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PREDICTION OF FORMATION EQUILIBRIUM TEMPERATURE WHILE DRILLING BASED ON DRILLING MUD TEMPERATURE: INVERSE PROBLEM USING TOUGH2 AND WELLBORE THERMAL MODEL

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ABSTRACT

This paper reports on an attempt to estimate the equilibrium formation temperature from the inlet and outlet mud temperatures while drilling. We have modified the well bore thermal simulator "GEOTEMP2," which was originally developed by Mondy and Duda (1984), in order to take into account lost circulation and convective flow within the formation. Our examination confirmed that estimated outlet mud temperatures match observed data quite well. Accordingly, we have developed a numerical inversion code (named "MWDTEMP2") for estimating formation temperatures from the outlet mud and bottom-hole temperatures while drilling (Takai *et al*., 1994, Takahashi *et al*., 1996). Preliminary examination reveals that formation temperature can be estimated from mud temperatures and, if available, bottom-hole temperatures based on the integrated finite difference method to calculate flows within the porous medium and Darcy's low (Takahashi *et al*., 1997). Since the fracture medium was necessary for geothermal system modeling, we replaced the original forward model code (porous medium) to TOUGH2 code and extended to the fracture model using MINC.

INTRODUCTION

Estimation of the formation temperature is an important process when deciding whether drilling should be stopped or continued. There are several methods of estimating of the formation temperatures, for example, the Horner-plot method (e.g. Parasnis, 1971), a curve fitting method based on a numerical model (Chiba *et al*., 1982) or analysis of fluid inclusion (e.g. Fujino and Yamasaki, 1985). However, all these methods are time consuming.

If formation temperature can be obtained from numerical simulation based on mud temperatures, the formation temperature can be monitored during drilling. Therefore, whether drilling should be stopped or continued can be judge immediately, and the cost of the rig can be reduced.

MODIFICATION OF FORWARD MODEL CODE FOR MODELING OF THE ACTUAL ROCK FORMATION

Modeling of Convective Flow within the Reservoir

The modified forward model based on "GEOTEMP2" has been developed for modeling of the actual rock formation before we started to develop the inversion algorithm program "MWDTEMP2". The developed code was named "GEOTEMP3". The original code GEOTEMP2 is a program used for the calculation of temperature changes within the well-bore and rock matrix during production, injection or drilling. Calculation is performed by considering only thermal conduction within the rock formation that serves as the source of the heat. However, because we thought convective flow within the reservoir should also be considered, we modified the program to model it.

We assume that the rock matrix is a porous medium and that fluid flow obeys Darcy's low. We also assume cylindrical symmetry and use the integrated finite difference method to calculate flows within the reservoir (Narasimhan and Witherspoon, 1976). The "MWDTEMP2" has been based on the "GEOTEMP2" and the result has been presented already (Takahashi *et al*., 1997).

We have often encountered a fracture medium in case of the volcanic rock formation with the difference thermal phenomenon from a porous medium. Therefore, we attempted to extend the original forward model code "GEOTEMP3" and it's inverse model code "MWDTEMP2" to "GEOTEMP4/ TOUGH2" and "MWDTEMP2/TOUGH2" for a fracture medium based on TOUGH2 and MINC in this paper.

Modeling of the Lost Circulation

Lost circulation occurring during drilling should quickly cool the formation along the high permeability fracture opposite the reservoir with only thermal convection. Consequently, modeling of lost circulation might be expected to improve the accuracy of the simulation.

Lost circulation from the well bore is treated as a mass and energy source term in the reservoir calculation, and fluid flow is assumed to obey Darcy's law at that time. With regard to movement of thermal energy, total enthalpy of lost circulation fluid from the total circulating fluid is assumed to flow into the formation. Consideration of the multiple lost circulation zone makes it possible to calculate the borehole temperature during lost circulation.

TEST OF MODIFIED FORWARD MODEL "GEOTEMP3" AND "GEOTEMP4/TOUGH2"

Parameter Study (1) - Convective Flow within the Reservoir

In order to see the effect of bottom-hole temperature recovery after drilling, changing rock permeability, which is the dominant parameter of a convective geothermal reservoir, performs parameter study. Values of permeability used here are 1.0×10^{-12} m^2, 1.0×10^{-15} m^2, and 1.0×10^{-17} m^2. Figure 1 shows input data for this study. We attempted to calculate the bottom-hole temperature recovery using GEOTEMP3 and GEOTEMP4/TOUGH2 in this condition.

