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ESTIMATING OF EQUILIBRIUM FORMATION TEMPERATURE BY CURVE FITTING METHOD AND IT'S PROBLEMS

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ABSTRACT

Determination of true formation temperature from measured bottom hole temperature is important for geothermal reservoir evaluation after completion of well drilling. For estimation of equilibrium formation temperature, we studied non-linear least squares fitting method adapting the Middleton Model (Chiba et al., 1988). It was pointed out that this method was applicable as simple and relatively reliable method for estimation of the equilibrium formation temperature after drilling.

As a next step, we are studying the estimation of equilibrium formation temperature from bottom hole temperature data measured by MWD (measurement while drilling system). In this study, we have evaluated availability of non-linear least squares fitting method adapting curve fitting method and the numerical simulator (GEOTEMP2) for estimation of the equilibrium formation temperature while drilling.

1. INTRODUCTION

Determination of true formation temperature from measured bottom-hole temperature is important for geothermal reservoir evaluations after the completion of well drilling, and sometimes useful in selecting lost circulation materials for remedy work. However, the original temperature field around a borehole is disturbed by circulating mud during drilling, and it takes a considerably long time to reach temperature equilibrium between the formation and drilling mud after drilling and mud circulation has ended. The Horner-plot method (Parasnis, 1971; Dowdle and Cobb, 1975; Fertl and Winchmann, 1977) has popularly been in use for estimating the formation temperature. But this method requires long-period temperature logging data up to about 120 hours to get the reliable estimation, particularly in case the geothermal gradient is relative high as in geothermal wells. Several mathematical models for bottom-hole temperature stabilization have been proposed for estimation of formation temperature from short-period logging data after cessation of circulation of drilling mud.

In this paper we, at first, tested some mathematical well models to estimate the equilibrium formation temperature using short-period logging data. Then, we applied an appropriate model to the estimation of formation temperature after and while drilling. For the temperature estimation while drilling, we also introduced the method of numerical simulation in addition to the curve fitting method.

2. OUTLINE OF THE CURVE FITTING METHOD

2.1 Mathematical Temperature Stabilization Model

Several mathematical temperature stabilization models were proposed in the past, such as Carslaw and Jaeger (1959), Luikov (1968), and Middleton (1979). Although Middleton's square well model does not look adequate as shown in Fig. 1, estimated formation temperature is more accurate than the others (refer to Table 2).

Middleton (1979) considered that a vertical cylinder of small radius could be approximated by a square cylinder in rectangular coordinates. Therefore, the temperature distribution BHTc (x, y, t), around a vertical cylinder of infinite length after cessation of mud circulation could be expressed as the following equation:

$$\mathrm{BHT}c(x,y,t)=\mathrm{T}m+\frac{1}{4}(\mathrm{T}f-\mathrm{T}m)$$
$$\times\left\{erfc\left(\frac{\mathrm{R}-x}{\tau}\right)+erfc\left(\frac{\mathrm{R}+x}{\tau}\right)\right\}$$
$$\times\left\{erfc\left(\frac{\mathrm{R}-y}{\tau}\right)+erfc\left(\frac{\mathrm{R}+y}{\tau}\right)\right\}\cdot\cdot\cdot\cdot\cdot(1)$$

where,

$$\tau=\sqrt{4\mathrm{K}t}$$
$$erfc(x)=\frac{2}{\sqrt{\pi}}\int_{x}^{\infty}exp(-t^2)dt$$

Tm is the mud temperature in the borehole at the instant that circulation ceases, Tf is the formation equilibrium temperature, R is the effective radius of the region affected by drilling, K is the thermal diffusivity of the well contents, x, y are the Cartesian coordinates in the horizontal plane, and t is the shut-in time after the termination of mud circulation.

