Statistical Analyses of Subsurface Temperature Data and Correction Methods

Thorsten Agemar

Leibniz Institute for Applied Geophysics, Stilleweg 2, D-30655 Hannover

thorsten.agemar@leibniz-liag.de

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ABSTRACT

Subsurface temperature is a key parameter for any geothermal exploration activity. In Germany, records of subsurface temperatures exist for approximately 11,000 wells. It is well known that the uncertainty of corrected BHTs is generally high on the order of ± 10 K. It might be even higher in the case of incomplete data sets. In this study, new correction methods based on statistical analyses were developed to improve the correction of BHTs if only one measurement is available. A test revealed a substantial improvement compared to the previously applied correction method. Since the corrected temperatures are used for the calculation of a geostatistical 3D temperature model, the assessment of uncertainty is very important. High quality data must be preferred over low quality data but low quality data might be better than remote or no data. Knowledge about the degree of certainty of specific data categories may help to improve subsurface temperature predictions for future geothermal projects.

1. INTRODUCTION

For the preparation of temperature maps and 3D temperature models, individual measurements in the deepest boreholes are used in addition to disturbed and undisturbed temperature logs, reservoir temperatures and production tests.

The Leibniz-Institute for Applied Geophysics has a long history of collecting and evaluating subsurface temperature data. It stores temperature data in the Geophysics Information System FIS-GP (www.fis-geophysik.de, Kühne et al. 2003). The FIS-GP contains data from the LIAG and from other institutions, too.

The geothermal subsystem of FIS-GP contains approx. 11,000 boreholes with temperature data. Equilibrium temperature logs and reservoir temperatures are considered optimal data which require no corrections. Because of the periodic monitoring of some production wells over many years, reservoir temperatures are available in time series; the fluctuation of these temperatures is mainly less than 1 K. Temperature measurements in the course of hydraulic production tests are generally also of high quality. The quality depends on the test duration. However, measurement results may be falsified by a previously performed injection test. Unfortunately, the bulk of subsurface temperature data is of lower quality, like for instance bottom-hole temperatures (BHT) which are recorded in almost all industrial boreholes at the deepest point of the well immediately after drilling has stopped. The temperature field around a borehole is usually disturbed by mud circulation related to the drilling process. A number of methods to extrapolate from BHT to the undisturbed temperature have therefore been developed based on various assumptions about the cooling effect of the circulating mud and the thermal behaviour of the borehole and the surrounding rock.

Different extrapolation methods can be used depending on the shut-in time (time elapsed after the end of drilling until measurement), the mud circulation time and the number of temperature values available for each depth (Agemar et al. 2012, Schulz and Schellschmidt 1991, Schulz et al. 1990, Schulz et al. 1992, Schulz and Werner 1987).

FIS-GP automatically suggests the most appropriate correction method for raw temperature according to availability of parameters like borehole radius, number of shut-in times /measurements and so on. However, operators are still able to override automatic decisions or to de-activate implausible measurements manually.

This study focusses on bottom hole temperature corrections with only one shut-in time available.

2. METHODS

If there are three or more BHT values at a depth at different shut-in times, the cylinder source correction might be used (Leblanc et al. 1982, Middleton 1982). With this approach, the temperature of the flushing liquid is assumed to be constant after stopping the circulation (t = 0) and deviates by the amount ΔT from the true equilibrium formation temperature.

$$T_\infty = \mathrm{BHT(t)} - \Delta T\left(e^{-a^2/4kt} - 1\right) \qquad [1]$$

With T_∞ = equilibrium formation temperature [°C]

BHT = measured bottom hole temperature [°C]

ΔT = initial temperature deviation [K]

a = borehole radius [m]

κ = thermal diffusivity [m²/s]

t = shut-in time [s]

T_∞ is calculated by a fitting approach that varies ΔT and κ, where κ is the effective thermal diffusivity of the flushing fluid and the surrounding rock (Schulz et al. 1992).

This method has also been used for BHT values with only one shut-in time (Schulz and Werner, 1987: p.14, Bolotovskiy et al. 2015). In this case, the initial temperature deviation instead of a second BHT value must be used for fitting. Originally, the initial temperature deviation was estimated relatively simply from the mean value of undisturbed equilibrium formation temperature and average surface temperature:

$$\Delta T = T_\infty - T_m = T_\infty - \frac{(T_\infty + T_0)}{2} \qquad [2]$$

With T_0 = mean annual soil temperature [°C]

T_m = mud temperature at the end of drilling [°C]

From equations [1] and [2] one obtains for the equilibrium temperature:

$$T_\infty = \mathrm{BHT(t)} + \frac{1-e^{-a^2/4kt}}{1+e^{-a^2/4kt}} (\mathrm{BHT(t)} - T_0) \qquad [3]$$

Fixed parameters were used for the corrections, which were determined on the basis of experience, numerical tests and statistical data (Bolotovskiy et al. 2015, Schulz and Werner 1987):

- well radius: a = 0,08 m (6 ¼" pipe)

- thermal diffusivity: κ = 0,15·10^{-6} m²/s.

