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ESTIMATION OF THE FORMATION TEMPERATURE FROM THE INLET AND OUTLET MUD TEMPERATURES WHILE DRILLING.

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ABSTRACT

This paper reports on an attempt to estimate 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 are now developing 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.

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 Honer-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 program 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).

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 ofthermal 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 bore-hole temperature during lost circulation.

TEST OF MODIFIED PROGRAM "GEOTEMP3"

parameter study (1) - Convective flow within the reservoir

methods

In order to see the effect of bottom-hole temperature recovery after drilling, parameter study is performed by changing rock permeability, which is the dominant parameter of a convective geothermal reservoir. Values of permeability used here are $1.0\times10^{-12}m^2$, $1.0\times10^{-15}m^2$, and $1.0\times10^{-17}m^2$. Fig. 1 shows input data for this study.

results

Fig. 2 shows the results of calculated bottom-hole temperature recovery based on changes permeability. **As** can be seen from the figure, all of these models yield almost the same temperature and the effect of convective flow around the well-bore on calculated temperature is very small.

parameter study (2) - lost circulation

methods

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 1,892.5l/min and 100l/min. Permeability of formation at the depth where lost circulation occurred is assumed to $1.0\times10^{-15}m^2$ and that at other depths are assumed to $1.0\times10^{-14}m^2$.Fig.3 shows the input data (Casing, lost circulation, formation temperature, thermal conductivity, permeability) for this parameter study.

results

Figs.4 and 5 show the results of simulation about temperature recovery in the case of the volume of the lost circulation are 1,892.5l/min and 100l/min.

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 phenomena 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.

Investigation based on actual well-bore data

methods

The actual drilling and well data we used for investigation are those for the depths between 1,900m and 2,300m of the well HDR-3, which was drilled by the Hijiori HDR project. We calculated the well-bore temperatures during drilling and especially compared outlet mud temperatures with measured data. Calculation was performed for both 2 cases, that is, considering the lost circulation and neglecting lost circulation.

The depth of the lost circulation was known from the temperature logging and the drilling history (drilling depth, drilling mud properties and the volume of the lost circulation) was taken from the daily reports. Thermal conductivity of the formation was assumed to be constant, and the value was derived from the core sample drilled from the bottom-hole of the another well. Permeability of formation at the depth lost circulation occurred is assumed to be $1.0\times10^{-12}m^2$ and that at other depths is assumed to be $1.0\times10^{-15}m^2$. Fig. 6 shows the input data (Casing, lost circulation, formation temperature, thermal conductivity, permeability) for the calculation.

results

Fig. 7 shows the calculated outlet mud temperatures while considering lost circulation and Fig. 8 shows the those calculated while neglecting lost circulation. These results shows that the estimated outlet mud temperatures calculated while consideration lost circulation match the observed temperature better than those calculated while neglecting lost circulation.

ESTIMATION OF THE FORMATION TEMPERATURE BY INVERSION CODE "MWDTEMP2"

Parameter fitting is done using non-liner least square and the Levenberg-Marquardt algorithm (Mrquardt, 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 Bottomhole 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 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. Fig. 9 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 GEOTEMP3. These temperatures were used as the input data for estimation of formation temperature.

Fig. 10 shows the results of the formation temperature estimated by inversion from inlet and outlet mud temperatures. Error of the estimated temperature tends to be large at depths greater than 1,000m. The standard deviation of the difference 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 is 10 times as large. In this case, error of estimated formation temperature is ±4℃(2σ) at depths of less than 1,000m and is ±40℃(2σ) above 1,000m.

The explanation for these results is thought to be as follows.

① Because this case formation temperatures were estimated from only inlet and outlet mud temperatures, the accuracy of the estimation temperatures degrades with increasing depth.

② In this case, the accuracy degrades due to temperature anomaly.

In an effort to confirm our supposition, we estimated the formation temperature by using not only inlet and outlet mud temperature but also bottom-hole temperature, which is calculated from the model. Fig. 11 shows that results. In this case, using bottom-hole temperature improved accuracy, that is, error of the estimated formation temperature is ±4℃(2σ) for depths of less than 1,000m and is ±10℃(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 taking into account bottom-hole temperature while drilling by MWD.

