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

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ABSTRACT

Formation temperature is an important parameter in geothermal drilling since it affects drilling fluid, operations and equipment, through mud temperatures. In this study formation temperatures of the five geothermal wells in Germencik-Omerbeyli field were estimated by using mud inlet and outlet temperatures obtained during drilling. GTEMP wellbore thermal simulation model was used to estimate the formation and bit temperatures of five wells. With the formation and bit temperature estimations of GTEMP and mud inlet and mud outlet temperature data from field; depth-temperature plots were obtained for two cases. In Case 1, cooling tower effect on mud temperatures was neglected whereas in Case 2 it was taken into account. When cooling tower effects were considered, the results were in accord with those obtained using Horner plot approach. The lowest and highest deviations of the estimations for the formation temperature were 1.5% and 24.5% respectively.

INTRODUCTION

In geothermal drilling, mud and formation temperatures play an important role on the performance of the operations as well as on the decision for the final depth of the well. Therefore, estimation of formation temperature while drilling is of primary importance. However, the temperature limitations of the logging and other measurement devices and the lack of data during drilling the partial and total loss sections set boundaries for these measurement while drilling techniques. Moreover, most of the models and methods developed to calculate formation temperature requires long term period data gathered after drilling.

Concerning the temperature limitations of the measurement devices and the data requirements of the current models; a method was developed for estimating the formation temperatures by GTEMP, using mud inlet and outlet temperatures measured during drilling. With this method, breakdown of the downhole tools and lost time at operations can be reduced which might be considered as more cost effective and easy to practice at field while drilling. Moreover, concerning the temperature at the target depth, decision on the final depth of the well can be performed simultaneously with drilling.

LITERATURE REVIEW

Several methods and computer models were developed to calculate and analyze the formation temperatures at geothermal wells. For the methods Curve fitting, Horner plot and Improved Horner plot; for the computer models GEOTEMP, GEOTEMP2, GEOTEMP3, MWDTEMP2 code, STATIC_TEMP code, GTEMP1 and GTEMP version 2 can be listed.

Takai et al. (1994) studied non-linear least squares fitting method adapting the Middleton Model (Middleton 1979) to estimate equilibrium formation temperature after drilling and compared this method with Horner plot method. It was concluded that curve fitting method achieved more accurate results than Horner plot in estimating formation temperature from short period such as 12 or 24 hours temperature logging during warm up. However, they examined the availability of non-linear least squares fitting method adapting curve fitting method while drilling and concluded that continuous temperature data for four hours was not enough for curve fitting method.

To estimate static reservoir temperature with Horner plot method (Parasnis 1971, Fertl and Winchmann 1997), long shut-in period data was required and static formation temperatures obtained were lower than the true reservoir temperature if short time temperature data was used in Horner plot method (Roux et al. 1980).

With some assumptions to Horner plot method, Roux et al. (1980) resulted in Improved Horner method which has the transient temperature in the formation around a well as well as a function of dimensionless radial distance and time. Therefore, the analysis can be done with short or long time period data.

GEOTEMP is a computer model constructed by Enertech Engineering and Research Co. for Sandia Laboratories to compute downhole temperatures in a geothermal well during injection, production, circulation and drilling. Wooley (1980) stated in the User's Manual for GEOTEMP that drilling was modeled as a special application of circulation in this model. Goodman (1981) defined GEOTEMP as accurate against analytic solutions for several heat transfer problems and as adequate for modeling flowing and shut-in conditions of field data.

GEOTEMP2 (Mitchell 1982) is a modified version of GEOTEMP and Duda (1984) studied GEOTEMP2 to simulate fluid circulation in the well models and it was found that the code predictions and the field data were in good agreement.

Takahashi et al. (1997) modified GEOTEMP2 as GEOTEMP3 to consider lost circulation and the convective flow within the formation and also developed a numerical inversion code, MWDTEMP2, to estimate formation temperature from the inlet and outlet mud temperatures while drilling. It was concluded that the accuracy of estimation improved if the bottom hole temperature data was used as input data in addition to mud inlet and outlet temperatures.

STATIC_TEMP is a computer code that uses five analytical methods to calculate static formation temperatures from actual bottom hole temperature data logged. Santoyo et al. (2000) concluded that STATIC_TEMP results were closer to the actual true formation temperatures except the two-point method. Moreover, exponential approach of cylindrical square method presented the best results among them.

