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

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

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

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Formation temperature is an important parameter in geothermal drilling since it affects all the components of the system such as drilling fluid, drilling operations and equipment through mud temperatures. The main objective of this study is to estimate the formation temperatures of five geothermal wells in Germencik-Ömerbeyli geothermal field by using inlet and outlet mud temperatures obtained during drilling. For this purpose, GTEMP, a wellbore thermal simulation model is used to simulate the process of drilling and to estimate the formation and bit temperatures of five wells. With the formation and bit temperature estimations of GTEMP and inlet and outlet mud temperature data from field; temperatures vs. depth graphs are plotted for five wells for two cases. In Case 1, cooling tower effect on mud temperatures is neglected whereas in Case 2 it is taken into account. For the estimation of formation temperature of the final depth, Case 2 showed better results with % 1,5-24,5 deviation compared to the % 3,6-25,2 deviation obtained in Case 1.

Keywords: Formation Temperature, Mud Temperature, Geothermal Drilling

ÖZ

JEOTERMAL FORMASYON SONDAJLARI ESNASINDAKİ ÇAMUR GİRİŞ VE ÇIKIŞ SICAKLIKLARINDAN FORMASYON SICAKLIĞININ HESAPLANMASI

Tekin, Sema

Yüksek Lisans, Petrol ve Doğal Gaz Mühendisliği Bölümü

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Jeotermal sondajlarda formasyon sıcaklığı; sondaj akışkanı, sondaj operasyonları ve ekipmanları gibi unsurları çamur sıcaklıkları aracılığıyla etkileyen önemli bir parametredir. Bu çalışmanın ana hedefi Germencik-Ömerbeyli jeotermal sahasındaki beş jeotermal kuyudaki formasyon sıcaklıklarının, sondaj esnasında elde edilen çamur giriş ve çıkış sıcaklık verileri kullanılarak hesaplanmasıdır. Bu amaçla, sondajın simüle edilmesi ve beş kuyudaki formasyon ve matkap sıcaklıklarının hesaplanması için bir kuyu termal simülatörü olan GTEMP kullanılmıştır. GTEMP'in formasyon ve matkap sıcaklık hesaplamaları ile çamur giriş ve çıkış saha sıcaklık verileri kullanılarak, beş kuyunun iki farklı durum için sıcaklık-derinlik grafikleri çizilmiştir. Durum 1'de soğutma kulesinin çamur sıcaklıkları üzerindeki etkisi ihmal edilirken, Durum 2'de bu etki hesaba katılmıştır. Son derinliğin formasyon sıcaklığının hesaplanmasında Durum 2 % 1,5-24,5 sapma ile Durum 1'in % 3,6-25,2 sapmasına göre daha iyi sonuç vermiştir.

Anahtar Sözcükler: Formasyon Sıcaklığı, Çamur Sıcaklığı, Jeotermal Sondaj

TO MY DAD

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NOMENCLATURE

2D	Two dimensional
3D	Three dimensional
Bbl	Barrel
BOP	Blow-out Preventer
BTC	Buttress Thread Cut
°C	Degree Celsius
Ca	Calcium
CSG	Casing
DC	Drill Collar
DEA	Drilling Engineering Association
Deg	Degree
DP	Drill Pipe
E-W	East to West
°F	Degree Fahrenheit
Ft	Feet
Gpm	Gallon per minute
Hr	Hour
HWDP	Heavy Weight Drill Pipe
in	Inch
ID	Inner Diameter
JAPEX	Japan Petroleum Exploration Co. Ltd.
K	Potassium
Km	Kilometer
m	Meter
m/hr	Meter/hour
Max.	Maximum
MD	Measured Depth

MIT	Mud Inlet Temperature
MOT	Mud Outlet Temperature
MTA	General Directorate of Mineral Research and Exploration
MWD	Measurement While Drilling
Na	Sodium
NRCS	Natural Resources Conservation Service
N-S	North to South
OD	Outer Diameter
PDC	Polycrystalline Diamond Compact
PDM	Positive Displacement Motor
ROP	Rate of Penetration
Temp.	Temperature
TSP	Thermally Stable Polycrystalline
TVD	True Vertical Depth
USDA	United States Department of Agriculture

CHAPTER 1

INTRODUCTION

In geothermal wells, drilling conditions differ from oil wells in many aspects such as high temperature, formation fluid composition, alterations and discordances of formation and extensively encountered faulty zones.

The primary difference between geothermal and oil well drilling, is the high mud temperatures encountered during drilling since it reflects lithology variations and hot water and steam quality. In addition to this, mud temperatures define the boundaries for the application of logging devices and drilling equipment and affect drilling and completion practices (Edwards et al. 1982). The temperature limitations of the downhole tools can be seen in Figure 1.1. Blowout, deterioration of the drilling fluid rheology and cement and breakdown at downhole tools are some of the problems that may occur with the increase of formation temperature and consequently mud temperatures.

Another remarkable difference is to continue with drilling for a while during partial or total loss situations instead of plugging the target zone with loss preventive materials. Although continuing drilling in these situations bring the risk of stuck pipe due to the lack of cuttings transportation. Moreover, the drilling fluid can not fulfill its main functions such as cooling and lubricating the bit and drill string, supporting weight of tubulars, exerting hydrostatic pressure and maintaining wellbore stability. It is also risky not to have temperature data since no mud returns to surface.

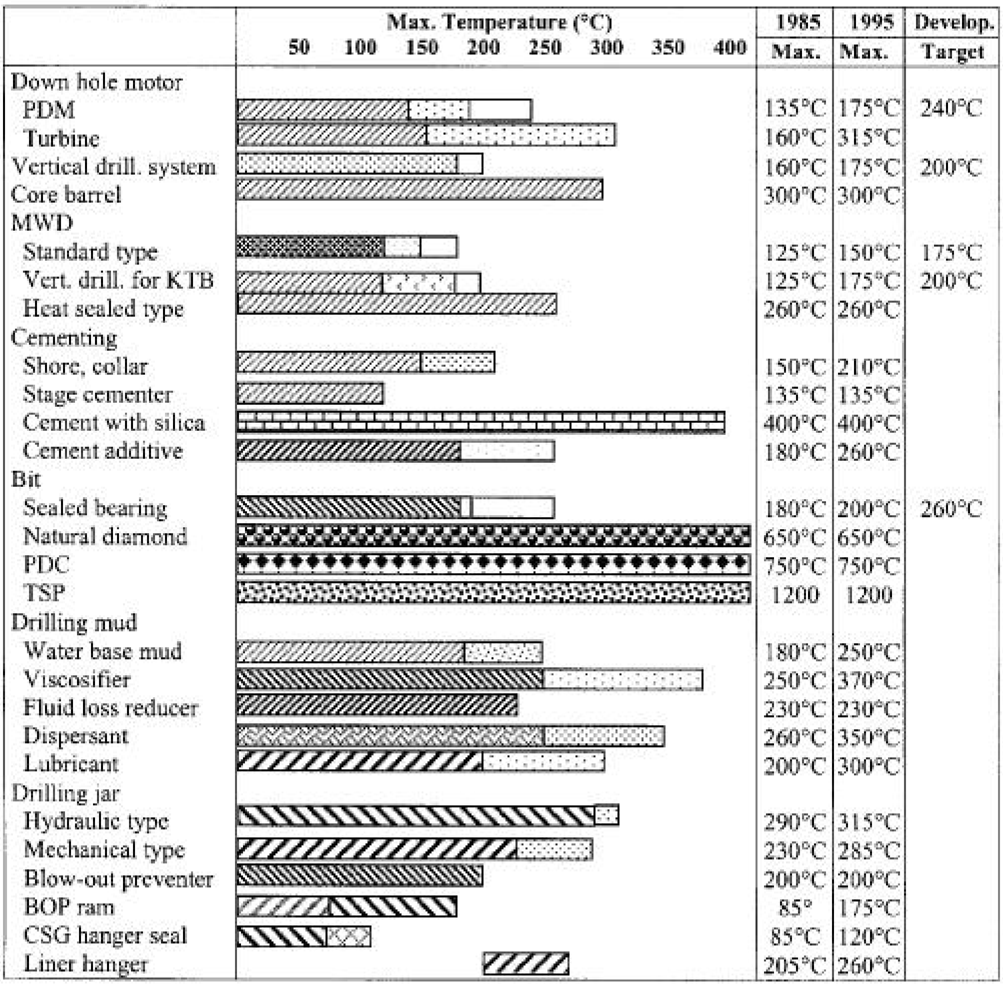


Figure 1.1. Temperature Limitations of Drilling Tools and Materials (from JAPEX) (Hefu 2000).

Therefore estimation of formation temperature while drilling especially in partial or total loss sections is of primary importance for controlling equipment and operations including drilling, cementing and logging. Moreover, with formation temperature estimation, a decision can be made on the final depth for a well regarding the evidences for reaching the target zone or the limitations of the equipment in the well.

There are several models and methods to calculate formation temperature but most of them require data for a long period of time. Using a simulation model to estimate formation temperature while drilling is more efficient compared to other methods. With GTEMP, formation temperatures can be estimated by using mud inlet and outlet temperature data measured during drilling. Mud inlet temperature is used as one of the input parameter and the calculated mud outlet temperature of the program is matched with the field measurement, giving the estimated formation temperature.