Assuming that the measurement is made at the center of the well (x = 0, y = 0), temperature becomes a function of time only:

$$\mathrm{BHT}c(t)=\mathrm{T}m+(\mathrm{T}f-\mathrm{T}m)\times\left\{erfc\left(\frac{\mathrm{R}}{\sqrt{4\mathrm{K}t}}\right)\right\}^2\cdot\cdot\cdot\cdot(2)$$

As apparent from the above equation, knowledge of circulation time of the drilling fluids, which is required in the Horner-plot method of correction for borehole temperature disturbance, is not necessary in this model. Because of this, the curve fitting method is more sensitive the Horner-plot method. The initial temperature distribution given by Equation (1) is shown in Fig. 1.

2.2 Analysis by the Curve Fitting Method

There are two methods of estimating formation temperature using mathematical models. One is a curve fitting technique by trial and error method, and the other is a non-linear least squares fitting method. In a curve fitting technique, the formation temperature can be obtained by superimposing a set of master curves, based on Equation (2), on observed data plotted at the same scale (refer to Fig. 2).

On the other hand, in a non-linear least squares fitting method, non-linear least squares method based upon Equation (3) is applied to obtain the formation temperature.

$$\mathrm{S}=\sum_{i=1}^{n}\{\mathrm{BHT}c(ti)-\mathrm{BHT}o(ti)\}^2\cdot\cdot\cdot\cdot(3)$$

where BHTc(ti) is the calculated value from Equation (2), BHTo(ti) is the observed temperature data, and optimum values of Tf and Tm can be obtained by the mathematical inversion technique to minimize the value of S in Equation (3).

Features of a non-linear least squares fitting method, in comparison with curve fitting technique, are in its rapidity and objectivity. Therefore, we call this inverse method the curve fitting method. Fig. 3 shows an example of the non-linear fitting result.

3. ESTIMATION OF THE EQUILIBRIUM FORMATION TEMPERATURE AFTER DRILLING

3.1 Comparison of the Curve Fitting Method and the Horner-plot Method

The Horner-plot method was devised by Parasnis (1971), Dowdle and Cobb (1975), and Fertl and Winchmann (1977), and is defined by Equation (4).

$$\mathrm{BHT}=\mathrm{T}f+\mathrm{C}\times log\left(\frac{t}{t_k+t}\right)\cdot\cdot\cdot\cdot\cdot(4)$$

where,

BHT : *Borehole temperature*
Tf : *Formation temperature*
C : *Constant*
t : *Period after cessation of mud circulation*
t_k : *Circulation period before the cessation*

In Equation (4), BHT becomes close to Tf asymptotically when t is infinite.

In order to evaluate the reliability of the curve fitting method, a comparison between the curve fitting method and the Horner-plot method has been made using temperature loggings during warm-up obtained in three wells at eight levels of depth in Hohi geothermal field in Kyushu. Shown in Table 1 are the data of comparison between Tfbuild, formation temperature estimated by the Horner-plot method, and Tffit, formation temperature estimated by the curve fitting method. In three wells temperature logging had taken place at 128, 122 and 113 days respectively after cessation of circulation, so these observed results are shown as Tfobs, assuming they can be approximated to an equilibrium formation temperature.

According to this example, the average difference temperature among Tfbuild, Tffit and Tfobs was as follows.

a) Average error between Tffit and Tfobs: 5.5°C
b) Average error between Tfbuild and Tfobs: 7.9°C

Assuming that Tfobs is the equilibrium formation temperature, the curve fitting method is found to suit the estimation of the formation temperature accurately enough compared with the Horner-plot method. This is because that a linear part in the Horner-plot for temperature loggings during warm-up is considerably short.

3.2 Factors Underlying Estimation Precision on the Curve Fitting Method

Da-Xin (1986) pointed out the limits of the application of the fitting method because some parameters in Equation (2), such as thermal diffusivity K and effective radius R, should be assumed to obtain the equilibrium formation temperature and this would cause large errors.

Consequently, effective radius; R and thermal diffusivity; K are evaluated the effectiveness of estimation precision from below. Also method for thermal recovery loggings is examined.

(1) Effective radius; R

As shown in Fig. 1, Middleton's wellbore model seems to depart from an ideal cylindrical shape but this rectangular coordinates are better to describe the real geometrical configuration of the well, such as wash-out or caving of poorly consolidated formation.