GTEMP1 is a wellbore thermal simulation model that has been jointly developed by Maurer Engineering Inc. and the Department of Modem Mechanics of the University of Science and Technology of China (USTC) as part of the DEA-67 project (Maurer Engineering Inc. 1996). GTEMP version 2 which is named as GTEMP in this paper is an upgraded and enhanced model of GTEMP1 (Maurer Engineering Inc. 2000).

THEORY OF GTEMP

This heading is briefly summarized from GTEMP User's Manual (Maurer Engineering Inc. 2000). GTEMP is a downhole thermal simulation model which is developed for improving the prediction of downhole temperatures. GTEMP models natural and forced convection, conduction within the wellbore, and heat conduction within the surrounding rock formation. Wellbore description of GTEMP for circulation is shown in Figure 1. Drill string is at the center and outside the borehole is the rock formation. The casings are production, intermediate, surface and conductor, respectively. Fluid enters the well at the surface, travels down the tubing, and returns up the annulus to the surface.

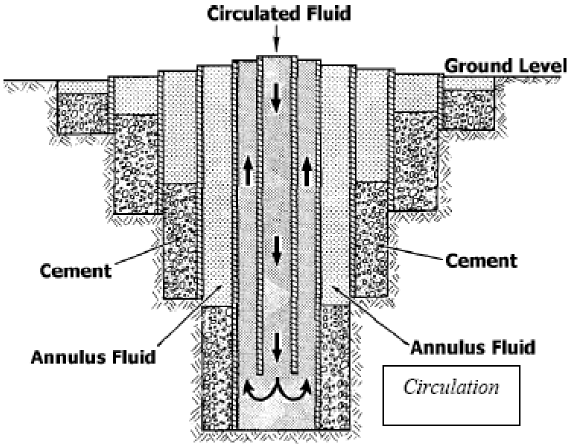


Figure 1: Wellbore Description for Circulation (Maurer Engineering Inc. 2000).

GTEMP computes three temperatures in the wellbore at each depth and the location of the temperature nodes are shown in Figure 2. The first node is for the fluid inside the drill string representing circulating fluid temperature. The second node is for the fluid inside the annulus representing annular fluid temperature during circulation. The third node is located at the well and rock interface.

Heat transfer between the well and the rock is robustly influenced by fluid density, viscosity, specific heat capacity and thermal conductivity. Fluid viscosity strongly affects heat transfer by convection. Specific heat capacity determines sensible heat and energy accumulation in a fluid. Moreover, thermal conductance is formulated from the properties of the materials like steel, cement, fluid and rock and the well geometry.

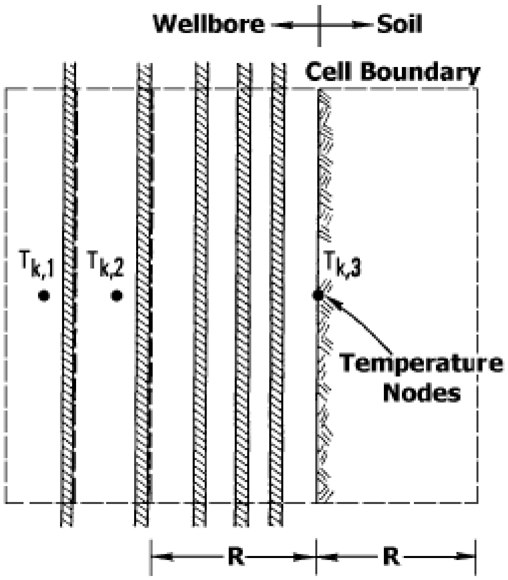


Figure 2: Locations of Temperature Nodes (Maurer Engineering Inc. 2000).

Energy balance is considered for each cell containing fluid and rock. Energy balance equations may be applied to every temperature node to form a system of simultaneous linear algebraic equations. These equations can be solved for finding the new temperature at each new time step, n+1.

Since the fluid temperature in the tank is different from the ambient temperature, heat transfer occurs between the tank and its environment. Moreover, during fluid circulation, the temperature of the fluid at the inlet often changes due to the fact that circulated fluids are mixed with the fluid in the tank. Thus, final temperature of the mixed fluid in the mud tank can be predicted with GTEMP.

In addition to these, some of the assumptions of GTEMP can be listed as:

- Heat conducted along the well axis in the wellbore is ignored.
- All solids properties like density, specific heat capacity and thermal conductivity are treated as constants.
- All fluid properties are assumed to be measured at 70°F.
- All fluids are assumed to be derived by adding solids to water.