CONCLUSIONS

①Observed outlet mud temperatures closely matched data calculated by modified well-bore thermal simulator GEOTEMP3. Therefore, the effect of lost circulation can be taken into account.

②Estimation 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 drilling depth is grater or if a formation temperature anomaly exists. In that case, the accuracy of estimation improves if the bottom-hole temperature is used.

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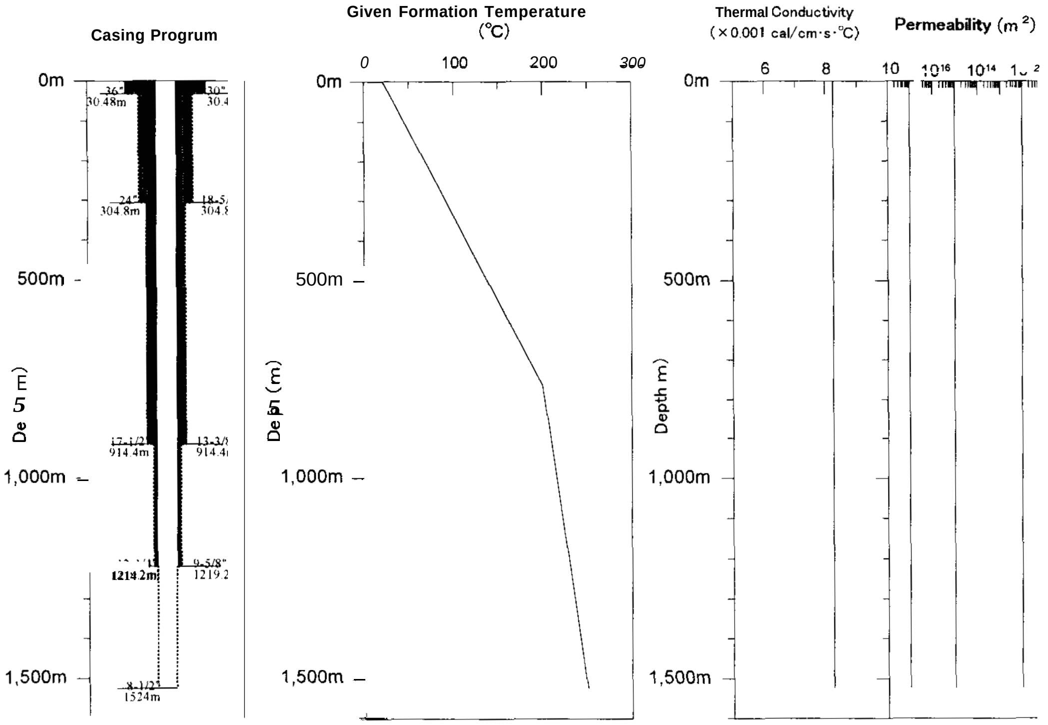

Fig. 1 Input data for parameter study of convecitve reservoir model.
(Casing Progrum, Given Formation Temp., Thermal Conductivity, Permeability)