Although other models, such as circular well proposed by Luikov (1968) or square well by Carslaw and Jaeger (1959), were derived and examined by Leblanc et al. (1981), Middleton's model would be appropriate if we use a half of bit size as an effective radius R as shown in Table 2.

(2) Thermal diffusivity; K

Four important physical quantities to be considered in the warm-up problem are thermal conductivity λ, specific heat Cp, density ρ, and thermal diffusivity K. These quantities are related by following equation:

$$K=\frac{\lambda}{\rho\times Cp}\cdot\cdot\cdot\cdot\cdot(5)$$

where,
K : *Thermal diffusivity*
λ : *Thermal conductivity*
Cp : *Specific heat*
ρ : *Density*

There are three ways described below to determine the value of thermal diffusivity in applying fitting method.

a) To use a typical assumed value of K, as Middleton (1979) or Leblanc et al. (1981, 1982) did.
b) To use measured physical quantities using geological samples (cores or cuttings) to calculate the value of K.
c) To handle K, in combination with R, as an inversion parameter in non-linear least square method in Equation (3), as Da-Xin (1986) did.

While we adopted b) in the latest analysis, Leblanc et al. (1982) empirically proposed 0.0035 cm^2/sec as the value for thermal diffusivity under the curve method.

Table 3 shows a comparison of estimated temperature between thermal diffusivity as calculated from core physical properties value and that as fixed at 0.0035 cm^2/sec proposed by Leblanc.

Using thermal diffusivity as a fixed value is considered undesirable in terms of accuracy since thermal conductivity, among other rock physical properties, shows a wide range of values depending on the proportions of component minerals, the presence of metamorphosis, etc.

Knowledge about thermal properties is needed for accurate estimation of formation temperature, but it is rare that the core samples can be obtained in normal drilling process.

(3) Ratio of R and K; α

We examined the ratio of R and K as α ($\alpha = R/\sqrt{K}$). 255 core samples acquired in Japanese geothermal wells were statically treated as concluded in Table 4. We found that α is between 55.0 and 318 and between 79.3 and 459 in case of 8-1/2" bit hole and 12-1/4" bit hole, respectively.

Therefore, we decided to apply α instead of R and K in the curve fitting method and to treat α as one of the parameter of inversion. Then, if α of inversion result is not adequate, we should consider reliability of estimated formation temperature is quite low.

(4) Procedure of temperature loggings during warm-up

However, the temperature loggings during warm-up, used in verifying the curve fitting technique, were presupposed to be analyzed by the Horner-plot method. Therefore, taking the following points into consideration in logging procedure would further improve the accuracy in estimated temperature by the fitting method.

1) More data in short-period

The non-linear least squares fitting technique, different from the Horner-plot method, is a theoretical method of solution, so improved accuracy is expected to result from an increased number of data in principle even if they are short-period ones.

Incidentally, Table 5 shows a comparison of the estimated temperature obtained by the use of all temperature loggings during warm-up and that obtained by the use of only the first two data.

The average error, from the formation equilibrium temperature Tfobs is not very great for estimation results from short-period and only two data. Estimating with this degree of accuracy would be impossible when a similar estimation were made by the Horner-plot method.

2) Correction for time lags during logging

When estimating the formation temperature from short-period logging data, it is necessary to determine the shut-in time as accurately as possible.

Correction was made in the latest analysis, too, since the cable speed and direction of logging (up/down survey) were definite.

Incidentally, it turned out in Table 6 that an error of 3.9°C on the average would occur by whether time lags were taken into consideration or not.

3.3 Case Study

Based upon previous discussion, we have acquired a set of temperature loggings during warm-up for the curve fitting method.

(1) Method

After cessation of circulation of drilling mud, 14 times of temperature loggings were conducted for 72.5 hours. Depth of this well was 800 meters. Logging data and estimated formation temperatures by the curve fitting method were plotted in Fig. 4. Logging tool could not go down to the bottom of the well after 48.5 hours because of mud gelation due to the temperature of the well at the deeper part.