CHAPTER 2

LITERATURE REVIEW

The most significant challenge encountered in geothermal drilling is high mud and formation temperatures that affect drilling operations and equipment. Therefore determining of mud and formation temperatures becomes important. For this purpose, temperature recording devices have been developed but these provide isolated data points for a transient quantity (Mitchell 1981) and also have temperature limitations. Consequently, a need for computing and analyzing downhole temperatures arise and several methods and computer models are developed.

2.1 Methods for Estimation of Formation Temperature

2.1.1 Curve Fitting Method

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. Middleton's square well model does not require data for circulation time of the drilling fluids and due to this feature, curve fitting method is considered as more sensitive than the Horner plot method. It is also 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.

In addition to this, 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 is not enough for curve fitting method.

2.1.2 Horner Plot Method

Using Horner plots for estimating static reservoir temperature from temperature buildup data is a common practice in geothermal sector. However, Horner-plot method (Parasnis 1971, Fertl and Winchmann 1997) requires long shut-in period data and static formation temperatures obtained are lower than the true reservoir temperature if short time temperature data is used (Roux et al. 1980).

Roux et al. (1980) added some assumptions to Horner method and 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.

2.2 Computer Models and Codes for Estimation of Formation Temperature

2.2.1 GEOTEMP

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. Temperatures are computed as a function of time in flowing fluids, annulus fluids, drill pipe and casings, cement and in the formation at all depths (Wooley 1979).

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.

Wooley (1980) states in User's Manual for GEOTEMP that drilling is modeled as a special application of circulation in this model. The depth of circulation varies with time and each day is divided into a circulating and a shut-in period. A drilling rate is computed based on the drilling time, depth and hours per day of circulation. From the drilling rate the depth of circulation is computed at each time step.

2.2.2 GEOTEMP2

GEOTEMP2 is a modified version of GEOTEMP improved at variable tubing flow areas, multiple fluids in the wellbore, deviated wellbore, air, nitrogen and mist drilling and two-phase steam production and injection (Mitchell 1982).

Duda (1984) studied GEOTEMP2 to simulate fluid circulation in the well models and good agreement was found between the code predictions and the field data.

Takai et al. (1994) also studied GEOTEMP2 and they concluded to develop an inverse program to calculate formation temperatures due to the reasons that GEOTEMP2 computes mud temperatures as results of numerical simulation. They compared mud temperatures at the surface with the simulated ones and analyzed that the simulated temperatures are 2°C to 10°C lower due to the reason that the unit of the computation is day, not hour.

2.2.3 GEOTEMP3

Takahashi et al. (1997) modified GEOTEMP2 to GEOTEMP3 in order to consider lost circulation and convective flow within the formation. It is observed that the effect of convective flow around the wellbore on calculated temperature is very small.

On the other hand, the estimated outlet mud temperatures match observed data quite well where lost circulation is taken into account compared to those where lost circulation is neglected.

2.2.4 MWDTEMP2

Takahashi et al. (1997) also developed a numerical inversion code, MWDTEMP2, to estimate formation temperature from the inlet and outlet mud temperatures while drilling. Mud inlet and mud outlet temperatures are calculated by GEOTEMP3 as input data for MWDTEMP2 to estimate formation temperatures. It is concluded that the accuracy of estimation improves if the bottom hole temperature data is used as input data in addition to mud inlet and outlet temperatures.

2.2.5 STATIC_TEMP

STATIC_TEMP is a computer code that uses five analytical methods to calculate static formation temperatures from actual bottom hole temperature data logged in geothermal wells. These methods are Horner plot method, Improved Horner method, Two point method, Spherical and radial heat flow method and Cylindrical square method including exponential, log linear and time-root approaches.

However, most of the methods require at least two or more temperature data measured at the same depth but at different times. Santoyo et al. (2000) concluded that STATIC_TEMP results were closer to the actual true formation temperatures except two-point method. Moreover, exponential approach of cylindrical square method presented the best results among them.

2.2.6 GTEMP1

GTEMP1 is a wellbore thermal simulation model that has been jointly developed by Maurer Engineering Inc. and the Department of Modern Mechanics of the University of Science and Technology of China (USTC) as part of the DEA-67 project. The program is written in Visual Basic (Maurer Engineering Inc. 1996).

GTEMPl, which is developed for improving the prediction of high downhole temperatures, models natural and forced convection and conduction within the wellbore and heat conduction within the surrounding rock formation.

A variety of well operations can be modeled including injection, production, forward and reverse circulation with liquid, gas, or two phase steam (Maurer Engineering Inc. 1996).

2.2.7 GTEMP Version 2

GTEMP Version 2 which will be called as GTEMP in this study is an upgraded and enhanced model of GTEMP1 (Maurer Engineering Inc. 2000). As mentioned in User's Manual of GTEMP (Maurer Engineering Inc. 2000), it has become more user-friendly and intuitive with new features like a modernized 32-bit operating system, a completely updated input/output interface, a utility for exporting results directly to Microsoft Office applications as a Word document, Excel workbook, and/or PowerPoint presentation and a comprehensive on-line help system which provides descriptions and instructions for every window and function.

CHAPTER 3

GEOLOGY OF FIELD

Turkey is located on the Alpine-Himalayan orogenic belt and has horst & graben systems, young volcanism and high geothermal potential (Simsek 2009). One of the most important geothermal provinces of Turkey is Büyük Menderes region that is placed at the western part of Turkey. Germencik-Ömerbeyli Geothermal Field is located at the west of Büyük Menderes Graben about 40 km from Aegean Sea (Simsek 2003) and within Ömerbeyli-Alangüllü residential areas in Aydın as can be seen in Figure 3.1 and has a high geothermal potential.

3.1 Field Discovery and Development

The field was discovered by MTA in 1967 and nine wells were drilled between 1982 and 1986 as shown in Table 3.1.

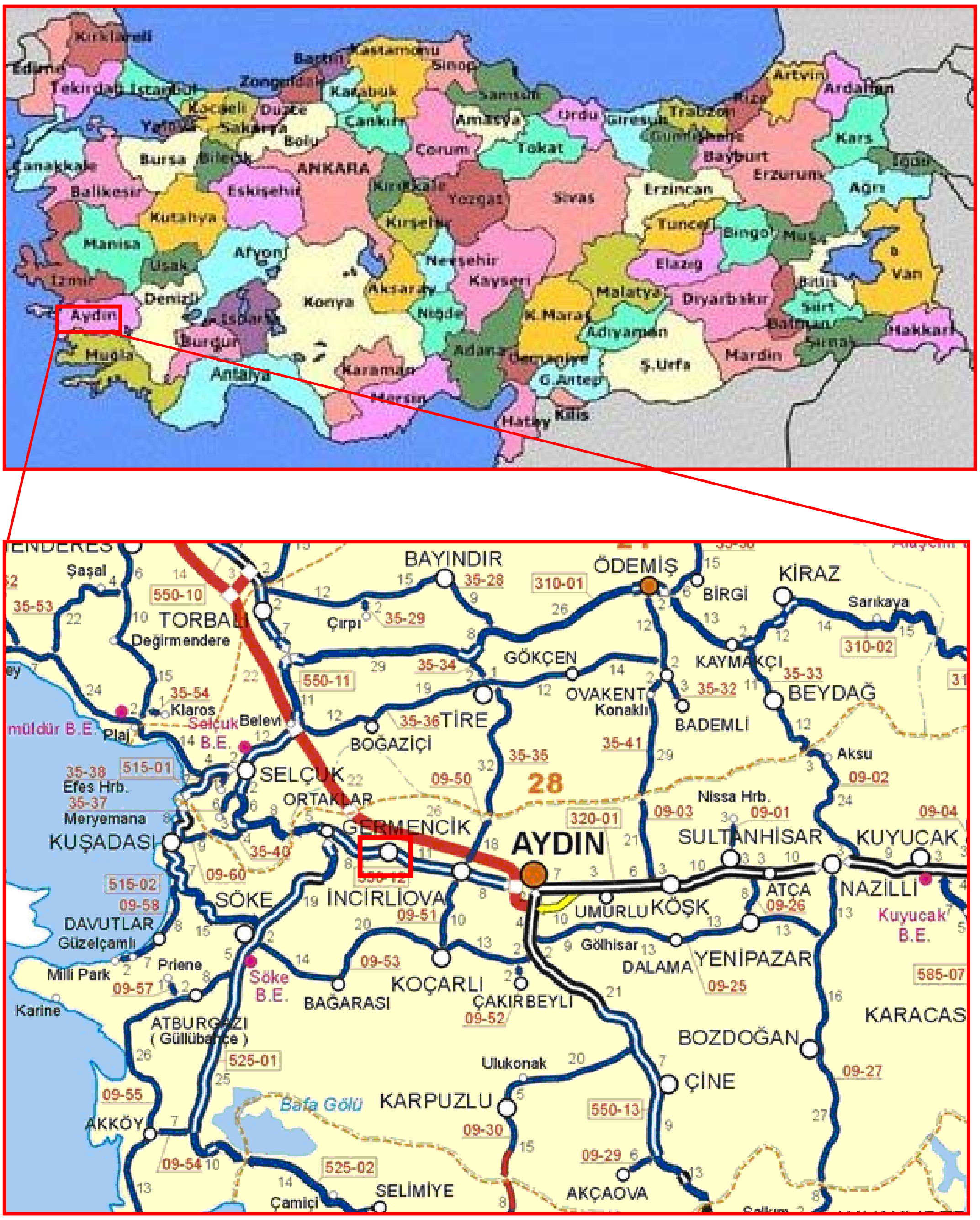


Figure 3.1. Location Map of Germencik-Ömerbeyli Geothermal Field.