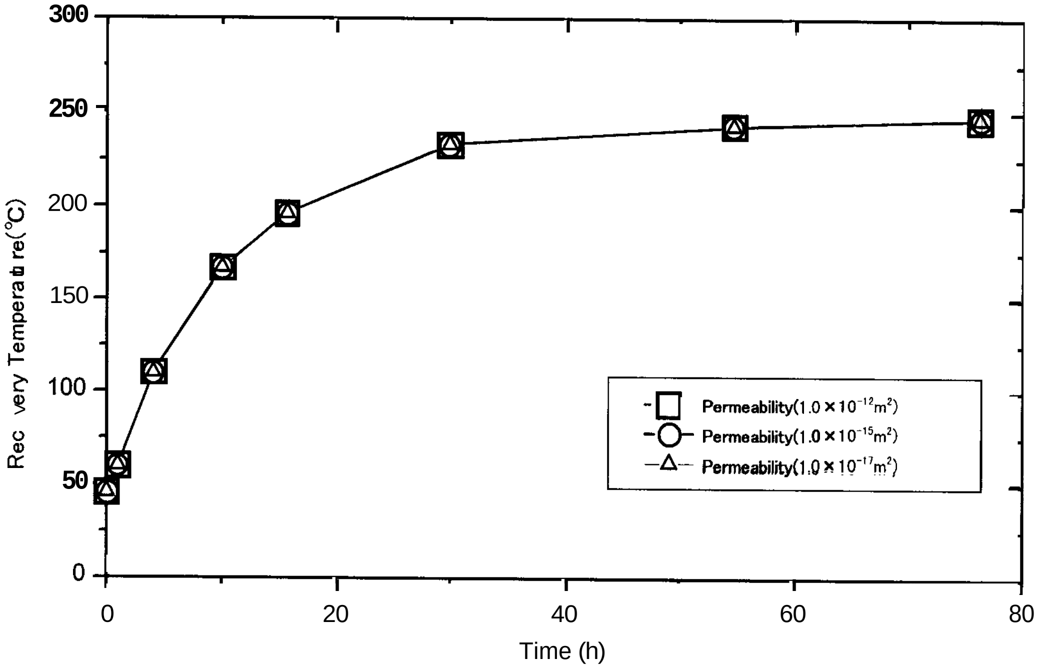

Fig.2 Estimated bottom-hole recovery temperature at 1,500m depth for each permeability.

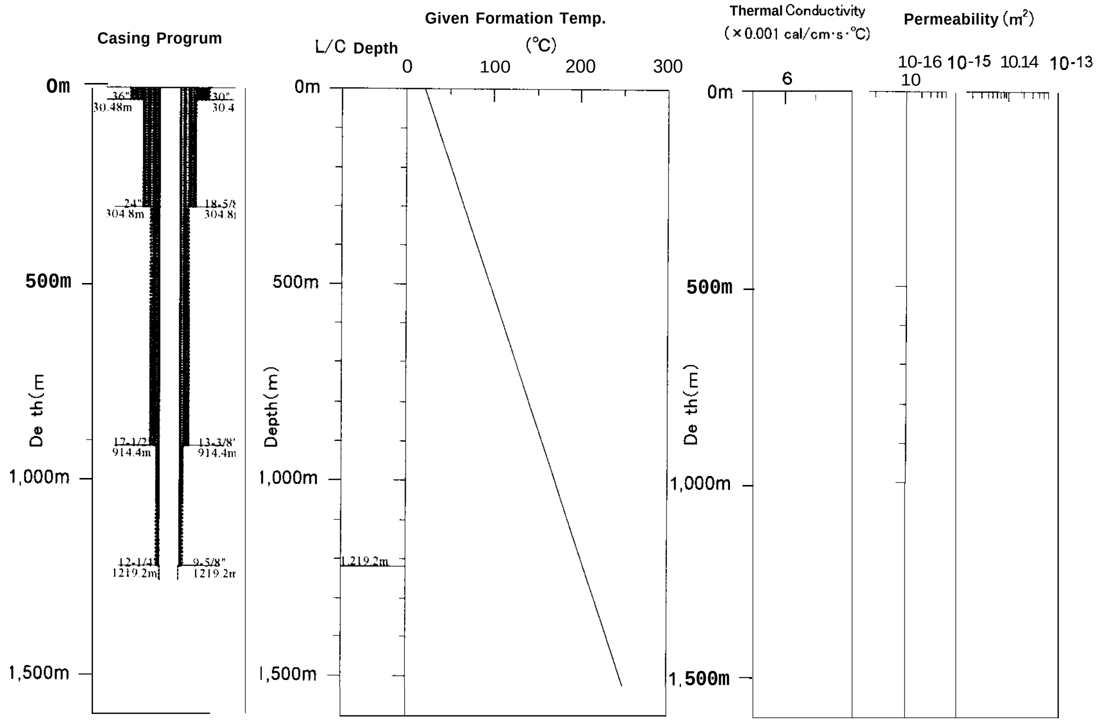

Fig.3 Input data for parameter study of lost circulation model(L/C model).