(2) Accuracy of the curve fitting method

1) Period

We evaluated the accuracy of the curve fitting method with the data acquired at the depth of 700 meters. As shown Table 7, 12 cases were examined. Since we did not have an exact formation temperature, we compared the temperature estimated using all data (Case 13) with the temperature estimated using less number and less recovery time data. Through this comparison,

a) the accuracy of the estimated formation temperature using 24.5 hours data is at most 5°C, and
b) using 18.5 hours data, the accuracy is at most 10°C.
c) Also α is stable in case we use 18.5 hours or more data.

This means the curve fitting method will be able to estimate the formation temperature more accurately than the Horner-plot method with short period data.

2) Number of data

24.5 hours data consists of nine data. Then we selected five data from nine data with several patterns as shown in Table 8. Case 2 is the most similar to the temperature estimated by nine data. This notifies us of the importance of periodical logging.

To approve this, a similar test using 48 hours data, which consists of 12 data, was conducted. In this case, six data were selected from 12 data with several patterns. Then the importance of periodical logging in log scale was approved, although it is more preferable to use long-period data, if possible.

(3) Conclusion

The curve fitting method is a rather reliable and easy way to estimate the formation temperature with short-period temperature loggings during warm-up.

4. ESTIMATION OF EQUILIBRIUM TEMPERATURE WHILE DRILLING

4.1 Objectives

It is important to know the formation temperature in real time, if possible. Because the formation temperature is the most consequent parameter for geothermal reservoir and warm-up after cessation of drilling mud circulation.

In this section, at first, we confirm the limitation of the curve fitting method, then we propose to apply GEOTEMP2 using bottom hole temperature measured by MWD.

4.2 Limitation of the Curve Fitting Method

We showed it is possible to estimate the formation temperature by several sets of temperature loggings during warm-up till 24 hours after cessation of drilling mud circulation in previous section. In this case, the data of recovery temperature is not continuous. Therefore, we have examined estimation of formation temperature using continuous warm-up measurement data at a certain depth.

We used the temperature data acquired while fall-off test, instead of four hours continuous measurement data just after cessation of mud circulation for our test purpose. We used also 95 hours warm-up measurement data, then we estimated the formation temperature using four hours continuous data and 95 hours warm-up measurement data. Estimated temperatures are shown in Table 9.

We should conclude by the curve fitting method that even four hours continuous temperature data is not enough. We noticed we need totally new idea instead of the curve fitting method for temperature estimation while drilling or at least just after drilling.

4.3 Formation Temperature Estimation Using MWD Bottom Hole Data

(1) GEOTEMP2

GEOTEMP2 is a wellbore thermal simulator designed for geothermal well drilling and production problems.

GEOTEMP2 has plenty of functions. One of these is to compute mud temperature while drilling as results of numerical simulation, and this function requires the formation temperature for numerical simulation. However, MWD will give us bottom hole temperature and mud logging system will give us mud temperatures at surface, although we will not have the formation temperature.

We have developed a prototype of inverse program to compute the formation temperature using bottom hole temperature by MWD and mud temperatures by the mud logging system. Namely GEOTEMP2 is forward program for our prototype inverse program using non-linear least squares fitting method.

(2) Feasibility study

We use GEOTEMP2 as forward modeling, therefore we needed to know the sufficiency of the forward model; GEOTEMP2. Comparison between mud temperature at surface and simulated one in Fig. 5 and between bottom hole temperature measured by maximum thermometer and simulated one in Fig. 6.

In both cases, simulated temperatures were 2°C to 10°C lower than measured ones. Reasons of this are examined as follows:

a) GEOTEMP2 allows to use very simple formation temperature distribution.
b) Unit of computation is day, not hour or minute, therefore it is impossible to simulate actual drilling procedure.

(3) Future task

We are modifying GEOTEMP2 according to our test results as mentioned above and are going to apply inverse method on it. The new code we are developing now will be able to estimate the formation temperature even while drilling using MWD and mud logging data.