Figure 2 shows the results of calculated bottom-hole temperature recovery based on changes permeability in both case of GEOTEMP3 and GEOTEMP4 (TOUGH2). As can be seen from the figure, both forward models using GEOTEMP3 and GEOTEMP4 (TOUGH2) yield almost the same temperature and the effect of convective flow around the well bore on calculated temperature is very small in case of porous medium.

Parameter Study (2) - Lost Circulation

In order to determine whether lost circulation has an effect on calculated temperature, we performed a parameter study by changing the volume of lost circulation. Lost circulation is assumed to have occurred at a depth of 1,219.2m and to have continued until drilling was stopped, and the volumes are assumed to be 100l/min. Permeability of formation at the depth where lost circulation occurred is assumed to 1.0×10^{-15}m^2 and that at other depths are assumed to 1.0×10^{-14}m^2. Figure 3 shows the input data (Casing, lost circulation, formation temperature, thermal conductivity, permeability) for this parameter study.

Figure 4 shows the results of simulation about temperature recovery in the case of the volume of the lost circulation is 100l/min in case of GEOTEMP3 in porous medium, GEOTEMP4 in porous medium or GEOTEMP4 in fracture medium using MINC. These results show that temperature becomes low at 1,219.2m, the depth of lost circulation, and the higher the volume of lost circulation, the more slowly temperature recovers. This phenomenon is consistent with temperature logging data with temperature anomaly at the lost circulation depth. Consequently, modified program is able to consider the effect of the lost circulation. In case of porous medium, we could not find out the difference between them but find out that the fracture reservoir was more cooled than the porous medium.

ESTIMATION OF THE FORMATION TEMPERATURE BY INVERSION CODE "MWDTEMP2"

Parameter fitting is done using non-liner least square and the Levenberg-Marquardt algorithm (Marquardt, 1963).

Outline of the Program

Three input data files were used for inversion;

1. Parameter file

   This file contains initial estimates of reservoir temperature and sets various options controlling the program.

2. Measured data file

   This file contains the measured data (Mud and Bottom hole temperature).

3. GEOTEMP3 (forward model calculation) file

   This file contains the input file for GEOTEMP3 (Casing data, Drilling time, Mud properties).

The process can be summarized as follows;

1. Estimate the formation temperature at several depths (e.g., every 50 meters)
2. On the basis of formation temperature, use GEOTEMP3 to calculate BHT and MUDOUT temperatures as a function of time.
3. Calculate the objective function to be minimized as

$$f\,(T_{fomation},loss) = \sum (T_{calc}(i) - T_{meas}(i))^2$$

4. Calculate updated estimates of formation temperature and loss water zones, if possible.
5. If calculated formation temperatures are still changing, repeat from step 2.

Examination of the Precision of Estimated Formation Temperature

In order to examine the precision of the estimated formation temperature by MWDTEMP2, calculation was performed using a geothermal well data (down to 1,505m) as the base model. Figure 5 shows the input data for this model. In this examination, drilling history was simplified and inlet and outlet mud temperature during drilling were pre-calculated from the model used by the simulator. These temperatures were used as the input data for estimation of formation temperature.

Figure 6 shows the results of the formation temperature estimated by inversion from inlet and outlet mud temperatures. The left side has been calculated by old inversion code “MWDTEMP2/ GEOTEMP3” with porous medium. In this case, error of the estimated temperature tends to be large at depths greater than 1,000m. Error between estimated and observed formation temperatures at depths of less than 1,000m is 2.0, whereas that for depths greater than 1,000m is 20.1, which was 10 times as large. In this case, error of the inversion was ±4 ℃ (2σ) at depths of less than 1,000m and is ±40 ℃ (2σ) above 1,000m. The explanation for these results was thought to be as the effect of fracture medium because the lower temperature peak at 1,219 m indicated the cooling effect of fracture medium.

In an effort to confirm our supposition, we estimated the formation temperature in condition of dual-porosity model based on MINC method of TOUGH2. The formation of 1,000m to 1,300m was replaced the porous medium with the equivalent MINC model (fracture space 1 meter) by the inversion code “MWDTEMP2/GEOTEMP4(TOUGH2)”.

The right side of Figure 6 shows that results. In this case, using fracture medium improved accuracy, that is, error of the estimated formation temperature is ±4 ℃ (2σ) for depths of less than 1,000m and is ±6 ℃ (2σ) for depth of grater than 1,000m. Therefore, in cases where depth is increased or temperature anomaly exists, the accuracy of the estimation of formation temperature is expected to be improved by GEOTEMP4/TOUGH2 with MINC fracture medium.

CONCLUSIONS

Observed outlet mud temperatures more closely matched data calculated by modified well-bore thermal simulator GEOTEMP4 (TOUGH2) with fracture medium (MINC) than GEOTEMP3 with porous medium. Therefore, the effect of lost circulation in fracture system can be taken into account.

