depth is greater than the drilled depth and this may be caused by stretching of the logging cable. Under these circumstances, the drilled depth is taken as the maximum depth at which the BHT was recorded (although it could be less if the hole is not vertical, if debris has accumulated at the bottom of the hole, or if the thermometer is not at the base of the drill string). The times when drilling and circulation stopped, and when the tool was on bottom, are generally available on older log headers (e.g., wells drilled during the 1960s and 1970s), but some of this information is missing for newer wells due to changes in log header formats. Typically, there is a lack of information on mud circulation time for newer wells but sometimes this information is available from the drilling reports in the well history files.

Correction of BHT data

BHTs measured during well logging are generally lower than true formation temperatures because the usually cooler drilling mud is not in thermal equilibrium with the surrounding rock (exceptions occur when the drilling mud is hotter than surrounding rock formations). Deming (1989) and Hermanrud *et al*. (1990) review various methods for correcting BHTs to obtain estimates of true formation temperature. A popular correction technique, commonly referred to as the Horner plot method due to its similarity with the analysis of reservoir pressure recovery (Horner, 1951), is based on an approximation to the full solution to Bullard's (1947) line source model (Lachenbruch and Brewer, 1959; Dowdle and Cobb, 1975; Fertl and Wichmann, 1977). The method extrapolates a "true" formation temperature from a series of temperature measurements made at different times after the end of mud circulation. Dowdle and Cobb (1975) showed that a Horner plot will lead to satisfactory approximations of true formation temperature for short circulation times and suitably long shut-in times. For the Horner plot technique, the relationship between true formation temperature (T_{fm}) and the measured BHT (T_m) is:

$$T_{fm} = T_m - C \log\left(\frac{\Delta t}{\Delta t + t_c}\right) \tag{1}$$

where Δt and t_c are as defined above, and C is a constant depending on a variety of factors (e.g., borehole diameter, duration of circulation, temperature difference between mud and rock, thermophysical properties of mud-rock system, etc.). In equation 1, for very large shut-in times, the ratio $\Delta t/(t_c+\Delta t)$ approaches unity and T_m should be close to T_{fm}.

Where possible, equation 1 was used to extrapolate BHTs to obtain estimates of true formation temperature for the Beaufort-Mackenzie Basin. For some wells, there is no information on t_c. Majorowicz *et al.* (1996) reported a median t_c value of 4 hours in their study of the Beaufort-Mackenzie thermal regime and this value was used to correct BHTs when t_c was not recorded. Figure 2 shows examples of the Horner plot method using BHT data from the Taglu G-33 well.

DATA QUALITY ASSESSMENT

Well test data quality

In general, DST values are considered to be the best temperature measurements available from petroleum exploration wells (e.g., Oxburgh and Wilson, 1989; Förster *et al*., 1997; Beardsmore and Cull, 2001, p. 59). Drilling creates temperature disturbances around the borehole through the cooling effects of mud circulation and the invasion of permeable formations by drilling mud which displaces and mixes with pore fluids. The quality of the DST temperature measurements will depend on whether or not a sufficient quantity of pristine formation fluid has been obtained from the region beyond the invaded and thermally disturbed zone. This will depend on factors such as formation permeability, degree of invasion, formation damage, and duration of testing that will influence fluid flow rates and the nature of fluid recovery.

Hermanrud *et al*. (1991) discuss how DST temperatures are influenced by factors such as the borehole environment, the characteristics (e.g., thermal response time) and position of the temperature recorders, and the duration of flow. In general, temperature sensors should be adjacent to the perforated zone or not more than 50 to 100 m above it for best results. The Joule-Thompson effect due to the pressure drop accompanying flow can lead to warming of liquids and cooling of gases (Steffensen and Smith, 1973) and it is most significant for large pressure drawdowns. Based on oil production simulations, App (2008) calculated near-wellbore temperature increases of 4 to 24 °F (2 to 13 °C) for drawdowns between 2000 to 10000 psia (13.8 – 68.9 MPa). A pulse-like temperature increase can sometimes occur immediately after shut-in (Hermanrud *et al*., 1991) and this has been attributed to compression effects (Perrier and Raiga-Clemenceau, 1983).