Within FIS-GP 2,156 BHT data sets exists with only one shut-in time. The equilibrium formation temperature was calculated in FIS-GP for these 2,156 BHT values until 2017. If the actual borehole diameter is used instead of the fixed diameter of 6.25 inches, the correction would be significantly too high for many BHT values. On the other hand, it is unsatisfactory that the known diameter is not used for the correction, although it is entered in the database for most BHT measurements with one available shut-in time. For some records, the diameter of the last drill section is not noted, but it can at least be guessed from the last pipe.

Doubts are also cast on formula [2], the estimation of ΔT, the temperature of the mud directly after the end of drilling. Although it is plausible that ΔT depends on the difference between rock temperature and surface temperature, whether and how ΔT and borehole diameter correlate with each other is less obvious. A larger mud volume should lead to a larger ΔT at the same mud speed. However, the use of a larger drill bit also increases the frictional heat to be dissipated. At the same time, the larger borehole wall leads to a higher heat exchange between the drilling fluid and the rock. Due to this complexity, an empirical determination by ΔT is proposed. Unfortunately, information on ΔT is generally not available. However, ΔT values can be estimated for wells for which three or more shut-in times are available for one depth. In this way, ΔT values for different borehole diameters could be obtained from 385 datasets. The results show that ΔT behaved reciprocally to the drill hole radius a (with a coefficient of determination r^2 = 0.52). The following empirically determined relation can be used as a new approach to estimating ΔT for data sets with only one shut-in time:

$$\Delta T = \frac{(T_\infty - T_0)}{31a} \qquad [4]$$

In Fig. 1, both approaches can be compared for the prognosis of ΔT. This shows that the ΔT values determined with formula [2] not only show a greater dispersion (r^2=0.42), but also tend to result in ΔT values that are too high, i.e. overestimate the initial temperature disturbance.

From the formulas [1] and [4] one obtains now for the equilibrium temperature:

$$T_\infty = \frac{BHT(t) \cdot 31a + T_0(e^{-a^2/4kt} - 1)}{31a + (e^{-a^2/4kt} - 1)} \qquad [5]$$

In contrast to the old correction method, the actual borehole radius a is again used instead of the fixed dimension 0.08 m (Ø 6¼" pipe). For the corrections, only the thermal diffusivity with κ = 0.15·10^{-6} [m²/s] is used as a fixed parameter, which was determined on the basis of experience, numerical tests and statistical data (Schulz and Werner 1987). This allows the estimation of undisturbed equilibrium formation temperature from only one shut-in time with greater accuracy than before.