Table 3.1. Wells drilled in Germencik-Ömerbeyli Geothermal Field by MTA (GÜRİŞ 2009).

Well Number	Depth (m)	Reservoir Temperature (°C)	Date
ÖB-1	1001	203	1982
ÖB-2	975	232	1982
ÖB-3	1195	232	1983
ÖB-4	285	217	1984
ÖB-5	1302	219	1984
ÖB-6	1100	221	1984
ÖB-7	2398	227	1985
ÖB-8	2000	221	1986
ÖB-9	1466	213	1986

After that, GÜRİŞ Construction And Engineering Co. Inc. has become the operator of the field and nine more wells were drilled between 2007 and 2008 as can be seen in Table 3.2.

3.2 Geologic Definition of Germencik-Ömerbeyli Geothermal Field

The authors that studied the geology of Germencik-Ömerbeyli Geothermal Field agree that the field consists of two reservoirs and generally the deepest reservoir is composed of Paleozoic aged gneiss, marble and schist which are named as Menderes Massif metamorphics, whereas the shallow reservoir is composed of Miocene to Pliocene aged sandstones and conglomerates.

Table 3.2. Wells Drilled in Germencik-Ömerbeyli Geothermal Field by GÜRİŞ (GÜRİŞ 2009).

Well Number	Depth (m)	Reservoir Temperature (°C)	Date
ÖB-10	1524	224	2007
ÖB-11	965	210	2007
ÖB-14	1205	228	2007
ÖB-17	1706	228	2008
ÖB-19	1651	227	2008
AG-22	2260	205	2008
AG-24	1252	199	2008
AG-25	1838	191	2008
AG-26	2432	195	2008

For the deepest reservoir; Filiz et al. (2000) stated that it is formed of Paleozoic aged Menderes Massif rocks which include fractured gneiss, quartz schist, and karstic marbles whereas the gneisses have been thrust over the schists.

Similarly, Özgür (2003) stated that the deep reservoir rocks are Paleozoic aged metamorphic rocks which are marble, quartzite and mica schist. And Şimşek (2003) defined the deepest reservoir as Paleozoic aged marble, quartzite and schist with a reservoir temperature between 216-232°C.

For the shallow reservoir; Filiz et al. (2000) stated that it is formed of Neogene aged sandstones and conglomerates. Similarly, Özgür (2003) stated that they are Miocene to Pliocene aged conglomerates. And Şimşek (2003) defined the shallow reservoir as Miocene aged conglomerates with a reservoir temperature between 203-214°C.

For the cap rocks; Filiz et al. (2000) stated that it is formed of Neogene aged impermeable claystone and mudstone. And Şimşek (2003) defined the cap rocks as Miocene and Pliocene aged sedimentary rocks.

As it is mentioned above, the deepest reservoir is formed of Menderes Massif metamorphics. Serpen et al. (2000) stated that “Menderes Massif, being one of the largest metamorphic massifs in Turkey, measures roughly 200 km N-S, and about 150 km E-W in western Anatolia and can described as a dome-like structure, broken by faulting during the Alpine orogeny. Moreover, Menderes Massif includes a core of paragneisses and orthogneisses wrapped in a variety of schists and dolomitic marbles”.

3.3 Fluid Definition of Germencik-Ömerbeyli Geothermal Field

Filiz et al. (2000) stated that the reservoir rock is recharged with meteoric waters along faults and fracture zones. 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, 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.

Şimşek (2003) stated that the type of the geothermal waters in Aydın region is generally of the Na-Ca-HCO3. Moreover, Şimşek (2003) mentioned that 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.

CHAPTER 4

STATEMENT OF THE PROBLEM

Geothermal drilling has many different aspects compared to conventional oil and gas drilling. In geothermal wells, high mud and formation temperatures are the biggest concern for the decision to continue drilling or not since they indicate lithology variations, hot water and steam quality and affect drilling operations and equipment.

Moreover, mud losses are highly encountered in geothermal wells and the risk of stuck pipe increases due to the lack of cuttings transportation while drilling with partial or total loss. Additionally, mud temperature data can not be gathered in total loss situations since mud does not return to surface.

Therefore estimation of formation temperature while drilling especially in partial or total loss sections plays an important role in controlling equipment and operations or deciding on the final depth of the well which can affect project design and cost. Therefore several methods and models are developed to estimate formation temperature. However most of them are considered as time consuming and not easy to practice while drilling at field.

CHAPTER 5

THEORY OF GTEMP

5.1 Introduction to GTEMP

GTEMP is a downhole thermal simulation model which is developed for improving the prediction of downhole temperatures. Unless otherwise stated, all the subject headings of this Chapter 5 are briefly summarized from GTEMP User's Manual (Maurer Engineering Inc. 2000). The program models natural and forced convection, conduction within the wellbore, and heat conduction within the surrounding rock formation. The operations that can be modeled include liquid or steam injection, liquid or steam production and forward and reverse circulation with liquid or gas. GTEMP is coded in Visual Basic 6.

As indicated in User's Manual of GTEMP (Maurer Engineering Inc. 2000), GTEMP models fully-transient heat conduction for wellbore flow stream and rock formations. Moreover, for circulation operations GTEMP takes into account the mixing and cooling at the surface fluid tanks.

5.2 Theory of GTEMP

5.2.1 Wellbore Description

Wellbore description for circulation is shown in Figure 5.1. Drill string is at the center and outside the borehole is the rock formation. The casings are production, intermediate, surface and conductor, respectively.

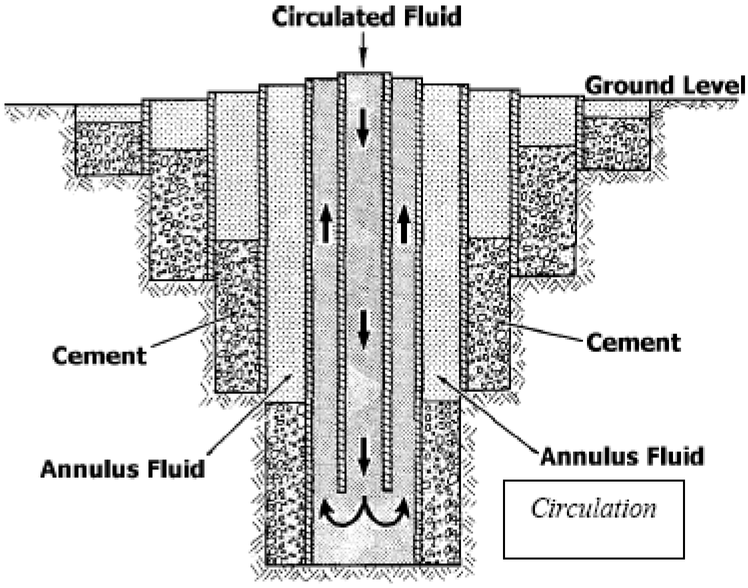


Figure 5.1. Wellbore Description for Circulation (Maurer Engineering Inc. 2000).

5.2.2 Numerical Grid

GTEMP computes three temperatures in the wellbore at each depth and the location of the temperature nodes are shown in Figure 5.2. 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. Fluid and rock cells are selected for computing the node temperatures and the radial boundaries of these cells are located at the well centerline, at the outside surface of the drill string and at the first casing string. The location of the outer boundary of the third cell is the radial position outside of the wellbore/rock interface. The distance from the borehole wall to the outer boundary is equal to the distance from the outside of the first casing string to the borehole wall

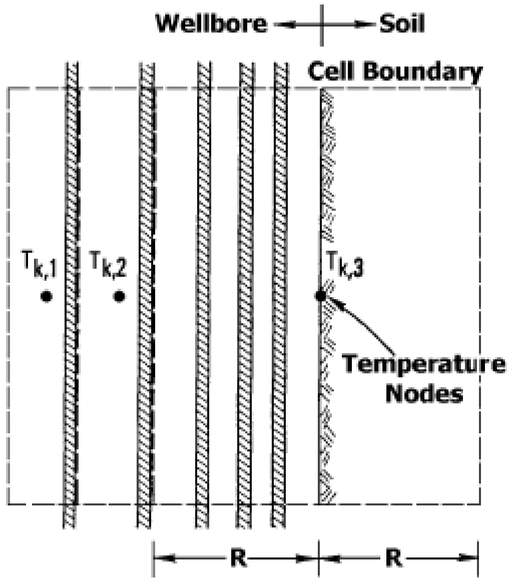


Figure 5.2. Locations of Temperature Nodes (Maurer Engineering Inc. 2000).