GERMENCIK-OMERBEYLI GEOTHERMAL FIELD

One of the important geothermal provinces of Turkey is Buyuk Menderes region that is placed at the western part of Turkey. Germencik-Omerbeyli geothermal field is located at the west of Buyuk Menderes Graben about 40 km from Aegean Sea (Simsek 2003) and within Omerbeyli-Alangullu residential areas in Aydin as can be seen in Figure 3 and has a high geothermal potential.

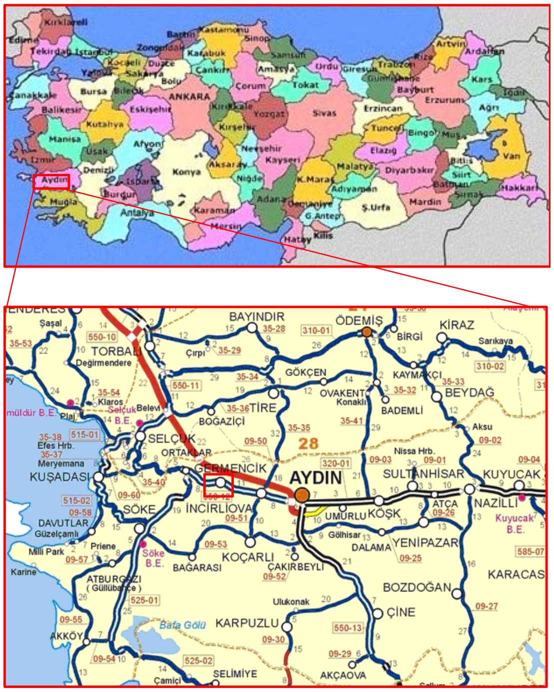


Figure 3: Location Map of Germencik-Omerbeyli Geothermal Field.

The field was discovered by MTA (General Directorate of Mineral Research and Exploration) in 1967 and nine wells were drilled between 1982 and 1986. After that, GURIS Construction and Engineering Co. Inc. has become the operator of the field and drilled nine more wells between 2007 and 2008 and constructed a 47.4 MWe power plant. The wells drilled in this field are shown in Table 1.

Geology of the Field

Germencik-Omerbeyli geothermal field consists of two reservoirs. The deepest reservoir is composed of Paleozoic aged gneiss, marble and schist which are named as Menderes Massif metamorphics, whereas the shallow reservoir is formed of Neogene aged sandstones and conglomerates (Filiz et al. 2000).

Geochemistry

The reservoir rock is recharged with meteoric waters along faults and fracture zones (Filiz et al. 2000). The waters are heated at depth and move up to the surface through the tectonic lines by convection. Filiz et al. (2000) also mentioned that the geothermal waters are high enthalpy, meteoric origin and old and are of the sodium, chloride and bicarbonate water type. Moreover, heat source is a magmatic intrusion intruded along the young faults by graben tectonism. The type of the geothermal waters in Aydin region is generally of the Na-Ca-HCO_3. The tritium content of the geothermal waters in Germencik, points to a residence time of recharging water in the geothermal system for more than 50 years (Simsek 2003).

Table 1: Germencik-Omerbeyli Geothermal Field Wells (GURIS 2009).

Well Number	Depth (m)	Reservoir Temperature (°C)	Date
OB-1	1001	203	1982
OB-2	975	232	1982
OB-3	1195	232	1983
OB-4	285	217	1984
OB-5	1302	219	1984
OB-6	1100	221	1984
OB-7	2398	227	1985
OB-8	2000	221	1986
OB-9	1466	213	1986
OB-10* (#1)	1524	224	2007
OB-14* (#2)	1205	228	2007
OB-11* (#3)	965	210	2007
AG-22* (#4)	2260	205	2008
AG-25* (#5)	1838	191	2008
OB-17* (#6)	1706	228	2008
AG-24* (#7)	1252	199	2008
AG-26* (#8)	2432	195	2008
OB-19* (#9)	1651	227	2008

*GURIS wells

METHOD OF SOLUTION

This study was conducted with the wells #3, #4, #5, #7 and #9 shown in Table 1 and data was obtained from the literature and personal communication with GURIS Engineering and Construction Co. Inc.