Estimation of formation temperature was found to be possible to a certain extent by applying the program MWDTEMP2 to inlet and outlet mud temperature. However, the estimation of formation temperature from only inlet and outlet mud temperature yields relatively large errors if the porous medium is assumed in geothermal system. In that case, the accuracy of estimation improves if the fracture medium is used in GEOTEMP4 (TOUGH2).

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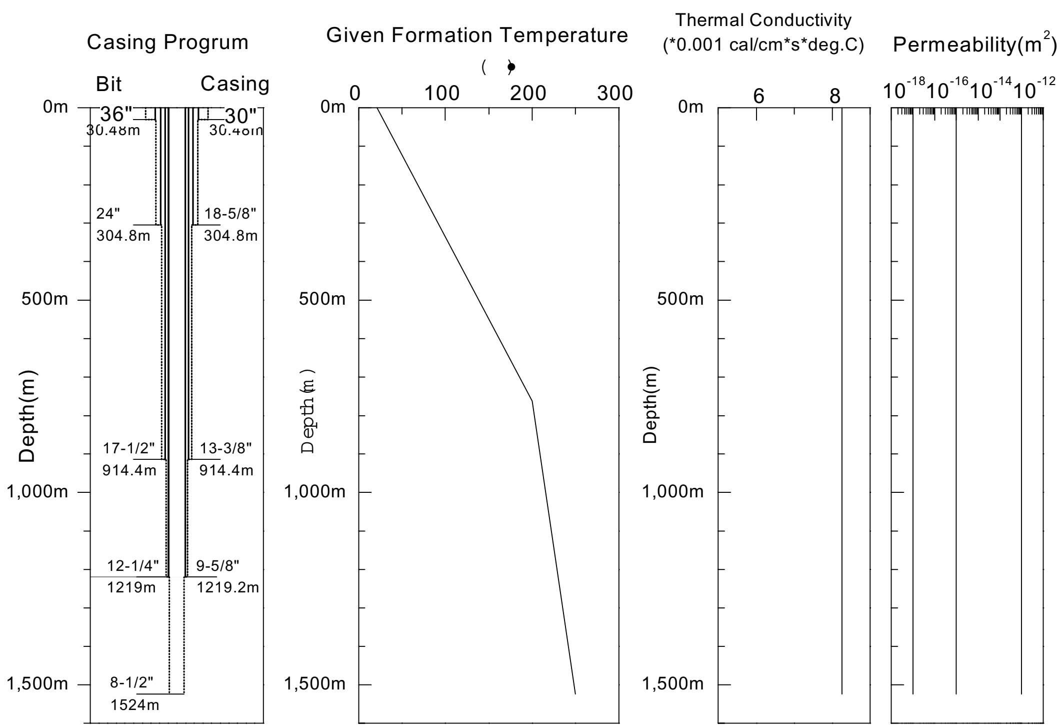

Fig.1 Well data for parameter study of convecitve reservoir model.
(Casing Progrum, Given Formation Temp., Thermal Conductivity, Permeability)

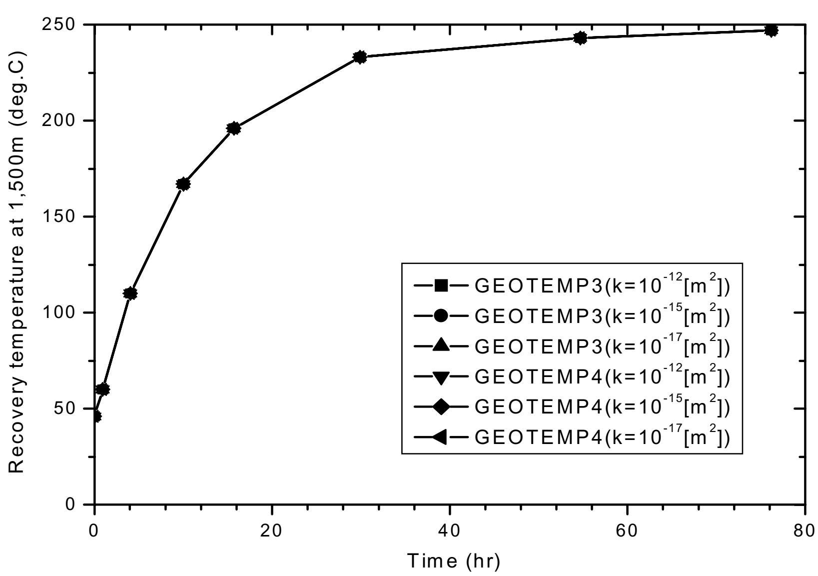

Fig.2 Estimated bottom-hole recovery temperature at 1,500m depth for each permeability.