5.2.3 Fluid Properties

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.

5.2.4 Thermal Conductance

The heat flowing between the rock and the well passes through several materials including steel, cement, fluid and rock. To describe the transfer of heat between the wellbore and rock, thermal conductance is formulated from the properties of these materials and well geometry. The rate of heat flow is written as:

$$q = U \, \Delta z \, \Delta T \tag{1}$$

where U is the overall heat transfer coefficient, Δz is the vertical length interval and ΔT is the temperature difference.

U is explained in User's Manual of GTEMP1 (Maurer Engineering Inc. 1996) as below. And it is stated that "This particular formulation is for fluid flowing inside a pipe with convection coefficient h and thermal conductivities, k_1, k_2, etc. k_1 may be the conductivity of steel, k_2 may relate to the natural convection occurring in the fluid in one of the annular regions, and h is the convection coefficient." Moreover r is the subscript denoting radial direction (Wooley 1979).

$$U = 2\Pi \left[\frac{1}{hr_1} + \frac{\ln(r_2/r_1)}{k_1} + \frac{\ln(r_3/r_2)}{k_2} + \ldots \right]^{-1} \tag{2}$$

5.2.5 Convection

Heat transfer from a well to the surrounding rock formation is also influenced by convection in wellbore fluids. Heat transfer occurring when fluid flows past a solid surface is called convection heat transfer. The rate of heat transfer through a solid surface is

$$q = h \, \Delta T \tag{3}$$

where ΔT is the temperature difference between the fluid and the solid, and h is the convection coefficient.

5.2.6 Energy Balance in a Fluid Cell

According to the first law of thermodynamics, energy must balance. Energy in a fluid cell obeys this law with the equation

$$T_{j,i}^{n+1} = A_{j,i} \quad T_{j-1,i}^{n+1} + \quad B_{j,i} \quad T_{j+1,i}^{n+1} + C_{j,i} \quad T_{j,i-1}^{n+1} + \quad D_{j,i} \quad T_{j,i+1}^{n+1} + \\ E_{j,i} \quad \left(T_{j,i}^{n} + T_{j-1,i}^{n}\right) \quad + F_{j,i} \quad T_{j-1,i-1}^{n+1} + \quad G_{j,i} \quad T_{j-1,i+1}^{n+1} \tag{4}$$

It is stated in User's Manual of GTEMP (Maurer Engineering Inc. 2000) that "This equation can be written for every position of j, i in the wellbore to yield a system of simultaneous linear algebraic equations. The unknowns are the temperatures at each node at time step n+1 for a total of $3N_z$ equations and unknowns, where N_z is the number of nodes in the vertical direction." Moreover the coefficients $A_{j,i}$, $B_{j,i}$ … are constants to be evaluated from thermal properties and dimensions (Wooley 1979).

5.2.7 Energy Balance in a Rock Cell

For each cell containing rock, energy balance is also required. This requirement is met by:

$$T_{j,i}^{n+1} = A_{j,i} \quad T_{j-1,i}^{n+1} + \quad B_{j,i} \quad T_{j+1,i}^{n+1} + C_{j,i} \quad T_{j,i-1}^{n+1} + \quad D_{j,i} \quad T_{j,i+1}^{n+1} + \quad E_{j,i} \quad T_{j,i}^{n} \tag{5}$$

It is stated in User's Manual of GTEMP (Maurer Engineering Inc. 2000) that "This equation may be applied to all nodes in the formation to produce a system of $(N_r - 3) \cdot Nz$ simultaneous algebraic equations, where N_r is the number of nodes in the radial direction. An equal number of unknowns exist for temperatures at the nodes.

These equations may be applied to every temperature node to form a system of simultaneous linear algebraic equations and can be solved for finding the new temperature at each new time step, n+1.”

5.2.8 Surface Mud Tank

GTEMP calculates the temperature of the mixed fluid at the surface tank as below:

$$\overline{T} = \frac{T_o(V - Qdt)\rho C_p + (Q\rho C_p + Q_2\rho_2 C_{p2})dtT_{out}}{V\rho C_p + Q_2\rho_2 C_{p2}dt} \tag{6}$$

where the parameters of the equation are as stated in User’s Manual of GTEMP1 (Maurer Engineering Inc. 1996).

T_o = fluid temperature in the tank
Q = fluid volume flow rate
Q_2 = volume flow rate of secondary flow (influx)
ρ = circulation fluid density
ρ_2 = secondary fluid density
C_p = circulation fluid specific heat capacity
C_{P2} = secondary fluid specific heat capacity
dt = circulation time increment
T_{out} = exit temperature of fluid
V = surface tank fluid volume

5.3 Input Data of GTEMP

GTEMP consists of six input pages for input data to calculate temperatures after a period of fluid movement in a wellbore. These pages are named as Project, Survey, Tubulars, Welbore, Fluids and Thermal.

Project page includes Project Description to store project documentation and Operation Options to select one of the seven operating modes which are Liquid Forward Circulation, Liquid Reverse Circulation, Liquid Injection, Liquid Production, Gas Forward Circulation, Steam Production and Steam Injection. Operation option defines flow and thermal boundary conditions for the analysis.

Survey page is to describe wellbore inclination and trajectory. By entering the survey data GTEMP plots three graphs which are Dogleg severity with depth, Inclination angle with depth, and 2D wellbore profile.

In the Tubulars page, the description of the string that is in the wellbore conducting the circulation is required in detail. The tubular database of the program can be used for importing data for a wide variety of pipe.

In the Wellbore page, to calculate thermal conductivity, casing geometry and cement placement along the wellbore is specified. The casing database of the program can be used for importing data for a wide variety of casings. Moreover, to provide boundary conditions, the undisturbed geothermal temperatures at the surface and at the bottom of the hole are required. In the Wellbore Geometry part, the diameter of the surface hole is required in order to define the outer limit of the radial zone where casing and cement is present.

In the Fluid Properties table of Fluids page, Bingham Plastic or Power-Law model is selected as mud rheology. Also Newtonian fluids can be specified by selecting

Bingham Plastic as the rheology model and entering zero for yield point. The parameters in addition to density are plastic viscosity and yield point for Bingham Plastic model and consistency coefficient (K) and flow behavior index (n) for Power-Law model. Bingham Plastic is stated as the most common rheological model for drilling mud. Moreover, the program can select the rheology model through the viscometer readings. In the Operation Schedule table, inlet temperature, flow rate and flow period are required as input data. The fluid present inside the drill string and the annulus prior to the beginning of the operation is defined in the Fluid Initially in Tubing and Casing part of Fluids page.

Another feature of GTEMP is that the final temperature of the mixed fluid in the mud tank can be predicted. The required parameters for tank mixed option at the Temperature at Inlet for Circulation part are tank volume, tank fluid surface area, tank environmental temperature and heat transfer coefficient. During fluid circulation, the temperature of the fluid at the inlet will often change due to the fact that circulated fluids are mixed with the fluid in the tank. Because fluid temperature in the tank is different from the ambient temperature, heat transfer will occur between the tank and its environment. In order to model the effect of this heat transfer the Tank Mixed option can be selected. This effect is neglected by selecting Single Pass option and the fluid will be treated as if it were circulated only once through the well and the inlet temperature of fluid will remain the same as prescribed in the Operation Schedule table of Fluids page.

In the Thermal page, thermal properties of drill pipe and casing are entered. Moreover, rock properties like conductivity, heat capacity and density are entered by specifying the rock layers through the wellbore. The database of the program can be used to select representative data for several common metals and rocks.

By using Calculation Grid in the Options Menu, the number of grids used in the 3D temperature calculations can be arranged. The size of the finite-element temperature matrix and therefore the resolution of the results are increased if a higher number of radial grids and a smaller vertical grid size are selected.

5.4 Output Data of GTEMP

A variety of output windows are generated by GTEMP which are Thermal Analysis, Pressure and Temperature at Fixed Time, 3D Temperature Distribution, and Pressure and Temperature at Fixed Depth.

In the Thermal Analysis window, Thermal Depth Graph shows the casing program along with cement columns and color-coded temperature of the fluid in the wellbore with depth. With this graph any specific depth and radius can be selected for detailed temperature analysis. Moreover there is a Radial Temperature Graph that shows temperature as a function of radius from the center of the wellbore where depth position is constant. Additionally, Measured Depth Temperature Graph shows temperature as a function of depth where the radial position from the center of the wellbore is constant.

In the Pressure and Temperature at Fixed Time window, temperatures in tubing and annulus are displayed with depth for one or more times which are specified on the Fluids page.

In the 3D Temperature Distribution window, the complete data matrix of temperature with depth, radius and time is shown in the 3D view. The operational time is initially set as the end of operation.

In the Pressure and Temperature at Fixed Depth window, a detailed temperature vs. time profile is shown for constant depth and time interval.

5.5 Assumptions in GTEMP

The assumptions of GTEMP are listed as below:

- At the Wellbore page, beyond the diameter of the surface hole from the center of the well only rock formation is assumed to be present.
- At the Fluid Initially in Tubing and Casing part of Fluids page, fluids present inside the drill string and the annulus prior to the beginning of the operation are assumed to be at geothermal temperature.
- 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.