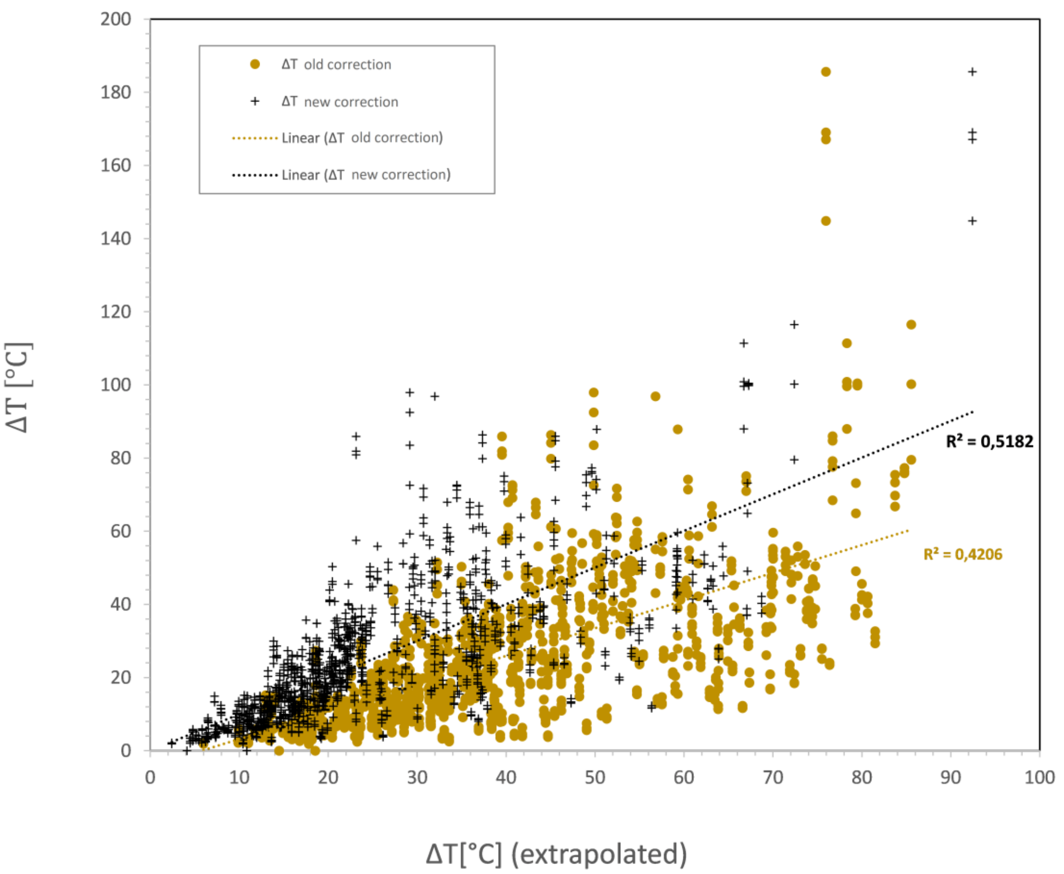

Fig. 1: ΔT values calculated according to formula 4 (crosses) and formula 2 (circles) plotted against extrapolated ΔT values from a sequence of 3 or more BHT measured values (cylinder source model approach).

3. RESULTS

In Figure 2, the corrected BHT values are plotted against each other according to the old and new correction methods. The BHT values corrected according to the old method are plotted on the abscissa. The BHT values corrected according to the new method are plotted on the ordinate. The results of the new correction procedure are very similar to the old estimates in most cases. If the geothermal gradients are determined from the newly corrected BHT values, the overall variance is somewhat lower (70 K^2 instead of 96 K^2). The mean value over all 2156 temperature values is only approx. 1.6 K lower for the newly corrected BHT values than for the BHT values corrected according to the old method. For comparison: If the raw temperatures were corrected with the current ΔT estimate according to formula 2 and the actual borehole diameters in Formula 1, the mean value of all corrected temperatures would be approx. 15 K higher (Figs. 3+4).

Nevertheless, the new correction procedure can make a significant difference in local temperature forecasts. This becomes particularly clear when comparing corrected BHT values with precisely measured temperatures in the immediate vicinity. Table 1 shows some examples where the two correction methods result in very different temperatures. A comparison with reliably measured temperatures in the immediate vicinity at approximately the same depth shows that the new correction method provides more reliable results. In addition, the lower variance of the corrected temperature values and the gradient derived from them also speak in favour of the new method. What speaks against the old method is that there is no empirical evidence for the estimation made in Formula 2 and that the cylinder source model correction was in most cases carried out with the wrong borehole radius.

Fig. 3 clearly shows that the corrected BHT values from boreholes at shallow depths (< 500 m) scatter very strongly. This effect becomes particularly clear when the gradients are considered (Fig. 4). It appears that BHT values measured at shallow depths are more difficult to correct than BHT values measured at greater depths. These values will therefore be deactivated in FIS-GP.