5. SUMMARY

For estimating the formation temperature from short-period such as 12 or 24 hours temperature loggings during warm-up, it has turned out that the curve fitting method is applicable as a simple and relatively reliable method. However, this method is essential when certain period (12 or 24 hours) data is available. Therefore, it is very useful for analysis of the temperature loggings during warm-up after cessation of mud circulation, not for while drilling.

Now for real time estimation of formation temperature while drilling, we are modifying GEOTEMP2 according to our tests results and are going to apply inversion scheme on it.

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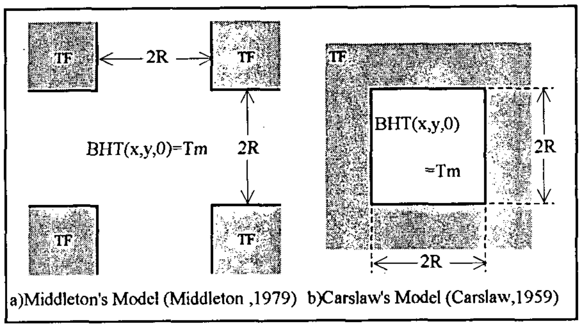

a)Middleton's Model (Middleton ,1979) b)Carslaw's Model (Carslaw,1959)

Fig.1 Mathematical well model

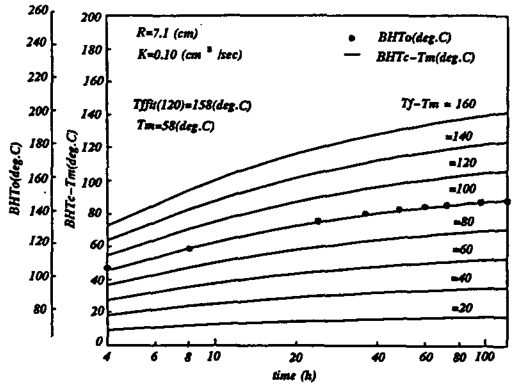

Fig.2 Example of curve fitting by Forward method

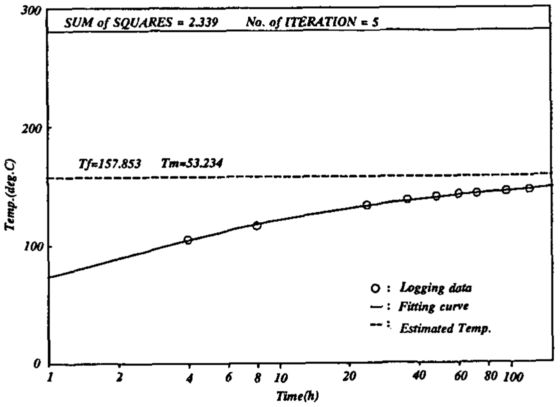

Fig.3 Example of curve fitting by Invers method

Table 1 Comparision of estimated formation temperature(TF) between curve fifitting method and Horner Plot method

Well	depth (m)	Data No.	TFbuild (deg-C)	TFfit (deg-C)	TFobs (deg-C)
A	700	7	209	188	190
	1,500		198	182	189
	1,600		193	180	185
	1,700		187	176	183
B	1,400	6	167	154	170
C	2,600	5	250	251	255
	2,700		254	261	262
	2,800		259	269	267

TFbuild ; Formation temperature estimated by Horner Plot
TFfit ; Formation temperature estimated by curve fitting method
TFobs ; Formation temperature measured by temperature logging

Table 2 Comparision of estimated formation temperature(TFfit) with different mathematical well model

Well	depth (m)	TFfit (deg-C)		TFobs (deg-C)
		Middleton * Model	Carslaw Model	
A	700	188	127	190
	1,500	182	146	189
	1,600	180	145	185
	1,700	176	144	183
B	1,400	154	141	170
C	2,600	251	230	255
	2,700	261	241	262
	2,800	269	253	267
A.E.		5.5 (deg-C)	34.3(deg-C)	