CHAPTER 6

METHOD OF SOLUTION

Input data for this study is obtained from literature and personal communication with GÜRİŞ Engineering And Construction Co. Inc. Computer runs are performed for every depth couple selected. For the wells #3, #4, #5, #7 and #9; 32, 34, 28, 26 and 31 depth couples were selected respectively.

A depth couple consists of two depth points named as first and second depth. The circulation system starts with the first depth’s mud inlet temperature (MIT), measured at the mud tanks and travels through the well and enters the shale shakers where the second depth’s mud outlet temperature (MOT) is measured as shown in Figure 6.1. Therefore, 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. And regarding the output data, mud outlet temperature value is of the second depth.

Moreover, the depth points are chosen carefully from the points that the drilling continues without interruption and no new mud addition to the system occurred. The interval between these two depths varied between 2,5-15 m except the total loss section. Since no temperature measurement can be performed during the total loss, the last two depths that mud temperature is measured are chosen and the final depth of the well is extrapolated through the program.

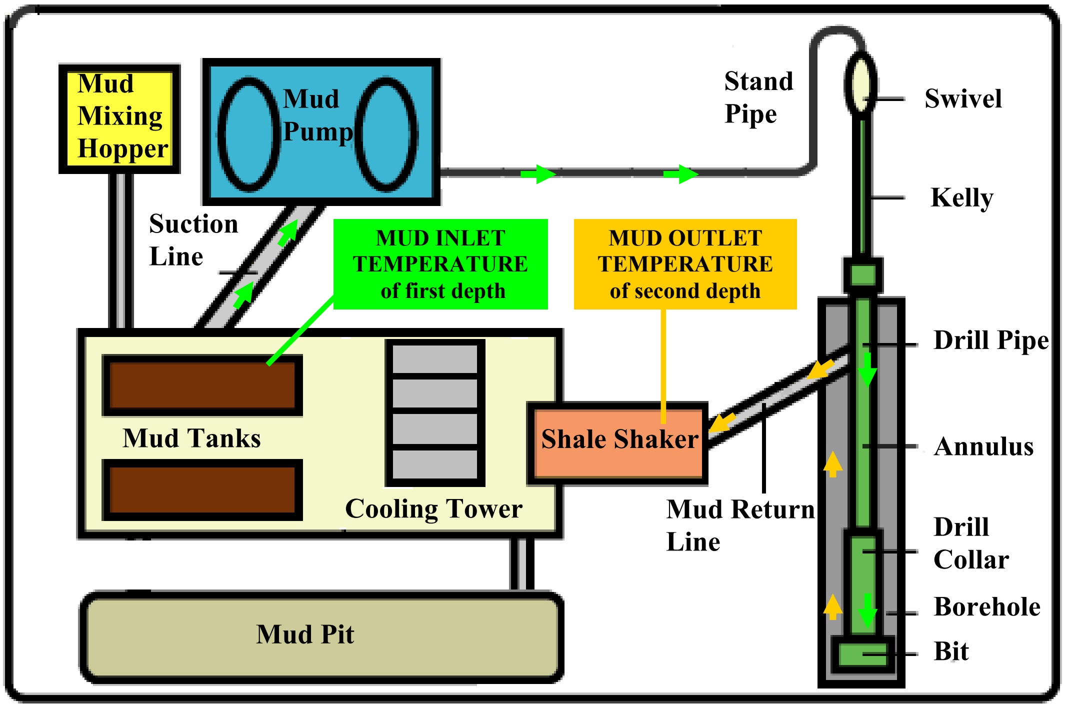


Figure 6.1. Mud Inlet and Outlet Temperatures and Their Measurement Places in the Circulation System (Modified from http://science.howstuffworks.com/oil-drilling4.htm 2001).

Computer simulation is developed in stages as can be seen in Figure 6.2. Input data is entered to the program for every depth couple. The object of computer run is to match the field and calculated mud outlet temperature of the second depth. To achieve this, bottom temperature input at the Wellbore page of the program is modified. The bottom temperature that realizes the match is accepted as formation temperature and the temperature inside the drill string at the bottom is accepted as bit temperature.

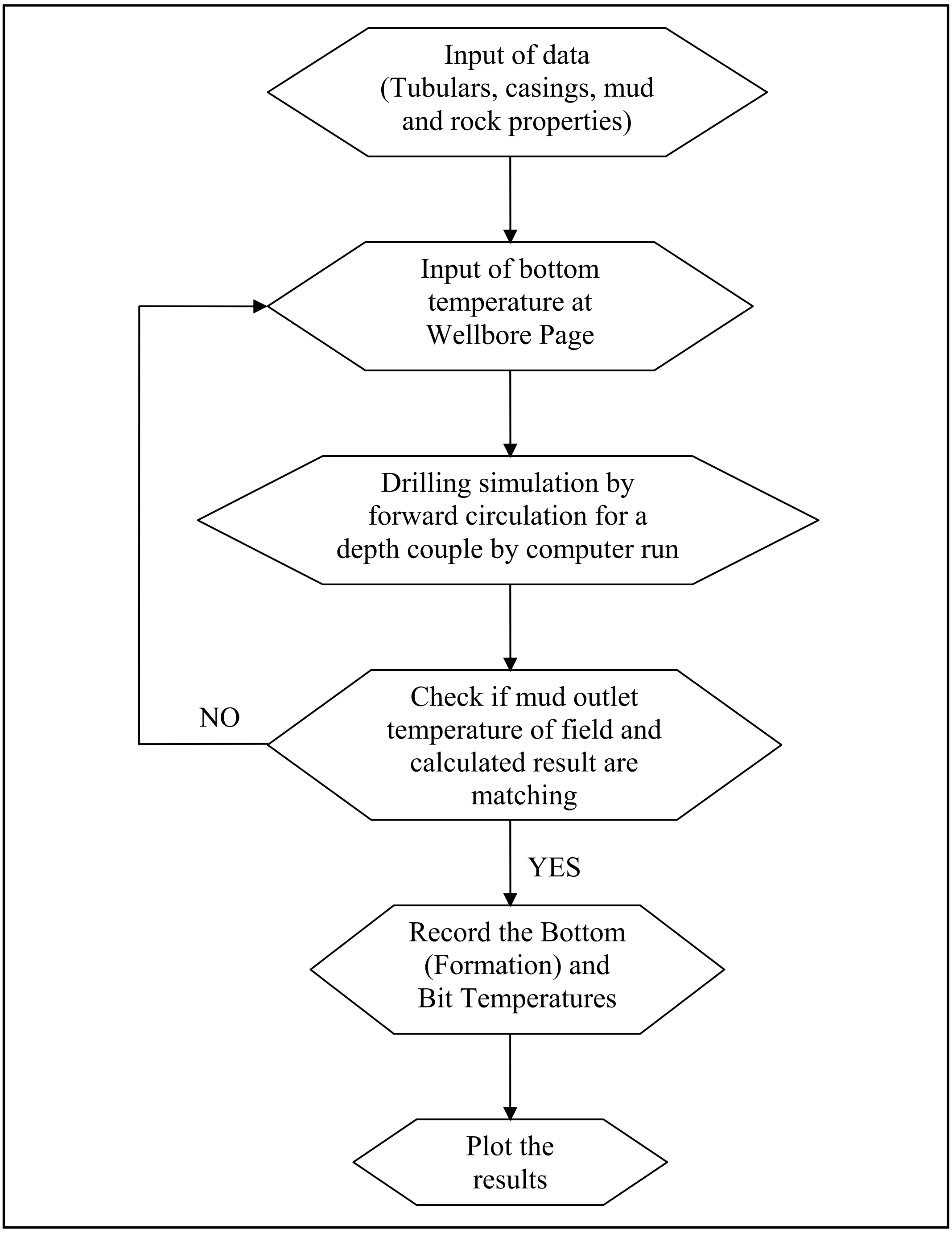


Figure 6.2. Method of Solution Flow Chart.

This process is performed for all the selected depth couples in a well and the results are documented in the form of plots of temperatures versus depth for five wells. Discussion and interpretation of results are presented for formation and bit temperature as a function of depth and mud inlet and outlet temperatures.

6.1 Drilling Data

6.1.1 Drilling Program in General

For this study, one shallow well, one deep well and three wells with medium depth are selected among the wells in Table 3.2 and named as #3, #4, #5, #7, #9 respectively. 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 according to daily drilling reports (GÜRİŞ 2010).

The mud type used during drilling the 26 in section is bentonite-water drilling fluid named as spud mud where the 17 ½ in, 12 ¼ in and 8 ½ in sections were drilled with lignosulfonate mud. Total loss sections were drilled with water. 20 in and 13 3/8 in casing is run in Sandstone, 9 5/8 in liner is run mostly in Gneiss and 7 in slotted liner is run in Marble-Schist and total loss formations according to daily drilling reports (GÜRİŞ 2010).

