ESTIMATION OF THE GEOTHERMAL GRADIENT FROM A SINGULAR TEMPERATURE LOG

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SUMMARY - The drilling process greatly disturbs the temperature of the formations around the wellbore. For this reason to determine the formations temperatures and geothermal gradients with a good accuracy, a certain length of shut-in time is required. It was shown earlier that at least two transient temperature surveys are needed to determine, the geothermal gradient with accuracy. However in many cases only one temperature log is conducted in a shut-in borehole. For these cases we propose an approximate method for estimation of the geothermal gradient. The utilization of this method is demonstrated on a field example.

1. INTRODUCTION

Temperature measurements in wells are used to determine the undisturbed (static) formation temperature, geothermal gradient and the heat flux density (heat flow). Knowledge of the geothermal temperature profiles is also needed to increase the accuracy of electric and temperature logs interpretations. The drilling process greatly disturbs the temperature of the formations around the wellbore. This temperature change is affected by the duration of drilling fluid circulation, the temperature difference between the formations and drilling fluid, the well radius, the thermal diffusivity of formations, and the drilling technology used. Given these factors, the exact determination of formation temperatures and geothermal gradients requires a certain length of time in which the well is not in operation. In theory, this shut-in time is infinitely long. There is, however, a practical limit to the time required for the difference in temperature between the well wall and the surrounding rocks to become vanishingly small. The temperature gradient is a differential quantity, hence the process by which the geothermal (undisturbed) gradient is restored is distinct fiom the temperature recovery process. For example, in the depth range of 500-700 m in the Namskoe well, (Sakha Republic, Russia; depth 3003 m, total drilling time 578 days) geothermal gradient was estimated with an accuracy of 6% after only 50 days of shut-in (Kutasov, 1999).

2. TEMPERATURE DISTURBANCE OF FORMATIONS

In many cases only one temperature log is conducted in a shut-in borehole. For these cases we suggest an approximate method for estimation of the geothermal gradient. It was shown that the thermal effect of drilling operations (at a given depth) can be approximated by a constant (effective) drilling mud temperature (Lachenbruch and Brewer, 1959; Jaeger, 1961; Kutasov, 1968; Kutasov, 1999). For a constant well wall temperature a solution which describes the dimensionless temperature distribution T_D in formation surrounding the wellbore during the fluid circulation is known but is expressed through a complex integral (Jaeger, 1956). By introducing the adjusted dimensionless circulation time t_D^* we have found (Kutasov, 1987, Kutasov, 1999) that the exponential integral (a tabulated function) can be used to approximate function T_D. For $r_D \geq 1$

$$T_D = \frac{T(r,t) - T_f}{T_c - T_f} = \frac{Ei(-\beta r_D^2)}{Ei(-\beta)} \qquad (1)$$

$$t_D = \frac{a t_c}{r_w^2} \qquad r_D = \frac{r}{r_w}; \qquad \beta = \frac{1}{4 t_D^*}$$

$$t_D^* = t_D[1 + 1/(1 + AF)]; \quad t_D \leq 10$$

$$F = [\ln(1 + t_D)]^n; \quad n = 2/3,$$

$$A = 7/8$$

For $t_D > 10$

$$t_D^* = t_D \frac{\ln t_D - \exp(-0.236\sqrt{t_D})}{\ln t_D - 1}$$

where r is the radial distance (at well axis $r = 0$), t_c is the drilling mud circulation time at a given depth, r_D is the dimensionless distance, r_w is the radius of the well, t_D is the dimensionless circulation time, $Ei(x)$ is the exponential integral, T_c is the circulation mud temperature, T_f is the formation (undisturbed) temperature, $T(r,t)$ is the radial temperature, $T_D(r_D,t_D)$ is the dimensionless radial temperature, and **a** is the thermal diffusivity of formations

3. WELLBORE SHUT-IN TEMPERATURE

For the initial temperature distribution (Equation 1) we obtained the following formula for the wellbore shut-in temperature T_s (Kutasov, **1987,** Kutasov, **1999):**

$$\gamma = T_{sD} = 1 - \frac{Ei[-\beta(1+t_D^*/t_{sD})]}{Ei(-\beta)} \qquad (2)$$

$$T_{sD} = \frac{T_s - T_f}{T_c - T_f}; \quad t_{sD} = \frac{at_s}{r_w^2}$$

where t_s is the shut-in time and t_{sD} is the dimensionless shut-in time. The derivation of equation **(2)** assumes that the difference in thermal properties of drilling mud and formations can be neglected. Although this is a conventional assumption even for interpreting bottomhole temperature surveys, when the circulation periods are small, equation **(2)** should be used with caution for very short shut-in times.