Although some of the above factors can contribute to heating of fluids, it is more likely that DST temperatures will underestimate rather than overestimate formation temperatures given the various sources of error. DSTs with high oil or water flow rates and low drawdowns may yield good results whereas those with low flow rates or expanding gas may cause measured temperatures to be too low. In many cases, we lack sufficient information to asses how well individual DST values approximate the true formation temperature. Rather than make *a priori* judgements on the quality of compiled DST temperature values, we grouped values into those from (a) successful tests and (b) unsuccessful tests (e.g., misrun due to a mechanical problem). A subsequent analysis of the spatial distribution of temperature data integrated with flow test results may allow for a better assessment of the quality of individual data points.

BHT data quality

In general, the Horner plot method will underestimate true formation temperature although errors should be small (<2%) for short t_c (≤3 hours) and moderately long Δt (5-15 hours) values under conductive heat flow conditions (Dowdle and Cobb, 1975). In some cases, even moderately long t_c values (12 hours) may still yield acceptable results (<5% error) (Luheshi, 1983). More sophisticated approaches that include finite t_c, variations in the drilling mud and formation thermal properties, fluid flow and free convection in forward analytical and numerical models (Middleton, 1982; Lee, 1982; Luheshi, 1983; Ribeiro and Hamza, 1986; Shen and Beck, 1986), and inverse models (Cao *et al*., 1988; Nielsen *et al*., 1990) provide insight into the problem but are difficult to use because the required parameters are generally poorly known. Based on these studies, the Horner plot method should give the best results for small borehole diameters (≤254 mm) and long shut-in times (≥ 5 x t_c).

In addition to uncertainties with BHT correction procedures, there are various possible sources of noise in the data. In most situations, BHT values will underestimate true formation temperatures. However, erroneously high temperatures can occur with maximum-recording mercury-in-glass thermometers due to the pressure increase associated with boiling of water if water is accidentally sealed in the thermometer tube (Oxburgh and Wilson, 1989). Vibration during logging can also alter temperature readings. Other common problems include improper calibration of thermometers, incorrect recording of time, depth and temperature information, variable depths of measurement between logging runs, insufficient time near the bottom of the well for the thermometer to stabilise, and even fabrication of data.

Commonly, BHTs at shallow depths in the Beaufort-Mackenzie Basin (within and below the permafrost zone) exceed those expected, but the cause is unclear. It may be related to heating of the formation by warmer drilling fluids or incorrect calibration of thermometers to these low-temperature conditions. In some cases, BHTs indicate a temperature decrease with time during logging which implies heating of the borehole wall by warmer drilling fluids. Although chilled mud was used in many cases to avoid destabilizing permafrost and gas hydrate during drilling, it would appear that some wells were drilled with a warmer mud. Jessop (1990, p. 64-68) discusses thawing of permafrost during drilling of the Reindeer D-27 well and the effect of latent heat on thermal recovery. Under such conditions, the Horner plot approximation will not be valid for the relatively short time scales involved in well logging. Also, unless maximum-recording thermometers are initialized to sub-zero temperatures at the surface, they may give false high temperatures at shallow depth (upper 1000 m) in areas of thick permafrost.

It is not possible to determine all sources of error in the BHT data. BHT temperature quality was assessed in terms of its suitability for correction using the Horner plot method. The BHT data are categorized into four groups:

a - Excellent: Corrected BHT values are based on three or more BHT data points with short circulation times (t_c < 10 hours) and long shut-in times ($\Delta t \geq 5 \times t_c$), and with all points conforming closely to the plotted Horner curve;

b - Good: Corrected BHT values are based on two or more BHT data points with short circulation times (t_c < 10 hours) and relatively long shut-in times, and minimal data scatter;

c - Fair: Corrected BHT values are based on two or more BHT values with t_c values < 20 hours (assumed to be 4 hours if unknown) and known Δt values, and limited data scatter;

d - Poor: 1) Corrected BHT values are based on multiple BHT values with long circulation times (t_c > 20 hours); or 2) a single BHT value with Δt and/or t_c known; or 3) BHT data with unknown Δt values; or 4) inconsistent BHT values; or 5) errors in times/dates; or 6) multiple circulation episodes.

Figure 2 shows examples of quality “a” (solid blue circles), “b” (solid green circles), “c” (open purple circles) and “d” (solid red triangles) BHT data for the Taglu G-33 well. BHT data are shown on a Horner plot and raw data from the well log headers are tabulated at the bottom of the figure. Fitted regression equations representing Horner corrections are shown for each type of data. The highest correlation coefficients and highest $\Delta t/t_c$ ratios are associated with “a” quality data. With the exception of the “d” quality data, the slope of the Horner correction increases with increasing depth and well temperature (Figure 2) as observed by Deming (1989).