6.1.2 Cooling Tower

During drilling operations, cooling tower is used in order to decrease the temperature of the mud that is circulating as can be seen in Figure 6.3. The working principle of the cooling tower is that the mud is pumped on top of it and is allowed to drop downwards while bumping the grills.

Figure 6.3. Cooling Tower (GÜRİŞ Drilling Project 2007).

Therefore, the mud will cool down by enlarging its surface area. It is generally placed after the shale shakers and before the mud tanks in the circulation system in order to cool the mud before entering the well.

Since it is important to keep the temperature of the mud at a reasonable value during drilling or circulation, cooling tower is generally turned on when the mud outlet temperature reaches to 50-80 ºC.

The average temperature decrease between mud outlet and mud inlet temperatures when cooling tower is used and not used are collected from geology reports (GÜRİŞ 2010) and Tables 6.1 and 6.2 are formed.

Table 6.1. Average Temperature Decrease between MOT & MIT When Cooling Tower is used.

Cooling Tower Used	
Depth (m)	Average Decrease btw. MOT & MIT (°C)
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

Table 6.2. Average Temperature Decrease between MOT & MIT When Cooling Tower is not used.

Cooling Tower Not Used	
Depth (m)	Average Decrease btw. MOT & MIT (°C)
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

6.1.3 Formations Encountered During Drilling

The formations encountered during the drilling of these five wells can be listed from surface to bottom as Alluvium, Sandstone, Gneiss, Marble, Marble-Schist and Schist according to geology reports (GÜRİŞ 2010).

Alluvium (Quaternary): Composed of coarse sand, conglomerate, clay and silt. Grains are composed of quartz, quartz schist and mica schist. It is loose cemented and oxidation is present.

Sandstone (Plio-quaternary, Pliocene, Miocene): Composed of sandstone, conglomerate, clay and silt.

Gneiss (Paleozoic): Composed of albite, quartz, muscovite, biotite, feldspar and gneiss.

Marble (Paleozoic): Composed of white, candy textured marble.

Marble-Schist (Paleozoic): Composed of white-grey-black-mottled marble, quartz, quartz schist, chlorite schist and mica schist.

Schist (Paleozoic): Quartz-graphite-biotite-muscovite schist, calc schist, chlorite schist, epidote schist and amphibole schist.

6.2 Input Data

6.2.1 Project Page

In Project page as shown in Figure 6.4, the project is described and the operation option is selected as Liquid Forward Circulation. The fluid enters the well at the surface, travels down the drill string, and returns up the annulus to the surface.

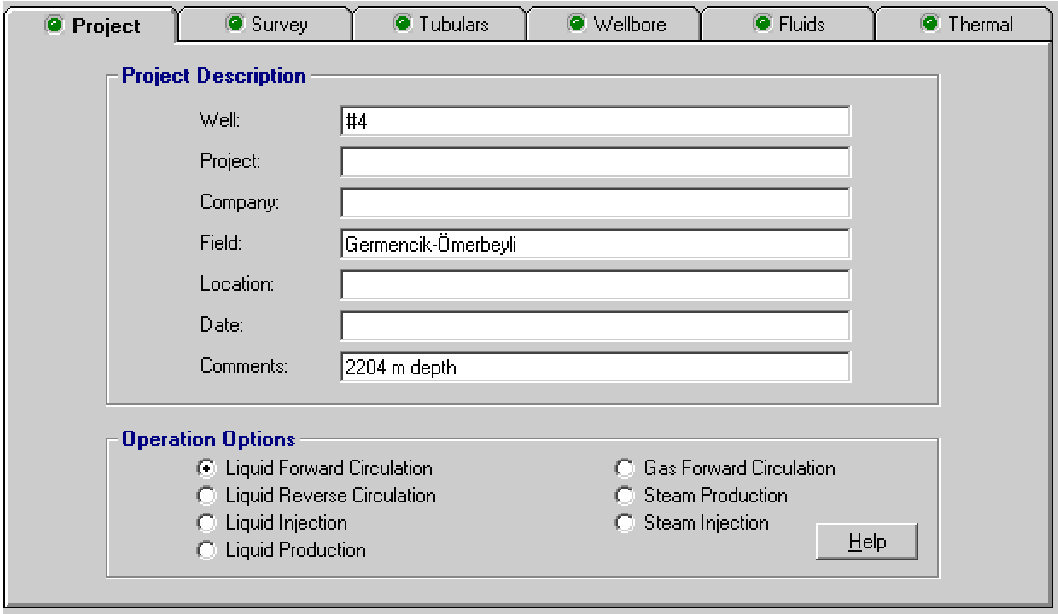


Figure 6.4. Project Page of GTEMP.

6.2.2 Survey Page

In Survey page as shown in Figure 6.5, measured depth (m), inclination (degree) and azimuth (degree) values are entered. In this study, inclination and azimuth values are taken as zero. The true vertical depth (m) and dogleg severity (deg/100 ft) are the calculated values.

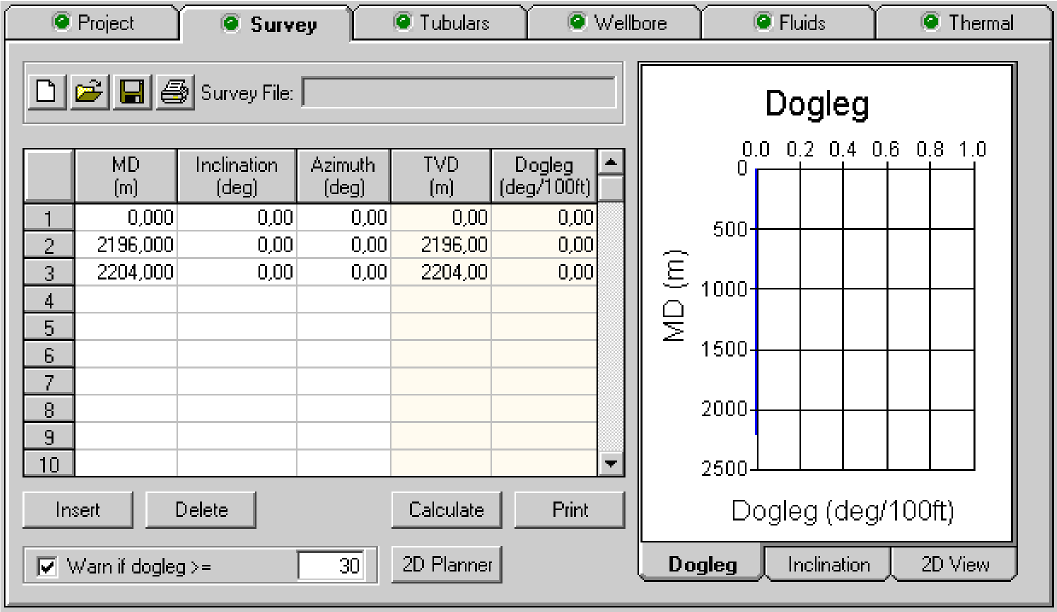


Figure 6.5. Survey Page of GTEMP.

6.2.3 Tubulars Page

In Tubulars page as can be seen in Figure 6.6, drill pipe data which are set depth (m), outer diameter (in), inner diameter (in) and cement length (m) are entered in the order of from surface to bottom.

For all tubulars, cement length is taken as zero and the values in Table 6.3 are used for outer and inner diameters.

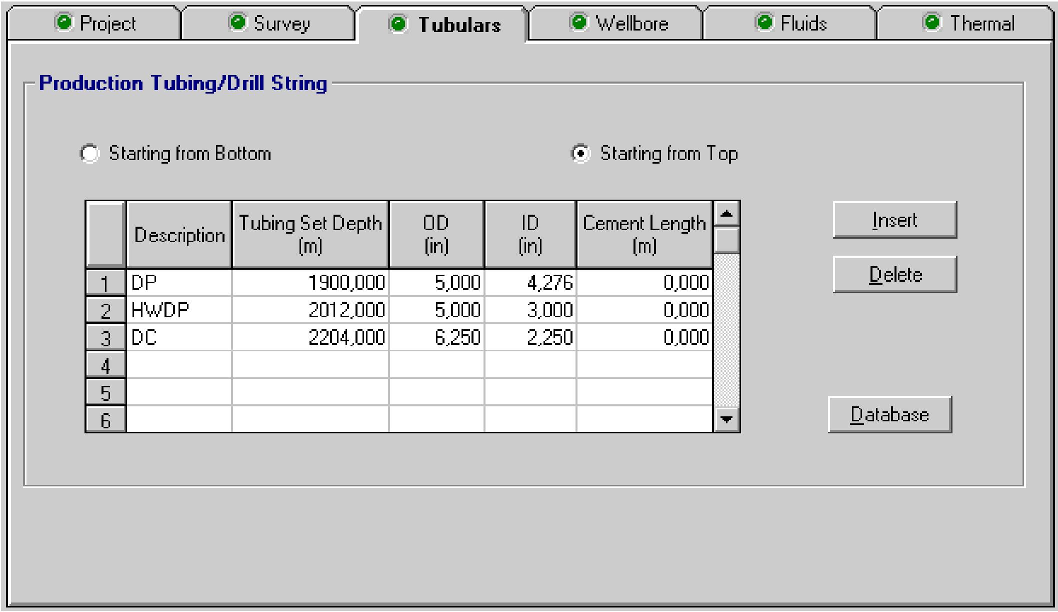


Figure 6.6. Tubulars Page of GTEMP.