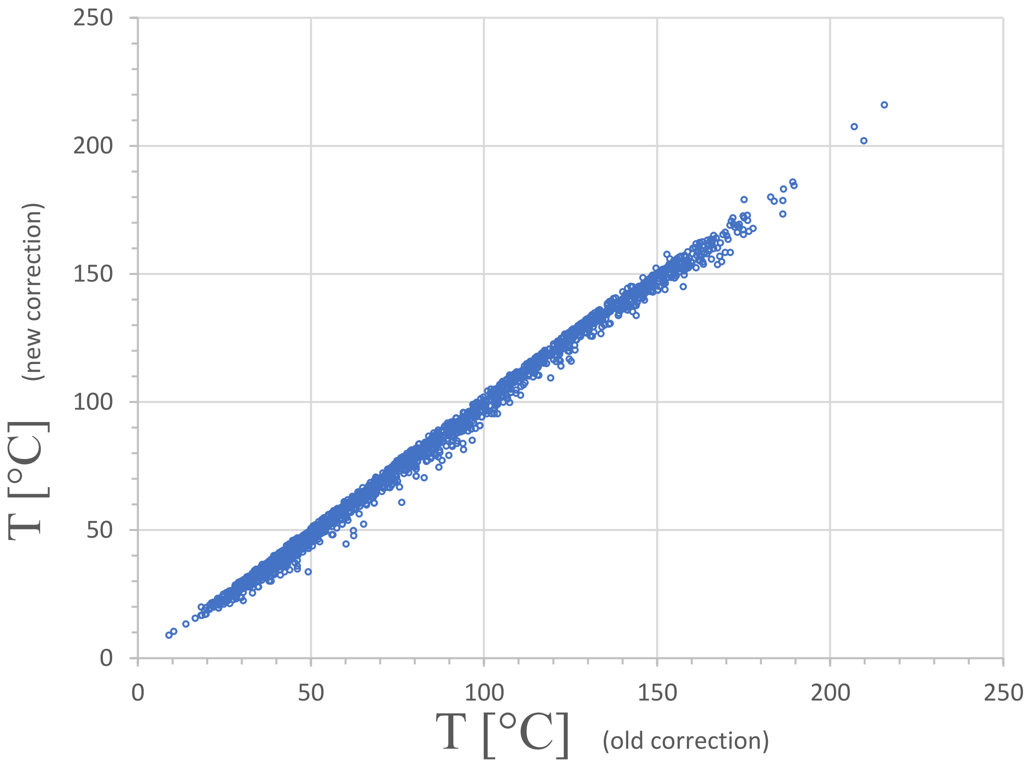

Figure 2: Comparison of the old and new correction procedure for BHT values with only one shut-in time at one depth.

If the borehole diameter is unknown, the average value of 0.12 m can be used for the radius a. If the shut-in time of a measurement is unknown, it is estimated in FIS-GP on the basis of a statistical estimate. As described by Bolotovskiy et al. (2015), the shut-in time t is determined as a function of the measurement depth:

$$t\ [s] = (3{,}612\ [h] + 0{,}001639\ [h/m] \cdot z\ [m]) \cdot 3600 \quad [6]$$

However, the use of equation [6] brings huge uncertainty to the determination of the initial temperature deviation ΔT. The use of corrected BHTs with statistical shut-in time estimate is not recommended.

Table 2: Formation temperatures determined according to formula [2] and [5] and comparative values from adjacent boreholes with high quality measurements at similar depths (in blue).

Borehole	Depth [m]	T [°C] –old-	T [°C] -new-	Type	Distance [km]
1 North German Basin	1727	82,69	70,52	BHT	
2 North German Basin	1791	86,88	74,66	BHT	1
V1+2	1650		72,4	equil. log	
3 Molasse Basin	1570	76,15	60,94	BHT	1
V3	1500		63,56	equil. log	
4 North German Basin	4577	169,64	158,5	BHT	10
V4	4652		152,0	hydr. test	
5 North German Basin	1187	62,23	49,95	BHT	
V5a	1200		44,42	equil. log	8
V5b	1200		43,91	equil. log	