A.E. ; Averaged error of TFfit from TFobs
TFfit ; Formation temperature estimated by curve fitting method
TFobs ; Formation temperature measured by temperature logging
*** Effective radius ; R is a half of bit size**

Table 3 Effect of thermal diffusivity(K) on foramtion temperature estimation (TFfit)

Well	depth (m)	TFfit (deg-C)		TFobs (deg-C)
		Measured Value of K	Fixed Value of K (K=0.0035)	
A	700	188(K=0.0085)	231	190
	1,500	182(K=0.0085)	200	189
	1,600	180(K=0.0085)	197	185
	1,700	176(K=0.0085)	191	183
B	1,400	154(K=0.0259)	163	170
C	2,600	251(K=0.0098)	255	255
	2,700	261(K=0.0098)	265	262
	2,800	264(K=0.0098)	272	267
A.E.		5.5 (deg-C)	10.9(deg-C)	

A.E. ; Averaged error of TFfit from TFobs
TFfit ; Formation temperature estimated by curve fitting method
TFobs ; Formation temperature measured by temperature logging

Table 4 Typical Thermal Conductivity(λ),Density (ρ), Specific Heat(Cp) and Thermal Diffusivity(K) in Japanese geothermal wells

	Number of Samples	Rang	
		Min.	Max.
λ : Thermal Conductivity ($10^{-3}\times$cal/cm·sec·deg.C)	255	1.0	10.0
ρ : Density (g/cm^{-3})	255	1.3	3.0
Cp : Specific Heat (cal/g·deg.C)	18	0.2	0.24
K : Thermal Diffusivity ($\times 10^{-2}$)		1.389	3.846

Table 5 Effect of Number of data on formation temperature estimation(TFfit)

Well	depth (m)	TFfit (deg-C)		TFobs (deg-C)
		Using all data	Using two data	
A	700	188 (7 data)	220	190
	1,500	182 (7 data)	188	189
	1,600	180 (7 data)	185	185
	1,700	176 (7 data)	185	183
B	1,400	154 (6 data)	147	170
C	2,600	251 (5 data)	242	255
	2,700	261(5 data)	251	262
	2,800	264 (5 data)	268	267
A.E.		5.5 (deg-C)	10.1(deg-C)	

A.E. ; Averaged error of TFfit from TFobs
TFfit ; Formation temperature estimated by curve fitting method
TFobs ; Formation temperature measured by temperature logging

Table 6 Effect of exact period after cessation of mud circulation on formation temperature estimation(TFfit)

Well	depth (m)	TFfit (deg-C) Corrected	TFfit (deg-C) Non-Corrected	TFobs (deg-C)
A	700	188(C.T.=1.16 h)	186	190
	1,500	182(C.T.=2.5 h)	177	189
	1,600	180(C.T.=2.67 h)	174	185
	1,700	176(C.T.=2.83 h)	171	183
B	1,400	154(C.T.=2.33 h)	151	170
C	2,600	251(C.T.=4.33 h)	246	255
	2,700	261(C.T.=4.5 h)	256	262
	2,800	269(C.T.=4.67 h)	265	267
A.E.		5.5(deg-C)	9.4(deg-C)	