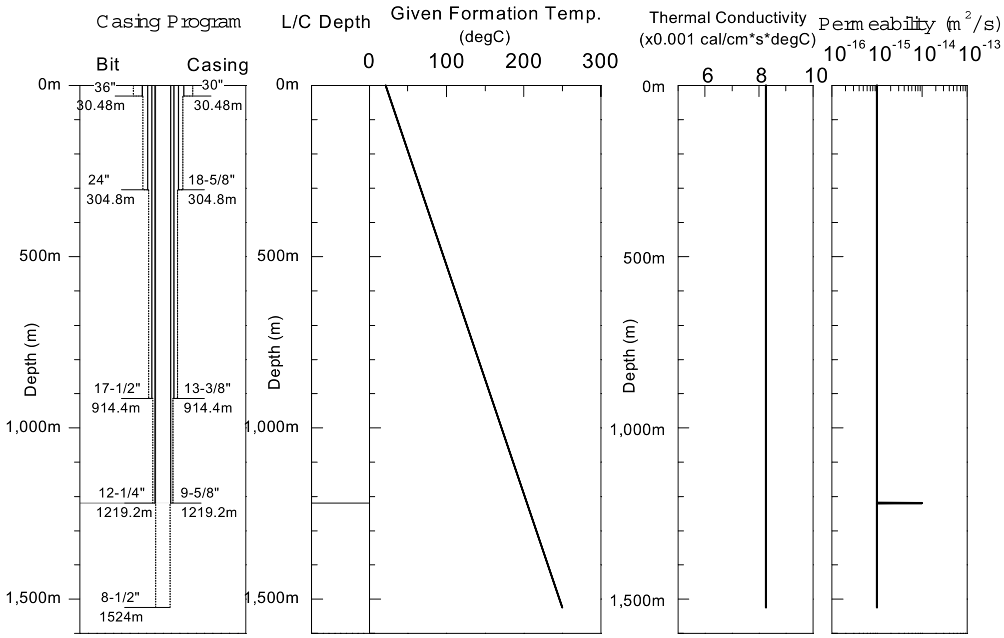

Fig.3 Well data for parameter study of lost circulation model(L/C model).
(Casing program, L/C Depth, Given Formation Temp.(input), Thermal Conductivity, Permeability)

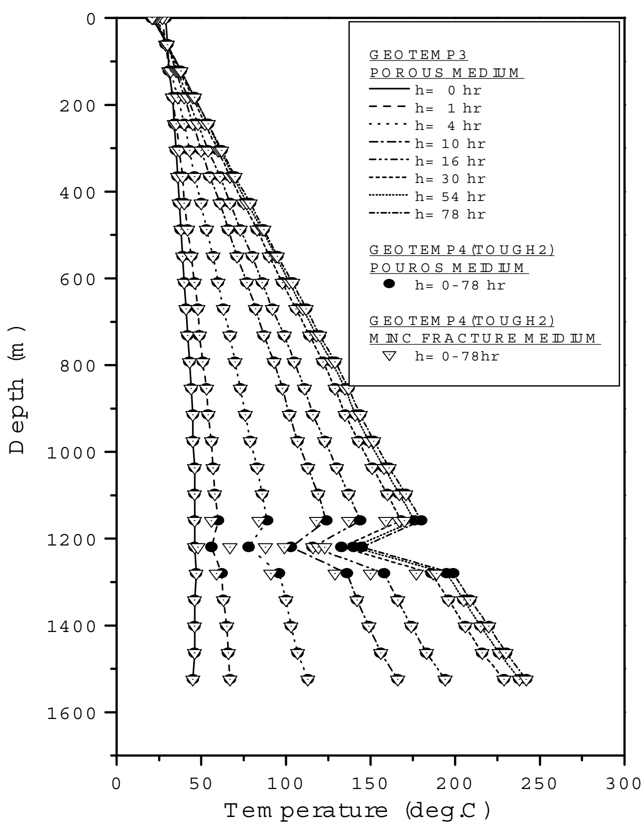

Figure 4. L/C at 1219.2 m calculated by GEOTEMP3/4 in porous medium or fracture medium