(Casing program, L/C Depth, Given Formation Temp.(input), Thermal Conductivity, Permeability)

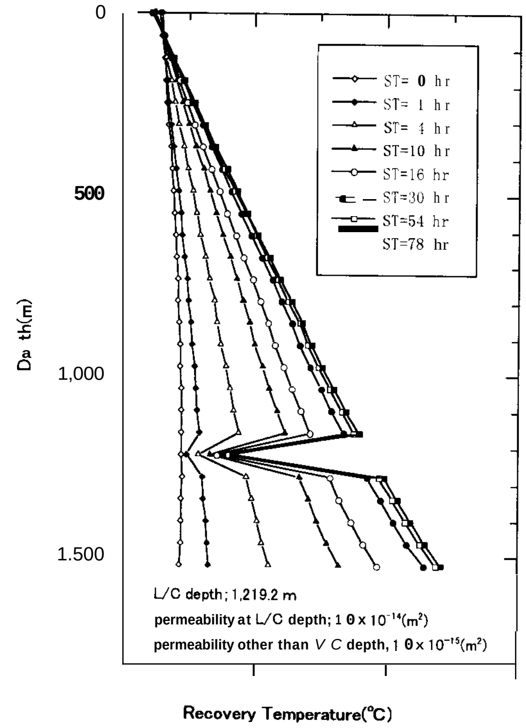

Fig.4 Parameter study results for L/C (=1892.5 l/min) model

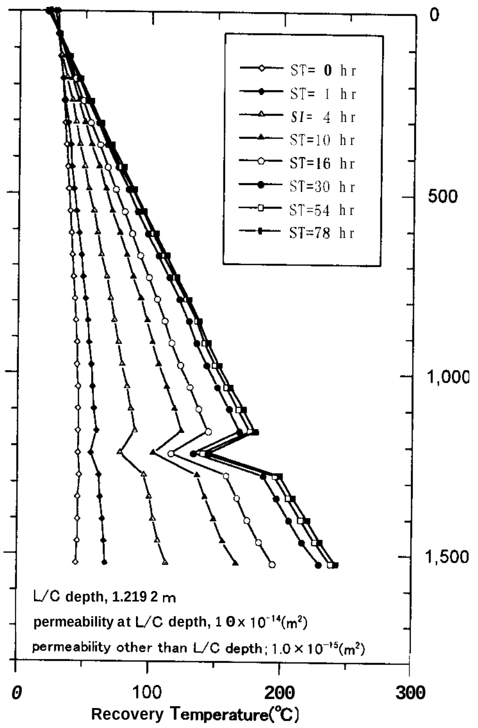

Fig5 parameter study results for L/C (=100 l/min) model

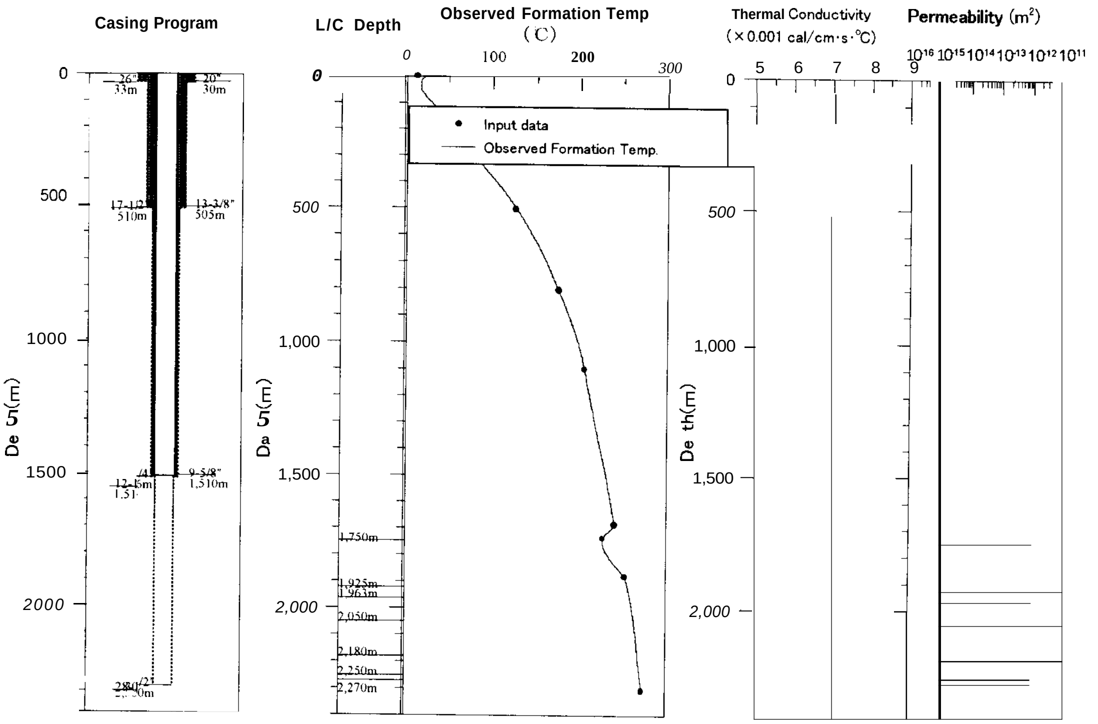

Fig.6 Input data for the actual well data test. (Casing program, L/C depth, Observed Formation Temp., Thermal Conductivity, Permeability)