TFfit ; Formation temperature estimated by curve fitting method

C.T. ; Corrected time

TFobs ; Formation temperature measured by temperature logging

A.E. ; Averaged Error of TFfit from TFobs

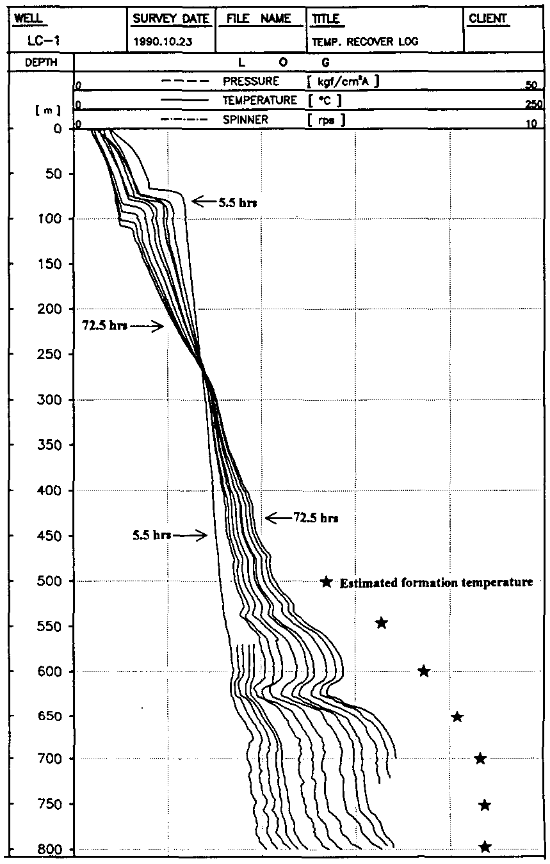

Fig.4 Temperature recovery logging data and estimated formation temperature

Table 7 Effect of period after cessation of mud circulation on formation temperature estimation(TFfit) at 700m

time	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10	Case11	Case12	Case13
5.5 h	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use
6.5 h	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use
7.5 h		Use	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use
8.5 h			Use	Use	Use	Use	Use	Use	Use	Use	Use	Use	Use
9.5 h				Use	Use	Use	Use	Use	Use	Use	Use	Use	Use
12.5 h					Use	Use	Use	Use	Use	Use	Use	Use	Use
15.5 h						Use	Use	Use	Use	Use	Use	Use	Use
18.5 h							Use	Use	Use	Use	Use	Use	Use
24.5 h								Use	Use	Use	Use	Use	Use
30.5 h									Use	Use	Use	Use	Use
36.5 h										Use	Use	Use	Use
48.5 h											Use	Use	Use
60.5 h												Use	Use
72.5 h													Use
E.F.T.	212.3	207.3	197.1	189.5	190.5	198	205.3	214.9	217.4	216	216	216	215.6
delt E.F.T.		-5	-10.2	-7.6	1	7.5	7.3	9.6	2.5	-1.4	0	0	-0.4
Alpha	160.70	160.70	161.00	160.70	164.10	158.70	137.40	120.50	101.40	101.20	112.4	129.30	120.50

E.F.T. ; Estimated Formation Temperature

delt E.F.T.=E.F.T.(i) - E.F.T.(i - 1)

Alpha=R/(K) $^{1/2}$

Table 8 Effect of time interval on formation temperature estimation(TFfit) (Max. 24 hours)

Elapsed time	Case1	Case2	Case3	Case4	Case5	Case6	Case7
5.5 h	Use	Use	Use		Use	Use	Use
6.5 h	Use		Use		Use	Use	Use
7.5 h	Use	Use	Use			Use	
8.5 h	Use		Use				
9.5 h	Use	Use		Use			Use
12.5 h	Use			Use			
15.5 h	Use	Use		Use	Use		
18.5 h	Use			Use	Use	Use	Use
24.5 h	Use	Use	Use	Use	Use	Use	Use
data No.	9	5	5	5	5	5	5
E.F.T.(deg-C)	214.9	216.2	208.8	228.9	220.2	210.2	209.9
Alpha	158.7	159.2	134.7	198.2	170.6	142.7	142

E.F.T. ; Estimated Formation Temperature
Alpha=R/(K) $^{1/2}$

Table 9 Estimation of formation temperature(TFfit) using continuous data

Time	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8
0.0833 h	Use	Use	Use	Use	Use	Use	Use	Use
0.1666 h	Use	Use	Use	Use	Use	Use	Use	Use
0.25 h	Use	Use	Use	Use	Use	Use	Use	Use
0.3333 h	Use	Use	Use	Use	Use	Use	Use	Use
0.5 h	Use	Use	Use	Use	Use	Use	Use	Use
1.0 h		Use	Use	Use	Use	Use	Use	Use
1.5 h			Use	Use	Use	Use	Use	Use
2.0 h				Use	Use	Use	Use	Use
2.5 h					Use	Use	Use	Use
3.0 h						Use	Use	Use
3.8 h							Use	Use
96 h								Use
E.F.T.	171.1	298.4	363.6	383.3	361.1	344.5	330.9	298.2
delt E.F.T.		127.3	65.2	19.7	-22.2	-16.6	-13.6	-32.7
Alpha	49.6	61.7	67.4	69.3	66.9	64.8	62.8	56.2