Table 6.3. Specification of Tubulars (GÜRİŞ 2010).

OD (in)	ID (in)
9,50 DC	3,000
8,00 DC	3,000
6,50 DC	2,250
6,25 DC	2,250
5,00 HWDP	3,000
5,00 DP	4,276

6.2.4 Wellbore Page

In Wellbore page as can be seen in Figure 6.7, casing data which are casing set depth (m), outer diameter (in), inner diameter (in) and cement length (m) are entered in the order of from smallest to largest. For the casings, the cement length is taken from the set depth to the surface except the conductor pipe. For the liners, cement length is taken from the set depth to the depth the liner is hanged. Diameter of surface hole is accepted as 32 in. And the outer and inner diameters that are in Table 6.4 are used for casings.

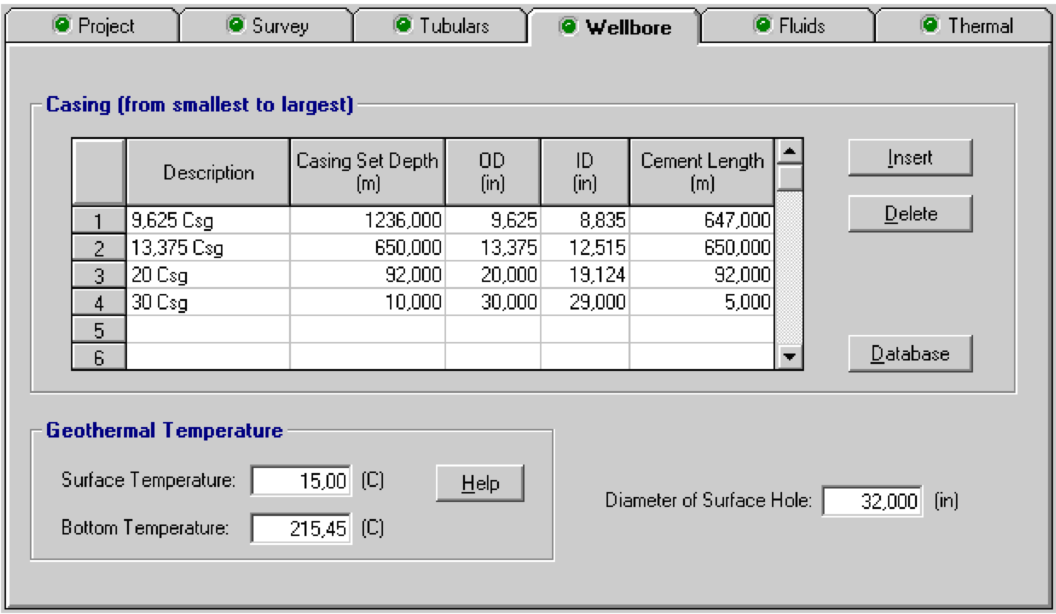


Figure 6.7. Wellbore Page of GTEMP.

Table 6.4. Specification of Casings (GÜRİŞ 2010).

CSG OD (in)	ID (in)
30,000	29,000
20,000	19,124
13,375	12,515
9,625	8,835
7,000	6,276

According to the World Soil Resources' Soil Temperature Regimes Map, Aydın region is standing in the thermic region as can be seen in Figure 6.8. It is stated that the mean annual soil temperature is 15 °C or higher but lower than 22 °C, and the difference between mean summer and mean winter soil temperatures is more than 6 °C either at a depth of 50 cm from the soil surface or at a densic, lithic, or paralithic contact, whichever is shallower (USDA-NRCS 2010).

As indicated in Keys to Soil Taxonomy (USDA-NRCS 2010), a densic contact is a contact between soil and densic materials which are relatively unaltered materials that have a non-cemented rupture-resistance class. A lithic contact is the boundary between soil and a coherent underlying material. A paralithic (lithic-like) contact is a contact between soil and paralithic materials which are relatively unaltered materials that have an extremely weakly cemented to moderately cemented rupture-resistance class.

For the wells drilled during the months between October and March, the surface temperature is accepted as 15 °C; and for the ones drilled between April and September, it is accepted as 22 °C.

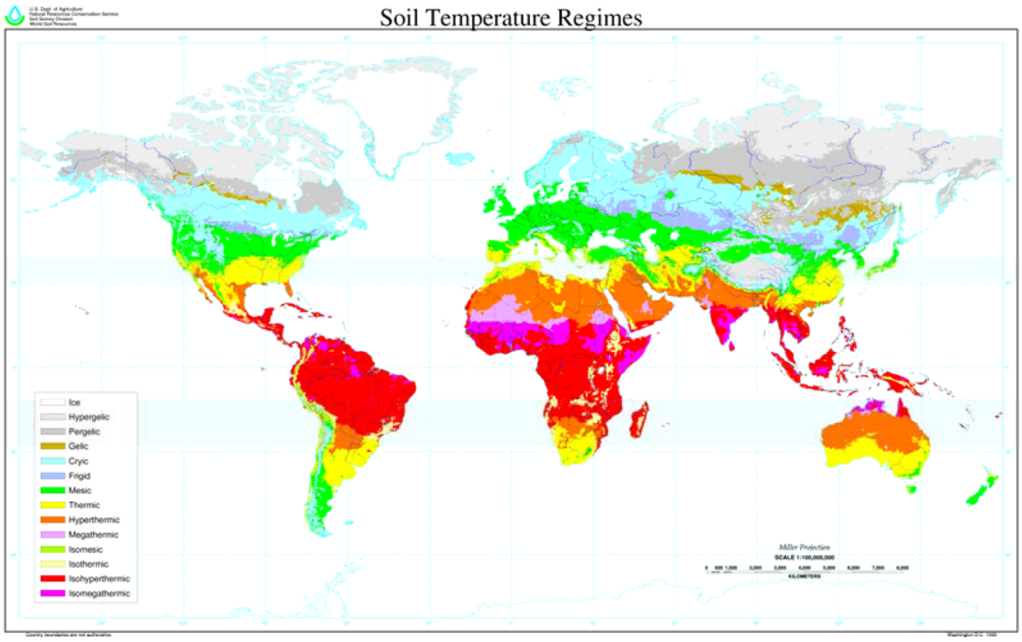


Figure 6.8. Soil Temperature Regimes Map (USDA-NRCS 1999).

As it is explained before, the bottom temperature is the one that a match is obtained between the calculated and the field measured mud outlet temperature.

6.2.5 Fluids Page

In Fluids page as shown in Figure 6.9, mud rheology model is selected and the values for density, viscosity and yield point are entered. In this study, mud rheology model is selected as Bingham Plastic since there is not significant difference between the results of Bingham Plastic and Power-Law. Besides, GTEMP also selects Bingham Plastic as rheology model with two viscometer readings as can be seen in Figure 6.10.

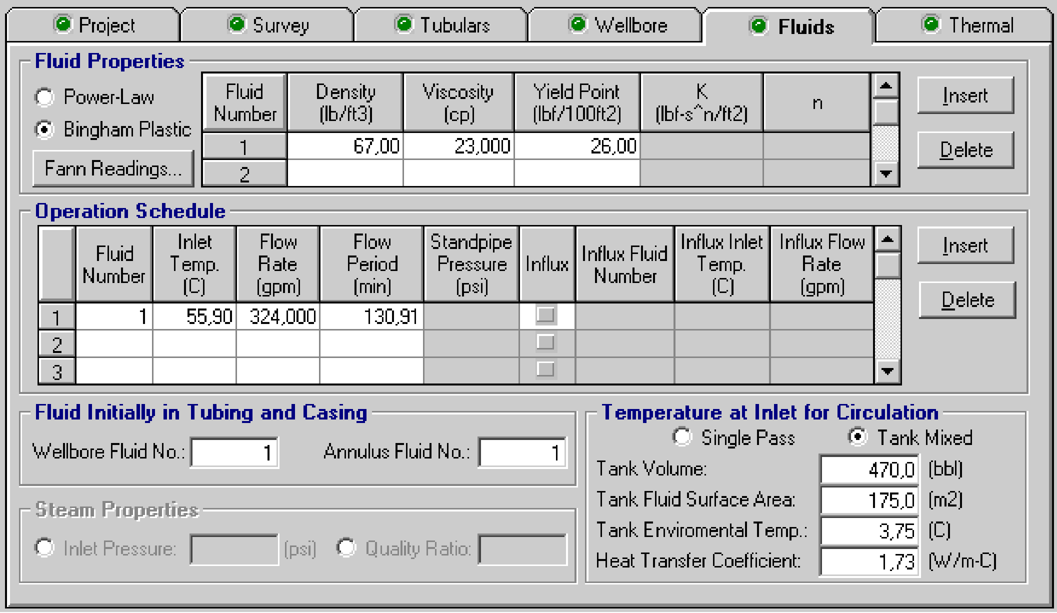


Figure 6.9. Fluids Page of GTEMP.