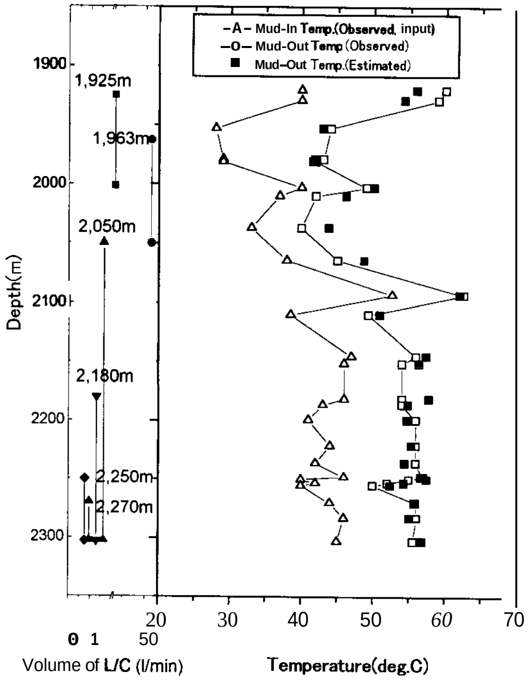

Fig.7 Estimated mud-out temperature with L/C and volume of L/C. (Investigation of the actul bore-hole data)

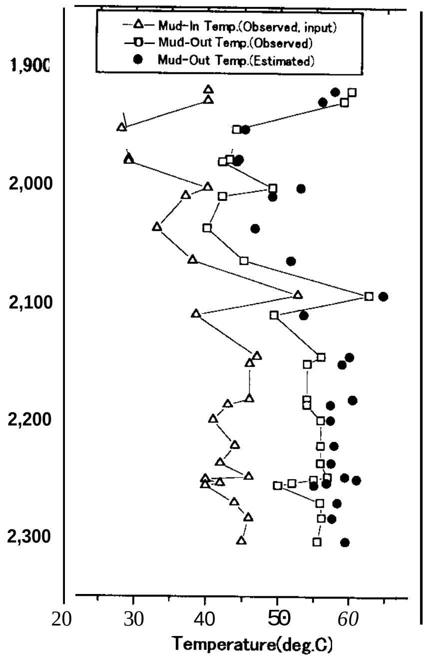

Fig.8 Estimated mud-out temperature without L/C. (Investigation of the actul borehole data)

