8. TEMPERATURE LOGS

8.1 Introduction

The *Temperature Log* is a tool for measuring the borehole temperature. Temperature sensors are attached to every tool combination that is run in a well for the measurement of the maximum temperature (assumed to be at the bottom of the well), and a few modern tools exist that can continuously measure temperature as the tool travels down the well.

Readings from a number of the maximum thermometers attached to different tool combinations and run at different times are analyzed to give the corrected temperature at the bottom of the borehole (*bottom hole temperature, BHT*).

The borehole temperature is an important parameter in the analysis of resistivity logs, but also for the detection of fluid movement, the analysis of fluid pressures and in geochemical modelling of formations and the maturity of hydrocarbons.

8.2 Theory

Temperature in the sub-surface increases with depth. The rate at which it does so is called the *geothermal gradient* or *geotherm*. Typical geotherms for reservoirs are about 20 to 35^{o}C/km, although significantly higher values (up to 85^{o}C/km) can be found in tectonically active areas, and lower ones (0.05^{o}C/km) in stable continental platforms. Hence, the bottom hole temperature (*BHT*) for a 3000 m well with a geotherm of 25^{o}C and a surface temperature of 15^{o}C is 90^{o}C.

Note that this assumes that the geothermal gradient is constant. In practice this is rarely the case because of differences in the thermal conductivities of rocks between the bottom of the hole and the surface, and fluctuations in the surface temperature which penetrate the sub-surface and perturb the sub-surface temperature. Low thermal conductivity rocks, such as shale, act as a thermal insulator and have a large temperature gradient across them, while high thermal conductivity rocks, such as salt, permit the conduction of heat efficiently, and have a small temperature gradient across them.

8.3 Borehole Temperature Measurement

Each tool combination is equipped with a temperature sensor. Temperature measurements are always made at the bottom of the well (highest temperature) and sometimes at intervals up the well. The temperature measuring devices can be as simple as a number of maximum temperature monitors that are attached to the outside of a tool string, and this was commonly the case until recently. In this case only the highest temperature (assumed to be at the bottom of the borehole) is measured. Recently a several special temperature logging sondes have been developed (the *AMS* of Schlumberger and the *Temperature Survey* of Western Atlas), which read temperature continuously up the well using a thermistor, and sometimes also read the temperature difference between two probes spaced along the tool.

The absolute accuracy of temperature measurements is low (±2.5^{o}C), but the resolution is good (0.025^{o}C).

It should be noted that the temperature logs are the only logs to be measured while the sensor is being lowered into the well. This is to reduce any temperature perturbations caused by the logging tool itself.

8.4 Borehole Temperature Corrections

The actual temperature measured is that of the drilling fluid not the formation. The drilling mud is circulated during drilling and prior to inserting the wireline tool, and this drilling mud is cold compared to the formation. The cold drilling fluid invades the formation and cools it down very efficiently *via* heat convection. During circulation of drilling fluid the temperature of the borehole reaches an equilibrium defined by the cooling effect of the drilling fluid and the heating effect of the formation. When the circulation of the drilling mud stops (for example, in preparation for the insertion of a wireline tool), the borehole gradually regains the true formation temperature, because the large mass of formation around the borehole heats the drilling fluid up to its ambient temperature. This process is slow because it occurs *via* heat conduction which is less efficient than heat convection. Equilibrium may only be attained after several months after stopping the circulation of the drilling fluid.

Hence, temperature measurements made during drilling (MWD and LWD) consistently underestimate the formation temperature because drilling mud is being circulated. Temperature measurements made on wireline logs sometime after the drilling fluid circulation has stopped also underestimate the formation temperature, but less than the MWD/LWD case as the formation is now in the process of reheating the borehole. Measurements of temperature made by wireline logs at increasing times after fluid circulation has stopped are closer and closer to the real formation temperature.

Various methods have been adopted in the past to correct the logged BHT to real formation temperatures. The most common method is the Horner plot. The Horner method, plots the measured temperature (at a given depth) from each of several logging runs, against $\log(T/(t+T))$, where T is the time since circulation of the drilling fluid was stopped (usually in hours), and t is the length of time of circulation of drilling fluid prior to this. The parameter t represents the length of time that the borehole was subjected to the cooling effects of the fluid, and T represents the time after circulation that the borehole has had to partially reheat. This plot is a straight line that intersects $T/(t+T)=1$ at the formation temperature.

For example, Table 8.1 gives the drilling, logging, and temperature data for three tool combinations that were run in a single hole one after another.

Table 8.1 Horner plot example.

Time	**Operation**	**Temperature (^{o}C)**	***T* (hours)**	***t* (hours)**	***T*/(*t*+*T*) (-)**
00:00	Circulation started	-	-	6	
06:00	Circulation stopped	-	0	6	
13:00	Run IEL log	100	7	6	0.538
17:30	Run Sonic log	105	11.5	6	0.671
01:30	Run FDC-CNL log	108	19.5	6	0.765

Figure 8.1 shows the Horner plot generated with this data, and the resulting formation temperature.

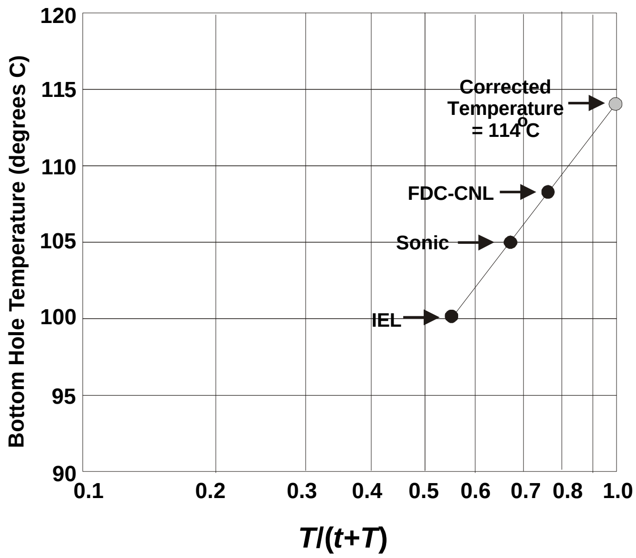

Figure 8.1 The Horner plot for correction of *BHT* at 3200 m in a well using data in Table 8.1.

8.5 Uses of Temperature Logs

Table 8.2 shows the main uses of the temperature log data.

Table 8.2 Uses of the temperature log.

Use	**Comment**
Correction of other tools	The sensors of other logging tools are sensitive to temperature. The temperature measurement can be used to correct for this, or to recognize temperatures that are outside the operating range of the tool and likely therefore to be erroneous..
Correction of measurements	Some parameters measured by other tools are sensitive to temperature. The best example is resistivity logs. The temperature data is used to correct ALL resistivity data to a standard 24°C (75°F) so they are not depth dependent and can be compared.
Hydrocarbon maturation	The maturity of hydrocarbons depends upon the maximum temperature that the organic remains have been subjected to, as well as time and pressure.
Correlation	Continuous temperature logs record differences in thermal gradient that result from differences in the thermal conductivity of the formations. These difference can be used for correlation.
Fluid movement	Continuous logs can observe intervals of raised (or lowered) temperature caused by the influx of hotter (or colder) fluids into the borehole through the rock matrix, or more usually, through patent fractures. This effect may also be due to cold drilling fluid escaping into the rock.
Overpressured zones	Continuous logs also note the presence of overpressured zones, where the hot overpressured fluids escape into the borehole and are noted by a rise in the measured temperature.