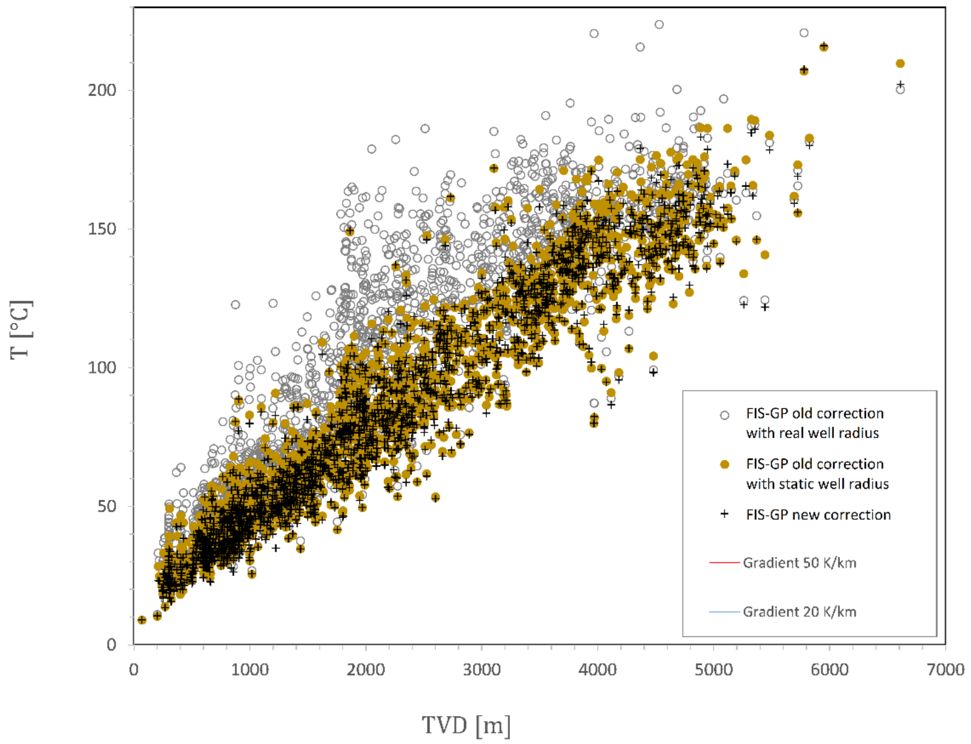

Figure 3: The formation temperatures determined from the corrected BHT values are plotted against the depth. Crosses refer to the new correction. Grey circles refer to the old correction if a fixed radius would have been used. Brown discs show corrected BHTs before the new correction method was introduced.

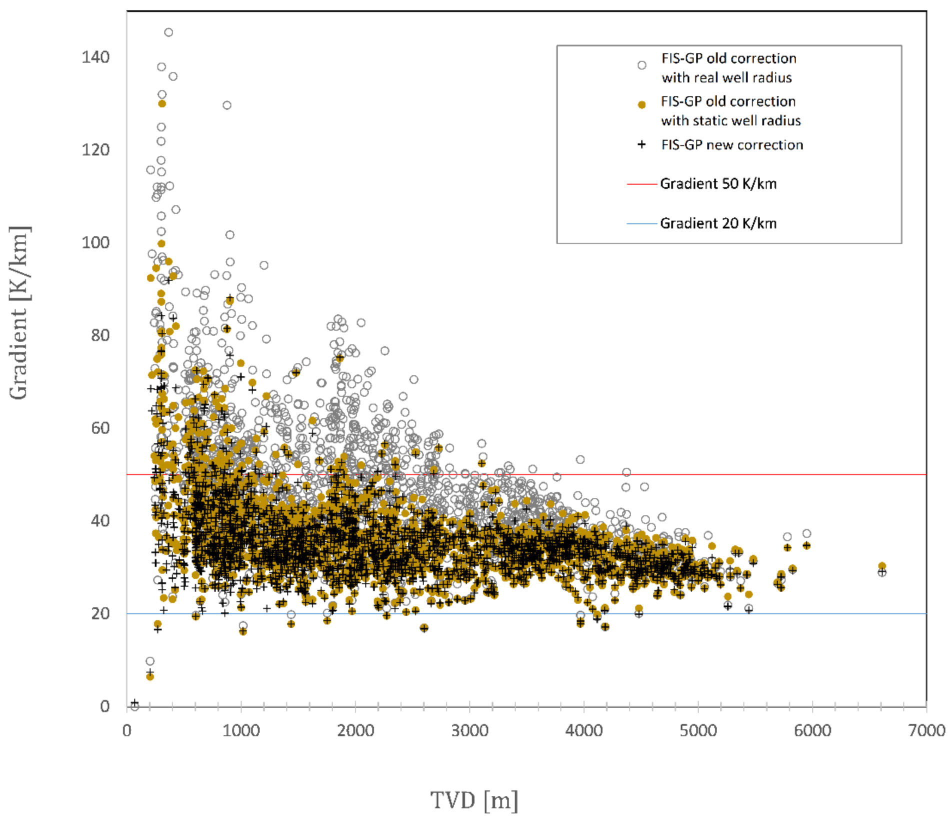

Figure 4: Gradients determined from the corrected BHT values are plotted against the depth. The strong scattering for depths less than 500 m is partly due to the fact that small changes in temperature cause large changes in the gradient.

4. CONCLUSION

It is well known that the uncertainty of corrected BHTs is generally high on the order of ± 8 K (Förster, A. 2001). It might be even higher in the case of incomplete data sets. In this study, new correction methods based on statistical analyses were developed to improve the correction of BHTs if only one measurement (shut-in time) is available. A test revealed a substantial improvement compared to the previously applied correction method. Since the corrected temperatures are used for the calculation of a geostatistical 3D temperature model, the assessment of uncertainty is very important. High quality data must be preferred over low quality data but low quality data might be better than remote or no data. Knowledge about the degree of certainty of specific data categories may help to improve subsurface temperature predictions for future geothermal projects. The comparison between corrected BHTs according to the new method and high quality temperature data (Table 2) indicates a standard error of just ± 5 K. However, as the random sample is very small, reliable information on the standard error cannot be provided.

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