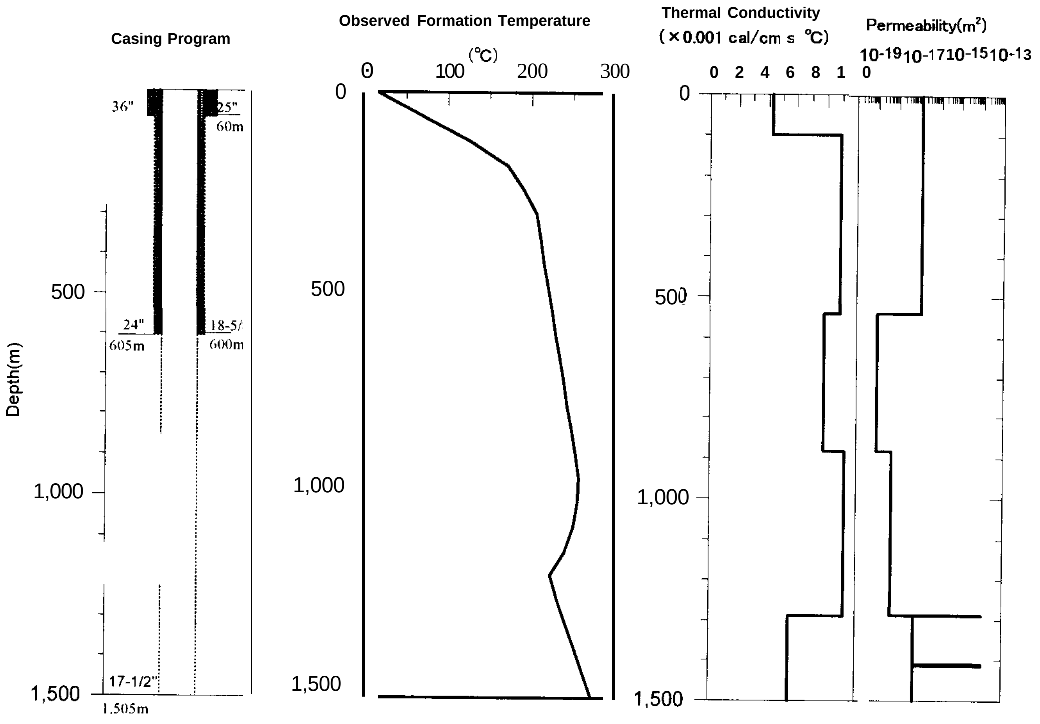

Fig.9 Well Data for inversion (Casing program. Observed Formation Temp., Thermal conductivity, Permeability)

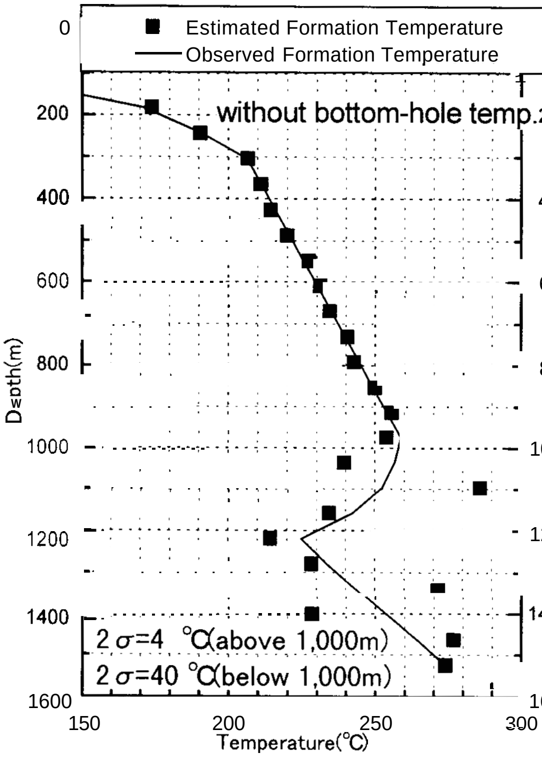

Fig 10 Estimated formation temperature by inversion without bottom-hole temperature data

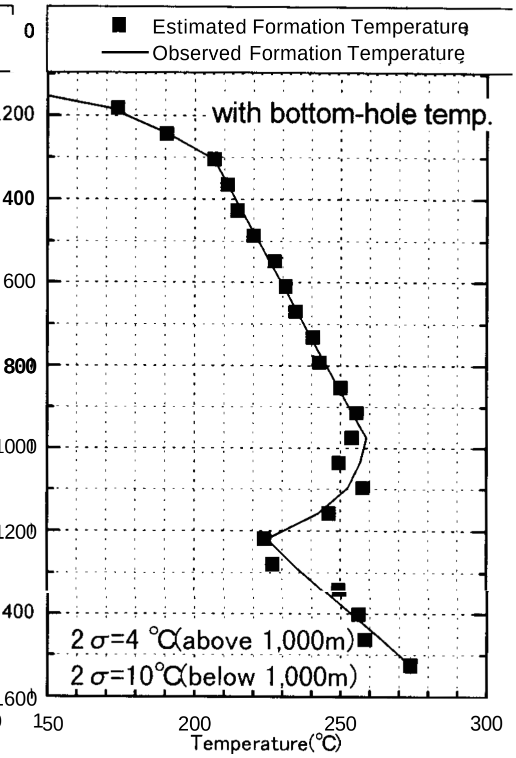

Fig.11 Estimated formation temperature by inversion with bottom-hole temperature data.