The overall quality of the BHT data set can be assessed by evaluating the criteria for a Horner plot correction. Figure 3a shows the distribution of all measured t_c values corresponding to 523 logged intervals within the study wells. Figure 3b shows the same plot but for 425 logged intervals that have sufficient information for a Horner plot correction (excludes corrected BHTs where t_c is assumed to be 4 hours). Nearly half the BHT data with complete information for a Horner correction have short circulation times of ≤5 hours and 70% of these data have t_c values of ≤10 hours. This suggests that, where complete information is available, a significant fraction of these Horner-corrected BHT values have the potential to be of "a" or "b" quality based on the criterion of short circulation time. Figure 4 is similar to Figure 3 but the scale has been enlarged and truncated to illustrate approximately 90% of the data (cumulative distribution curves are shown in red). Figure 4a shows the distribution of t_c values for 473 logged intervals and Figure 4b shows the same plot for 385 corrected BHT values. Corresponding median t_c values are 6 and 5.3 hours which are slightly higher than the value of 4 hours given by Majorowicz *et al.* (1996) that was used to correct "c" quality BHT data.

Borehole size and shut-in time also affect the quality of the Horner correction. Luheshi (1983) suggests that the Bullard (1947) line source model and its Horner approximation work best for smaller diameter boreholes (≤254 mm). Drill bit size should approximate borehole diameter unless there has been substantial caving of the borehole wall. Figure 5a shows the distribution of bit sizes corresponding to corrected BHT data with known t_c. Fifty-six percent of these corrected BHT values come from boreholes with diameters of ≤254 mm. Figure 5b shows the distribution of the ratio, $\Delta t/t_c$, for all corrected BHT values with known t_c. The largest Δt value was used to calculate the ratio for each corrected BHT. Forty percent of these corrected BHTs have Δt values that are ≥5 times larger than t_c.

TEMPERATURE DATA

Table 1 contains 2236 temperature values for 258 wells in the Beaufort-Mackenzie Basin. There are 1078 quality-ranked temperatures from BHT measurements for 258 wells and 1158 temperatures from well fluid tests for 181 wells. For the BHT data, measured well depth and true vertical depth (for deviated wells) are given in metres with respect to Kelly Bushing (KB) elevation and ground elevation (GL; onshore wells) or sea floor (SF; offshore wells). For the well test temperature data, the test interval (start and end depths), the mid-point depth or recorded depth, and corresponding true vertical depth are listed.

The criteria for "a" or "b" quality data are fairly stringent. Although 425 logged intervals have complete information for a Horner correction, and many of these have short circulation times (≤5 hours; 49%) (Figures 3 and 4), small borehole diameters (≤254 mm; 56%) (Figure 5a), and long shut-in times ($\Delta t/t_c \geq 5$; 40%) (Figure 5b), only 129 points (12% of the BHT data in Table 1) are of “a” or “b” quality. For various reasons, the other 296 corrected BHT values are of “c” quality. An additional 131 logged intervals that lack information on t_c have Horner-corrected BHT values based on an assumed t_c of 4 hours. Therefore, there are 427 corrected BHT values of “c” quality, which represents approximately 40% of the BHT data in Table 1. In some cases, “c” quality data may give results that are as accurate as “a” quality data if the assumed t_c value is close to the true value. In total, 556 points, or 52% of the BHT data, are Horner-corrected values of quality “a”, “b”, or “c”. There are 1032 temperatures from successful well tests (“a” quality), which represents 89% of the well test temperature data.

Figure 6 is a plot of all the temperature data in Table 1. Data points are identified using different coloured symbols according to their quality ranking and data type (triangles for BHT values; circles for well test data). Both the well test temperature data and the BHT data exhibit a similar range of values. Even most of the lower quality BHT (“d” quality) and DST (“b” quality) data fall within the range defined by the higher quality data. Linear regression yields an average geothermal gradient of 25.5 °C/km.