For each well, depth couples were selected from the depths that drilling continues without interruption and no new mud addition to the system occurred. A depth couple consists of two depth points named as first and second depth. The circulation system starts with the first depth's MIT (Mud inlet temperature), measured at the mud tanks and travels through the well and enters the shale shakers where the second depth's MOT (Mud outlet temperature) is measured as shown in Figure 4.The interval between these two depths varied between 2.5 and 15 m except the total loss section. Since no temperature measurement occurred during the total loss, the last two depths that mud temperature measured were chosen and the final depth of the well was extrapolated through the program. Total numbers of the depth couples are 32, 34, 28, 26 and 31 for the wells #3, #4, #5, #7 and #9, respectively.

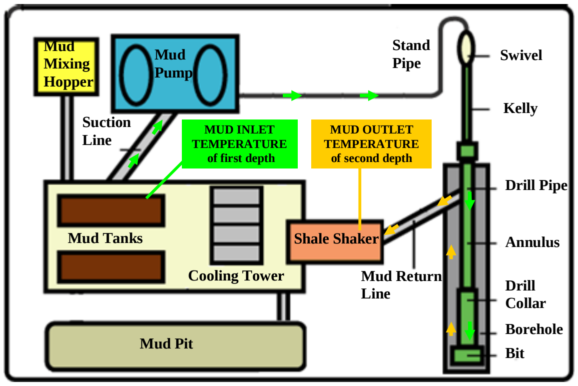


Figure 4: Mud Inlet and Mud Outlet Temperature and Their Measurement Places in the Circulation System (Modified from http://science.howstuffworks.com/oil-drilling4.htm 2001).

Regarding the input data, mud inlet temperature and mud property values are of the first depth whereas tubular, casing and rock property values are of the second depth. Regarding the output data, mud outlet temperature value is of the second depth.

Computer simulation was developed in stages as shown in Figure 5 and performed for every depth couple selected. Input data was entered to the program. The object of computer run was to match the field measurement and the simulated mud outlet temperature of the second depth. In order to achieve this purpose, bottom temperature input at the Wellbore page of the program was modified. The bottom temperature that realizes the match was recorded as formation temperature and the temperature inside the drill string at the bottom was recorded as bit temperature.

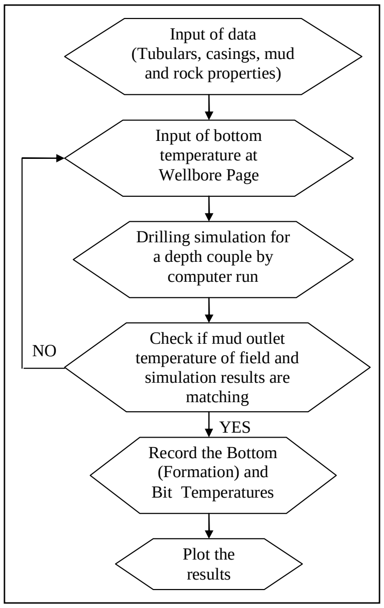


Figure 5: Method of Solution Flow Chart.

Drilling Data

Formations encountered during drilling

The formations encountered during drilling of these five wells can be listed from surface to bottom as Alluvium (Quaternary), Sandstone (Plio-quaternary, Pliocene, Miocene), Gneiss (Paleozoic), Marble (Paleozoic), Marble-Schist (Paleozoic) and Schist (Paleozoic) (GURIS 2010).

Well design and drilling fluid

For 26” section bentonite-water (spud mud) and for the 17½”, 12¼” and 8½” sections lignosulfonate mud was used. During drilling marble and schist formations; total loss occurred in wells #3 and #7, partial loss occurred in well #9 and partial and total loss occurred in wells #4 and #5. Total loss sections were drilled with water. 20” and 13 ⅜” casings were run in Sandstone, 9 ⅝” liner was run mostly in Gneiss and 7” slotted liner was run in Marble-Schist and total loss formations (GURIS 2010).

Cooling Tower

During drilling operations, cooling tower was used in order to decrease the temperature of the circulating mud. It was turned on when the mud outlet temperature reached to 50-80 ºC. The average temperature decreases between mud outlet and mud inlet temperatures when cooling tower is used and not used were composed from geology reports (GURIS 2010) and are shown in Table 2.

Input Data

The operation was selected as Liquid Forward Circulation which was considered as the closest option to drilling simulation. The drill string and casing diameters and setting depths, surface and bottom temperatures were entered. For the wells drilled during the months between October and March, the surface temperature was accepted as 15 °C; and for the ones drilled between April and September, it was accepted as 22°C regarding Aydin is standing in the thermic region according to the World Soil Resources’ Soil Temperature Regimes Map (USDA-NRCS 1999).