4. PREDICTION OF THE GEOTHERMAL GRADIENT

For deep wells $y = y(t_D, t_{sD})$ and for small section of the well we can assume that $\gamma \approx$ ***constant.*** Let us assume that Γ is the geothermal gradient, T_1 is the formation temperature at the vertical depth h_1 and T_f is the formation temperature at the some depth h_2 ($h_1 < h_2$), **then**

$$T_f = T_1 + \Gamma x; \quad x = h_2 - h_1 \qquad (3)$$

Combining equations **2** and **3** we obtain the following linear equation

$$T_s = \Gamma x(1-\gamma) + B; \quad B = T_1 + \gamma(T_c - T_1) \qquad (4)$$

To estimate the value y we suggest the following procedure: calculate the average vertical depth $h_{av} = h_1 + h_2)/2$ and then estimate the disturbance time (mud circulation time) for this depth

$$t_c \approx t_t - t_{av}$$

where t_t is the total drilling time, t_{av} is period of time needed to reach the depth h_{av}. The value of t_{av} can be determined from drilling records. When drilling records are not available the following formula can be used:

$$t_c = t_t\,(1 - h_{av}/H)$$

where H is the total vertical depth of the well. Theoretically only shut-in temperatures at two depths are nedeed to estimate the value of the geothermal gradient. However, processing temperature data by a linear regression program will provide more dependable results. To speed up calculations we prepared a computer **(FORTRAN)** program "ONELOG" (available on a request). Below this program was utilized **to** process field **data**.

5. FIELDEXAMPLE

Well No. **275 was** drilled for **116** days to the total vertical depth of **3295** m and the well diameter is **17.5** inches (Judge et al., **1981).** The first temperature survey was taken **on** December **18, 1975** and the last temperature log was conducted on July 19, **1979.** In Tables **1** and **2** values of Γ calculated after formula **(4)** and the results of direct estimations of the geothermal gradients **from** long term temperature logs are compared. The agreement between the values of Γ by these two methods is seen to be good. We should note that the suggested method (in this case) allowed the calculation of the value of the geothermal gradient (Table **2)** which is very close to the value of Γ determined fkom the temperature log taken after **1309** days of borehole shut-in (Table **2).** At the same time one can see that the estimated temperature gradient **(0.01508** °C/m) fkom the first temperature survey (a linear regression program was used to process field data) differs significantly from the geothermal gradient Γ = **0.02801 °C/m** (Table **2).**

6. CONCLUSIONS

An approximate method of determination of the geothermal gradient is proposed. Only one temperature log is needed to use this method. More field **data** are needed to verify the suggested method.

Table 1. Results of calculations for the 426.7-609.6 m interval. Shut-in time - 8 days.

h m	T_s °C	a m^2/hr	Γ °C/m
426.7	10.04	0.0030	0.02799
457.2	11.03	0.0040	0.02693
487.7	11.79	0.0050	0.02622
518.5	12.50		
648.6	12.87		
579.1	13.41		
609.6	14.12		

Table 2. Estimation of the geothermal gradient fi-om field data.

Shut-in time: 8 days		Shut-in time: 1309 days	
h m	T_s °C	h m	T_s °C
426.7	10.04	433.1	2.70
457.2	11.03	447.9	2.95
487.7	11.79	463.0	3.67
518.5	12.50	479.3	4.06
648.6	12.87	494.1	4.46
579.1	13.41	509.6	4.90
609.6	14.12	525.0	5.30
		555.8	6.20
		586.1	6.87
		617.2	7.90
$\Gamma = 0.01508$, °C/m		$\Gamma = 0.02801$, °C/m	

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