Figure 7 shows that the temperature-depth distribution is very similar for Horner-corrected BHT data and DST data. In Figure 7a, “a”, “b”, and “c” quality BHT data give a linearly regressed geothermal gradient of 24.8 °C/km whereas “a” quality DST data give a gradient of 25.7 °C/km (Figure 7b). The BHT and DST temperature data are very similar below 1000 m; the main reason for the small difference in geothermal gradient is that there are more BHT temperature data at <1000 m depth. As mentioned above, there are many anomalously high temperature values within and below the permafrost zone and this shifts the surface temperature intercept to a positive value (note the nearly 4 °C difference in surface temperature intercept between Figures 7a and 7b). Depth to base of permafrost varies from 0 to 740 m across the study area (Issler *et al.*, in press) so high variability in temperature is expected at shallow depth. Within the permafrost zone, there are eight “c” quality and 20 “d” quality BHT values. Exclusion of these eight “c” quality values had a negligible effect on the temperature-depth plot of Figure 7a. Figures 6 and 7 illustrate linear first-order fits to the temperature data. However, it is recognized that temperature varies nonlinearly at shallow depths (Taylor *et al.*, 1982).

Horner-corrected BHT data can yield temperatures 5 to >10% lower than DST temperatures (e.g. Hermanrud *et al*., 1990; Nielsen *et al*., 1990; Waples and Pedersen, 2004), depending on data quality, completeness of information, and the duration of Δt. Typically, Horner-corrected temperatures are less than DST temperatures because Δt values are too low. In a study of the Po Plain region in Italy, Pasquale et al. (2008) obtained good agreement between Horner-corrected temperatures and DST temperatures (both yielded similar geothermal gradients) when Δt was > 10 hours. For Δt < 10 hours, Horner-corrected BHT values were too low by 2 °C on average.

The overall good agreement between BHTs and DST temperatures (Figures 6 and 7) provides confidence in this data set. Individual well temperature-depth plots (not shown) confirm that higher quality BHT and DST data give consistent temperature-depth trends. The Beaufort-Mackenzie Basin is in a remote, harsh, and ecologically sensitive area that is subject to strict regulatory control that makes drilling very expensive (single wells cost several tens of millions of dollars or more). As a result, it appears that a significant effort was made to acquire well data carefully.

Although this is a good temperature data set, much more could be done to improve it, particularly with regard to "c" and "d" quality BHT data. Table 2 contains the raw BHT data and associated information (if available) from log headers necessary for Horner plot temperature corrections. The table includes depth, measured BHT, t_c, Δt, and drill bit size for 258 wells, used in our data quality ranking scheme. These data are available to facilitate further analysis using other temperature correction methods. For example, in a study of the Taranaki Basin of New Zealand, Funnell *et al*. (1996) used an exact solution to Bullard's model rather than the Horner approximation in order to better correct BHT data with short Δts and large-diameter boreholes. Such an approach could be used to improve temperature estimates for some of the lower-ranked data in Table 1. Some of the "d" quality single-point BHT data could be corrected using empirical methods that determine the Horner thermal recovery slope as a function of depth (e.g., Deming, 1989; Majorowicz *et al*., 1996; Pasquale *et al*., 2008). Empirical methods based on DST temperatures can also be used to correct BHT data (e.g. Förster *et al*., 1997; Waples *et al*., 2004).

It is also possible to improve on the quality ranking of DST temperature data that currently are classified as (a) successful or (b) unsuccessful tests. It should be possible to set up objective criteria for including or excluding DST temperature data based on the results of flow tests. This work can be done in conjunction with the spatial analysis of BHT and DST temperature data to aid in the identification of anomalous or poor quality data. Some spatial analysis of these data has already been undertaken to investigate the Beaufort-Mackenzie thermal regime (Chen *et al*., 2008; Issler *et al*., in press). Tabulated DST temperatures (Table 1) are maximum recorded temperatures from DST reports and usually this is the only information available. However, some of the newer wells contain digital temperature records that may allow for a more in-depth analysis of DST temperatures (e.g. Hermanrud *et al*., 1991).

ACKNOWLEDGEMENTS

We would like to thank reviewers, Dr. Glen Stockmal and Dr. Zhuoheng Chen, for their helpful comments that improved this report. This work was supported by current (BP Canada Energy Company, Chevron Canada Limited, ConocoPhillips Canada Resources Corporation, Imperial Oil Resources Ventures Limited, MGM Energy Corporation and Shell Exploration and Production Company) and former (Anadarko Canada Corporation, Burlington Resources, Devon Canada Corporation, EnCana Corporation, Petro-Canada, Shell Canada Limited) members of the Beaufort-Mackenzie consortium, the Program on Energy Research and Development (PERD) and the Earth Sciences Sector of Natural Resources Canada through the Northern Resources Development, Secure Canadian Energy Supply and GEM Energy programs.

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