Mud rheology was selected as Bingham Plastic since GTEMP also selected Bingham Plastic as rheology model with two viscometer readings. The values for density, viscosity and yield point were entered. Moreover, mud inlet temperature, flow rate and flow period (min) values were entered. Flow period was considered as the time passed while drilling between the two depths of the depth couple and calculated by dividing the drilled meterage between these depths to the rate of penetration.

Table 2: Average Temperature Decrease between MOT & MIT.

Depth (m)	Average Decrease btw. MOT & MIT (°C)
Cooling Tower Used	
600-800	7.0
800-1000	9.0
1000-1200	10.0
1200-1400	12.0
1400-1600	14.0
1600-1800	15.0
1800-2000	17.0
2000-2100	18.0
2100-2200	20.0
Cooling Tower Not Used	
0-300	1.0
300-500	2.0
500-900	3.0
900-1250	3.5
1250-1350	4.0
1350-1450	5.0
1450-1650	5.5
1650-1850	6.0
1850-2050	7.0
2050-2200	9.0

In order to consider the heat transfer between the tank and its environment, tank mixed option was selected. The volume and fluid surface area of the sand trap, precipitation and suction tanks were used.

Additionally, tubing and casing thermal properties such as conductivity (Btu/h-ft-F), heat capacity (Btu/lb-F) and density (lb/ft^3) were selected from the database. All required properties for Alluvium and Sandstone were obtained from the database of the program. For the other formations, a literature survey was conducted and the values are shown in Table 3.

Moreover, for the marble-schist formation, the percentage of marble and schist were composed from geology reports (GURIS 2010) through a defined path as shown in Table 4. According to the percentages, weighted averages of the properties of the marble-schist formations were calculated for every well.

Assumptions for Input Data

- •The length of kelly was assumed to be equal to that of the drill collar, heavy weight drill pipe or drill pipe whichever comes afterwards the kelly.
- •Since there is no liner option in the program, 9 ⅝” liner was assumed as casing connected to surface.

Table 3: Rock Properties.

Formation	Conductivity (W/m-°C)	Heat Capacity (Btu/lb-F)	Density (kg/m^3)
Alluvium	1.281$^{(1)}$ (value of soil)	0.21$^{(1)}$ (value of soil)	1457.6$^{(1)}$ (value of soil)
Sandstone	1.869$^{(1)}$	0.17$^{(1)}$	2231.3$^{(1)}$
Gneiss	2.60$^{(2)}$	0.20$^{(1)}$ (value of granite)	2867$^{(3)}$
Marble	3.20$^{(2)}$	0.21$^{(4)}$	2563$^{(3)}$
Schist	1.5$^{(2)}$	0.30$^{(1)}$ (value of shale)	2650$^{(5)}$

(1)GTEMP Database;
(2) Cote, J. and Konrad J.M., 2005;
(3)http://www.simetric.co.uk/si_materials.htm;
(4)http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html;
(5)http://www.engineeringtoolbox.com/density-solids-d_1265.html).

Table 4: Percentage of Marble and Schist in a Marble-Schist Formation.

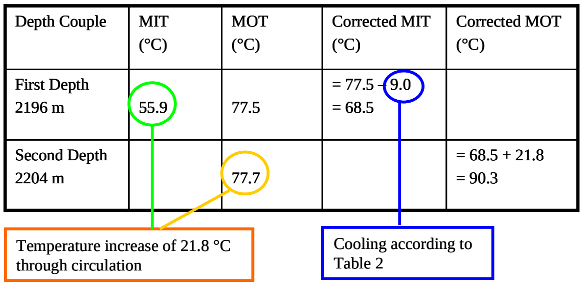
Formation	Marble %	Schist %
Marble, schist varieties	60	40
Schist varieties, marble	40	60
Intensely marble, schist varieties	70	30
Intensely schist varieties, marble	30	70
Poor marble	20	80
Poor schist varieties	80	20
Intercalation of marble	20	80
Intercalation of schist varieties	80	20
Slight marble	10	90
Slight schist varieties	90	10
Very poor marble	10	90
Very poor schist varieties	90	10
Very poor marble scraps	5	95
Very poor schist variety scraps	95	5

- Since there is no bit diameter option in the program, the diameter of the drilled section is the same with the previous casings' diameter.
- Mud rheology was assumed as Bingham Plastic. However, during the drilling of total loss sections, water was used with the properties of Density: 62.4 lb/ft^3, PV:1 cp, YP:0 lbf/100 ft^2.
- Since no drill cutting comes to surface during total loss sections, these sections were accepted as the continuation of the previous formation. Likewise, drilling fluid invading the formation was neglected for these sections.