E.F.T. ; Estimated Formation Temperature
delt E.F.T.=E.F.T.(i) - E.F.T.(i - 1)
Alpha=R/(K) $^{1/2}$

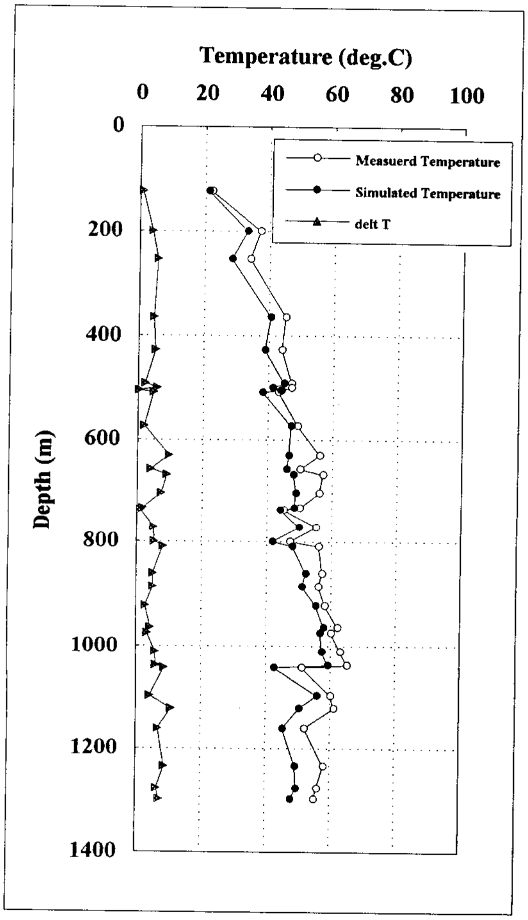

Fig.5 Comparison of simulated temperature and measured mud temperature at surface while drilling

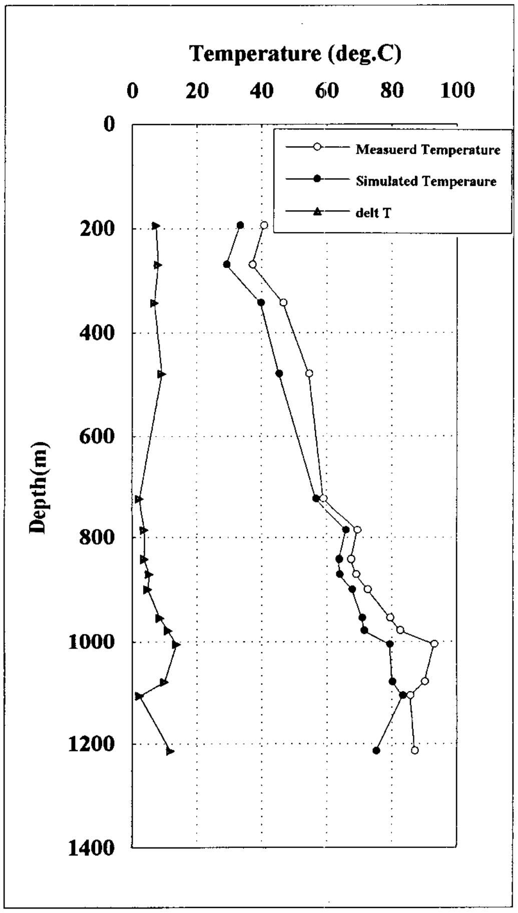

Fig.6 Comparison of simulated temperature and bottom hole temperature measured by maximum thermometer while drilling