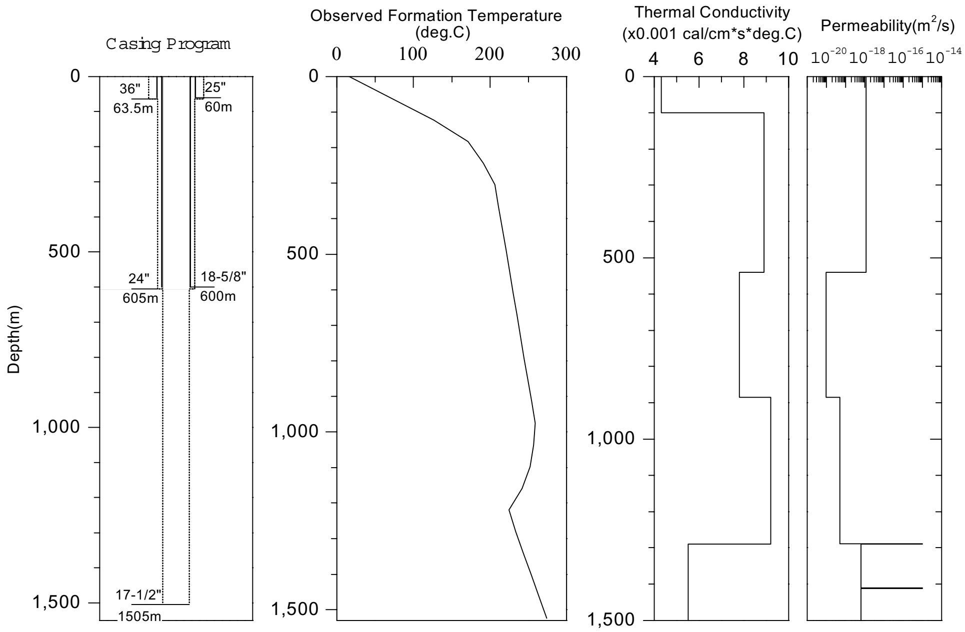

Fig.5 Well Data for inversion (Casing program, Observed Formation Temp., Thermal conductivity, Permeability)

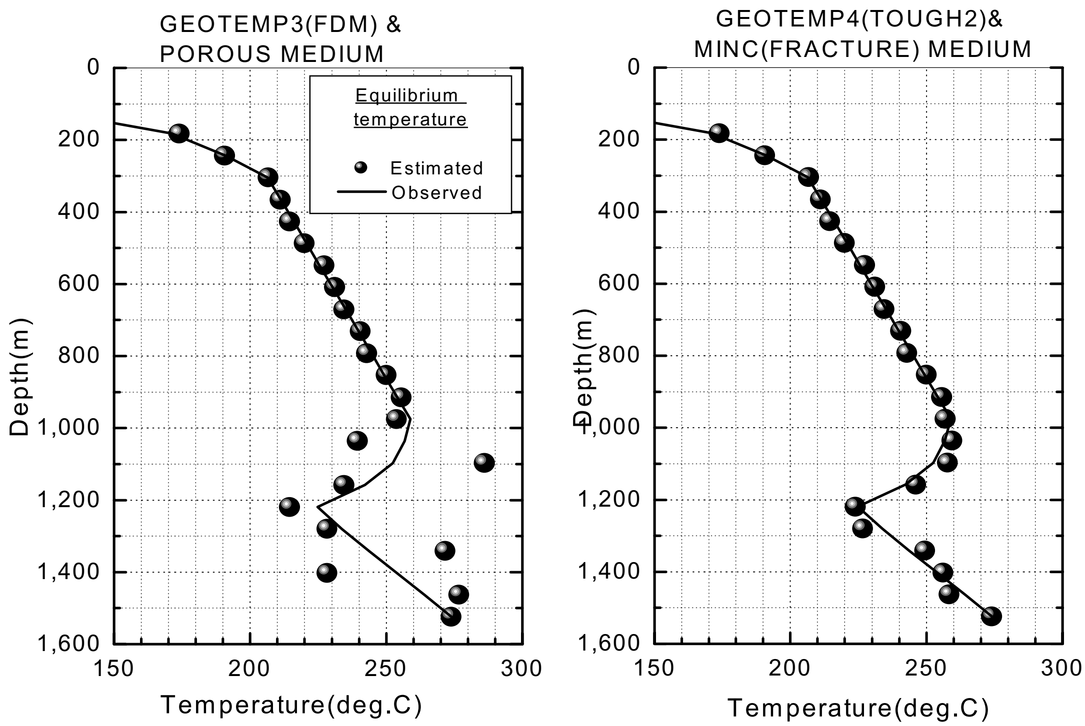

Figure 6. Comparison of observed and estimated temperature using MWDTEMP2 (Left: using GEOTEMP3 and porous medium, Right: using GEOTEMP4 (TOUGH20 and MINC(fracture) medium