Case Definition

This study was performed in two different cases for every well concerning cooling tower effect to mud temperatures. In Case 1, cooling tower effect was not taken into account, therefore no modification was conducted on mud temperatures measured at field.

In Case 2, cooling tower effect was taken into account and the field parameters of mud inlet and mud outlet temperatures were modified to the values that would be if the cooling tower was not used as illustrated in Figure 6. For this modification, mud outlet temperature of the first depth was decreased according to Table 2 and corrected mud inlet temperature of the first depth was obtained. Corrected mud outlet temperature of the second depth was obtained by adding the difference between the first depth's mud inlet temperature and second depth's mud outlet temperature to the corrected mud inlet temperature of the first depth.



Depth Couple	MIT (°C)	MOT (°C)	Corrected MIT (°C)	Corrected MOT (°C)
First Depth 2196 m	55.9	77.5	= 77.5 – 9.0 = 68.5	
Second Depth 2204 m		77.7		= 68.5 + 21.8 = 90.3

Temperature increase of 21.8 °C through circulation

Cooling according to Table 2

Figure 6: Mud Inlet and Outlet Temperature Correction Procedure.

Figure 7 shows a sample plot for depth versus mud inlet and outlet temperature obtained after applying the aforementioned correction procedure.

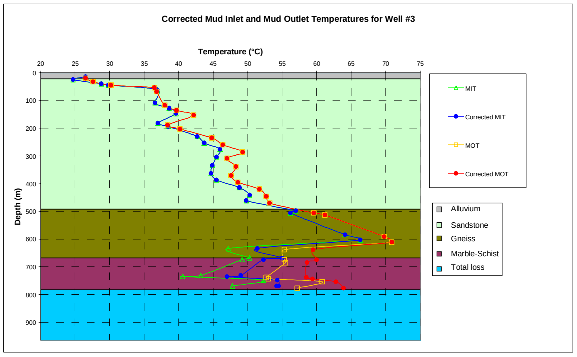


Figure 7: Depth versus Corrected Mud Inlet and Mud Outlet Temperature Plot for Well #3.

RESULTS AND DISCUSSION

For this study, one shallow well, one deep well and three wells with medium depth were selected and named as #3, #4, #5, #7, #9 respectively.

Detailed information for Well #3 and depth versus temperatures plots for five wells are given below.

The final depth of Well #3 is 965 m and the reservoir temperature is 210 °C. Cooling tower was used after 634 m. Total loss was encountered between 778 and 965 m right after marble-schist formation. 32 computer runs were conducted and the formation temperature of the final depth was estimated with 769-777 m depth couple and computer run for total loss section was conducted with water. Depth versus temperatures plots of Well #3 for Case 1 and 2 are shown in Figures 8 and 9.

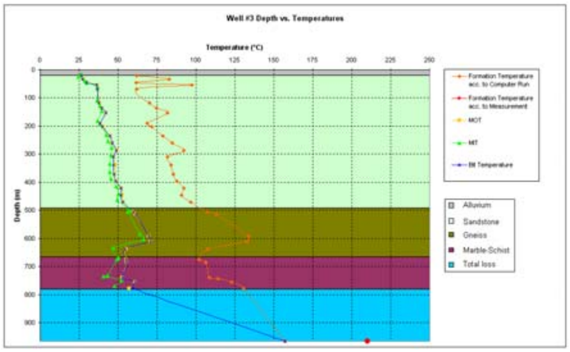


Figure 8: Depth versus Temperatures Plot for Well #3 (Case 1: with cooling tower).

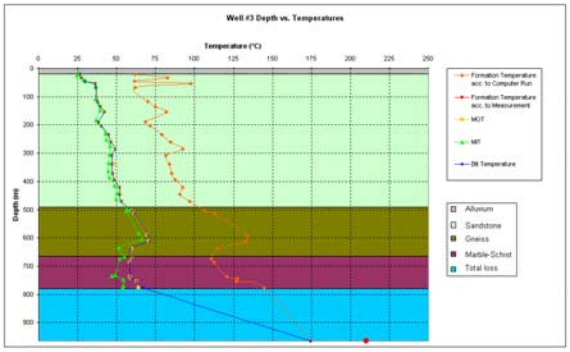


Figure 9: Depth versus Temperatures Plot for Well #3 (Case 2: without cooling tower).

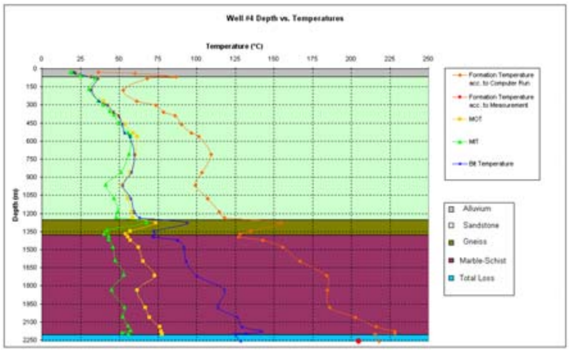


Figure 10: Depth versus Temperatures Plot for Well #4 (Case 1: with cooling tower).

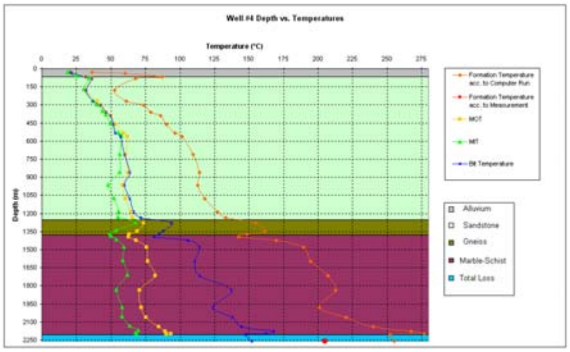


Figure 11: Depth versus Temperatures Plot for Well #4 (Case 2: without cooling tower).

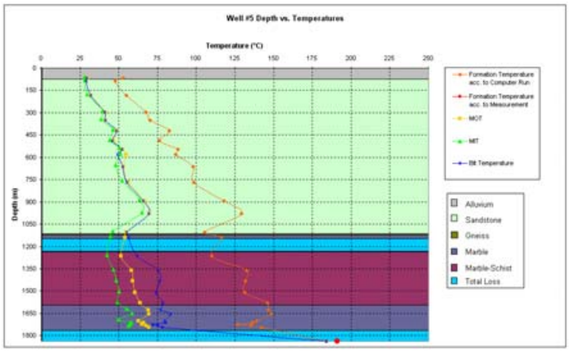


Figure 12: Depth versus Temperatures Plot for Well #5 (Case 1: with cooling tower).

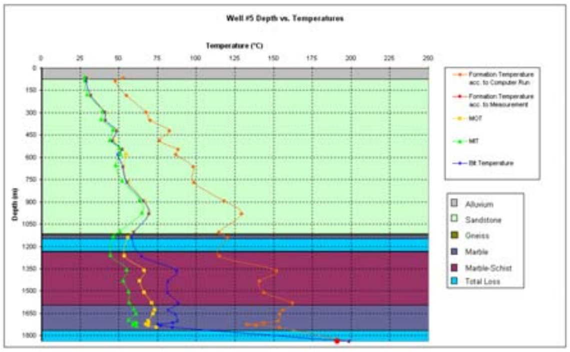


Figure 13: Depth versus Temperatures Plot for Well #5 (Case 2: without cooling tower).

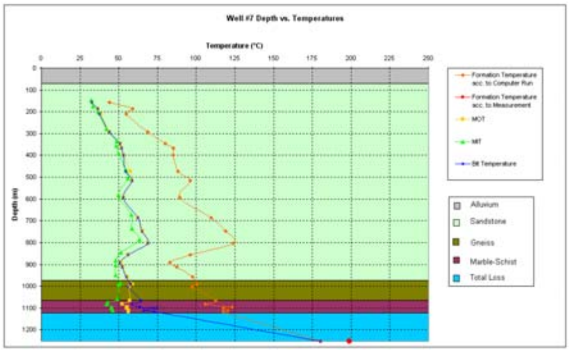


Figure 14: Depth versus Temperatures Plot for Well #7 (Case 1: with cooling tower).

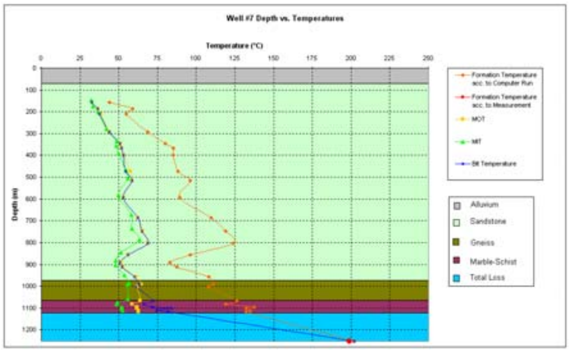


Figure 15: Depth versus Temperatures Plot for Well #7 (Case 2: without cooling tower).

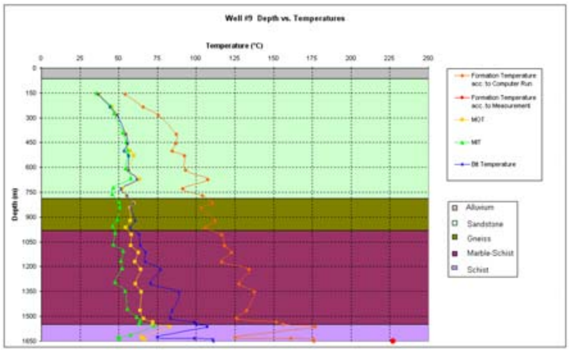


Figure 16: Depth versus Temperatures Plot for Well #9 (Case 1: with cooling tower).

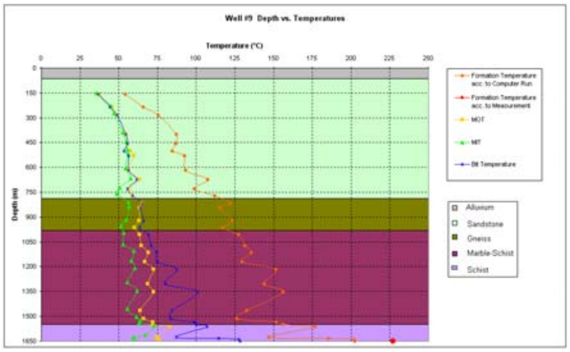


Figure 17: Depth versus Temperatures Plot for Well #9 (Case 2: without cooling tower).

The deviations between the estimated formation temperatures using Horner Plot method with those obtained using GTEMP with (Case 1) and without (Case 2) addition of cooling tower for five wells are shown in Table 5. The lowest difference was observed in Well #5 where Case 1 and Case 2 agreed with Horner Plot method. On the other hand, for Well #3, #7 and #9, deviations were somewhat smaller in Case 2 compared to Case 1. Moreover, formation temperature estimation was better in Case 1 rather than Case 2 for Well #4 which is the deepest well in this study.

Table 5: Comparison of Cases 1 and 2 for Five Wells.

Well No	Case 1		Case 2		$T_{Reservoir}$ (°C)	Depth (m)
	T (°C)	Diff (%)	T (°C)	Diff (%)		
3	157.11	-25.2	174.22	-17.0	210	965
4	217.94	6.3	255.25	24.5	205	2260
5	184.09	-3.6	198.72	4.0	191	1838
7	180.22	-9.4	202.08	1.5	199	1252
9	176.16	-22.4	202.29	-10.9	227	1651

CONCLUSIONS

The formation temperatures for five different geothermal wells in Germencik-Omerbeyli geothermal field were estimated by using mud inlet and mud outlet temperatures obtained during drilling. A wellbore thermal simulator, GTEMP, was used for this purpose. Since GTEMP does not offer a cooling tower option, estimations were conducted for two cases for every five well concerning the cooling tower effect. In Case 1, cooling tower effect was not taken into account and mud inlet and outlet temperatures were used without modification. On the other hand, in Case 2, cooling tower effect was taken into account and mud inlet and outlet temperatures were modified in a defined path.

The estimated formation temperatures of the final depth of five wells were compared with reservoir temperature data obtained with Horner Plot method. Estimations deviated within 3.6% to 25.2% in Case 1 and 1.5% to 24.5% in Case 2. The best matches were mostly obtained with Case 2 where cooling tower effect was taken into account.

RECOMMENDATIONS

To achieve more optimized match results for estimating formation temperatures with GTEMP, a few recommendations can be stated.

In order to reflect cooling tower effect on mud temperatures more efficiently, this effect can be simulated in another model and the results can be used as mud temperatures or the tank surface area option in GTEMP can be modified in a consistent way.

Moreover, the types of the formations at the database can be increased in variety and drill bit and liner options can be included in order to imitate well conditions in detail.

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