In the Operation Schedule table, mud inlet temperature (°C), flow rate (gpm), and flow period (min) values are entered. Flow period is considered as the time passed while drilling between the two depth points and calculated by dividing the drilled meterage between these depths to the rate of penetration.

In order to consider the heat transfer between the tank and its environment, tank mixed option is selected. The volume and fluid surface area of the tanks including sand trap, precipitation tank and suction tank are calculated as 470 bbl and 175 m^2. Tank environmental temperature is the average of the environment temperatures measured at surface that corresponds to the two depths of a depth couple. Heat transfer coefficient is taken as 1,73 W/m-°C.

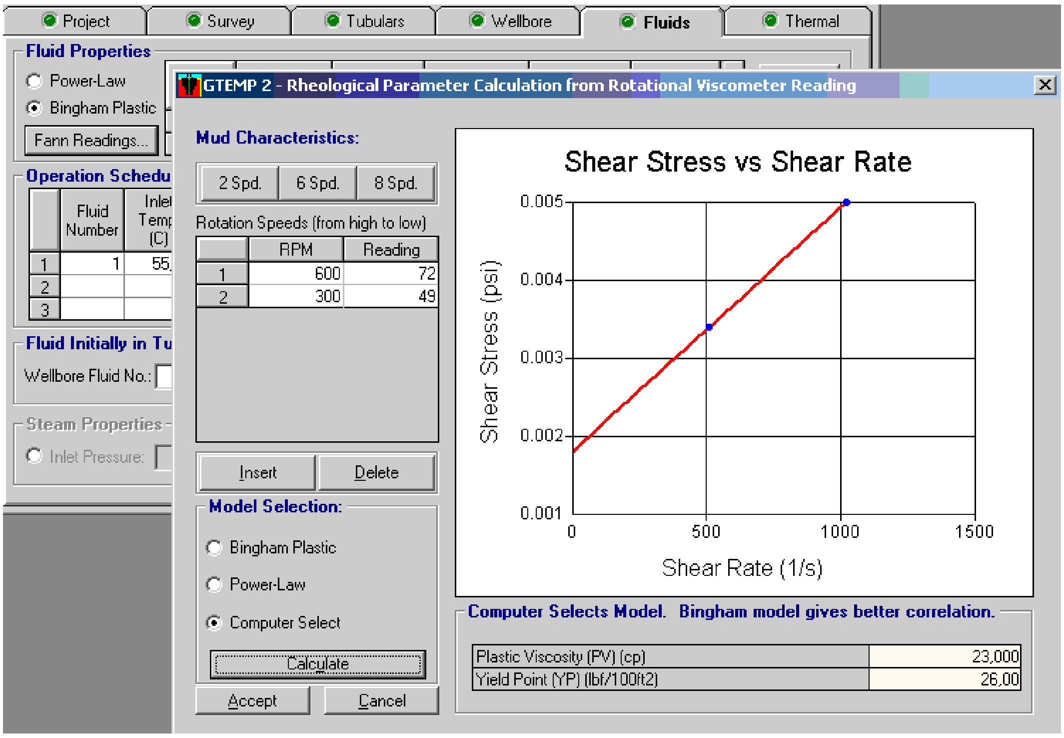


Figure 6.10. Computer Selects Rheology Model.

6.2.6 Thermal Page

In Thermal page as shown in Figure 6.11, tubing and casing thermal properties such as conductivity (Btu/h-ft-F), heat capacity (Btu/lb-F) and density (lb/ft^3) are entered by using database of the program.

All required properties for Alluvium and Sandstone are obtained from the database of the program. For the other formations, a literature survey is conducted and the values are shown in Table 6.5.

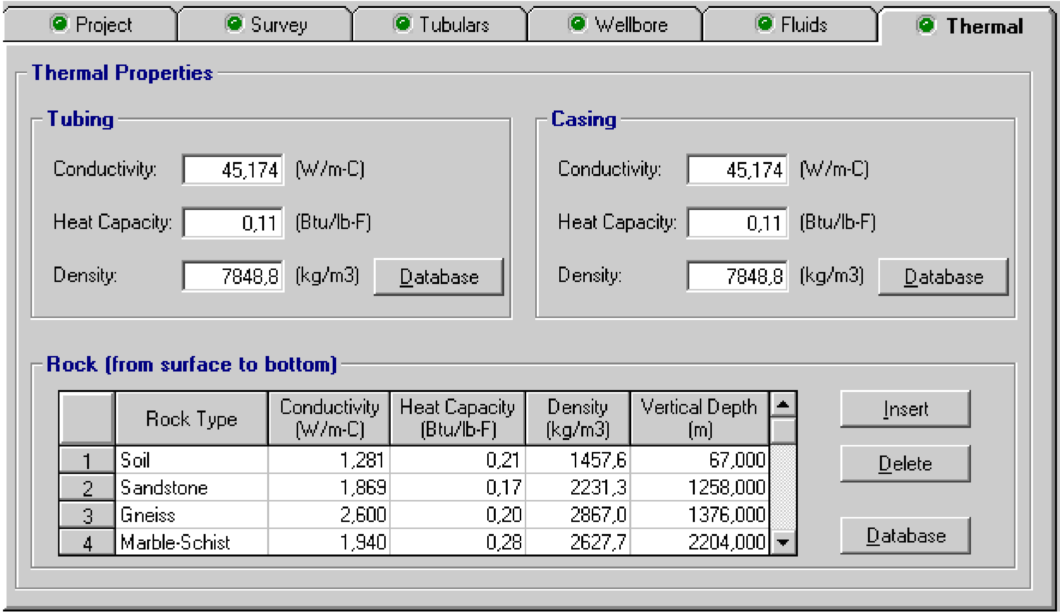


Figure 6.11. Thermal Page of GTEMP.

Table 6.5. Rock Properties.

Formation	Conductivity (W/m-°C)	Heat Capacity (Btu/lb-F)	Density (kg/m^3)
Alluvium	1,281 (1)	0,21 (1)	1457,6 (1)
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 and Konrad 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).

Moreover, for the marble-schist formation, the percentage of marble and schist are calculated from geology reports (GÜRİŞ 2010) through a defined path as shown in Table 6.6. And according to the percentages, weighted averages of the properties of marble-schist formations are calculated for every well as shown in Table 6.7.

Table 6.6. Percentage of Marble and Schist in a Marble-Schist Formation.

Formation Definition	Marble Percentage (%)	Schist Percentage (%)
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

Table 6.7. Weighted Averages of the Properties of Marble-Schist Formation.

Well No	Marble Percentage (%)	Schist Percentage (%)	Conductivity (W/m-°C)	Heat Capacity (Btu/lb-F)	Density (kg/m3)
#3	36	64	2,11	0,27	2618,73
#4	25,66	74,34	1,94	0,28	2627,68
#5	47,8	52,2	2,31	0,26	2608,41
#7	43,45	56,55	2,24	0,26	2612,19
#9	52,42	47,58	2,39	0,25	2604,39

6.3 Assumptions for Input Data

- In Tubulars Page, the length of kelly is assumed to be as drill collar, heavy weight drill pipe or drill pipe whichever comes afterwards the kelly.
- Since liner can not be defined through the program, 9 5/8 in liner is assumed as casing to surface in Tubulars page.
- Bit diameter can not be defined through the program. Therefore the sections drilled are of the diameter of the previous casing.
- In Fluids Page, mud rheology is assumed as Bingham Plastic. However, during the drilling of total loss sections, water is used with the properties of Density: 62,4 lb/ft^3, PV:1 cp, YP:0 lbf/100 ft^2.
- Since no information can be obtained from the literature and the database of the program about the properties of Alluvium; soil properties from database are used for Alluvium in Thermal page.
- Since no cutting comes to surface, total loss sections are accepted as the continuation of the previous formation.
- Total loss or partial loss is not defined in program. Therefore drilling fluid invading the formation is neglected.

- Drilling is not defined in program. Therefore drilling is simulated by liquid forward circulation option.
- Cooling of mud is defined only in surface mud tanks and cooling tower is not defined in the program. Due to this reason, cooling tower effect is reflected by modifying mud temperatures in Case 2 as explained in Section 6.5 Case Definition.
- In Well #7 and #9, mud inlet temperature data was lacking at some depths. Lacking mud inlet temperatures are calculated by decreasing the mud outlet temperature with the average temperature values as shown in Tables 6.1 and 6.2 concerning the cooling tower is used or not.
- The temperature decreases between MOT and MIT mentioned in Tables 6.1 and 6.2 are assumed as same for different environment conditions such as winter, summer, day, night, windy, sunny.

6.4 Output Data

After the program is run, an output window is obtained as can be seen in Figure 6.12. The temperatures estimated by GTEMP are obtained from 3D Temperature Distribution Window as shown in Figure 6.13. In 3D Temperature Table, as can be seen in Figures 6.14 and 6.15, mud outlet temperature calculated by the GTEMP is matched with field measurement by modifying bottom temperature in the Wellbore page. Temperatures inside drill string and annulus, especially the calculated mud outlet temperature can also be seen from Temperature at Fixed Time Window in Figure 6.16.

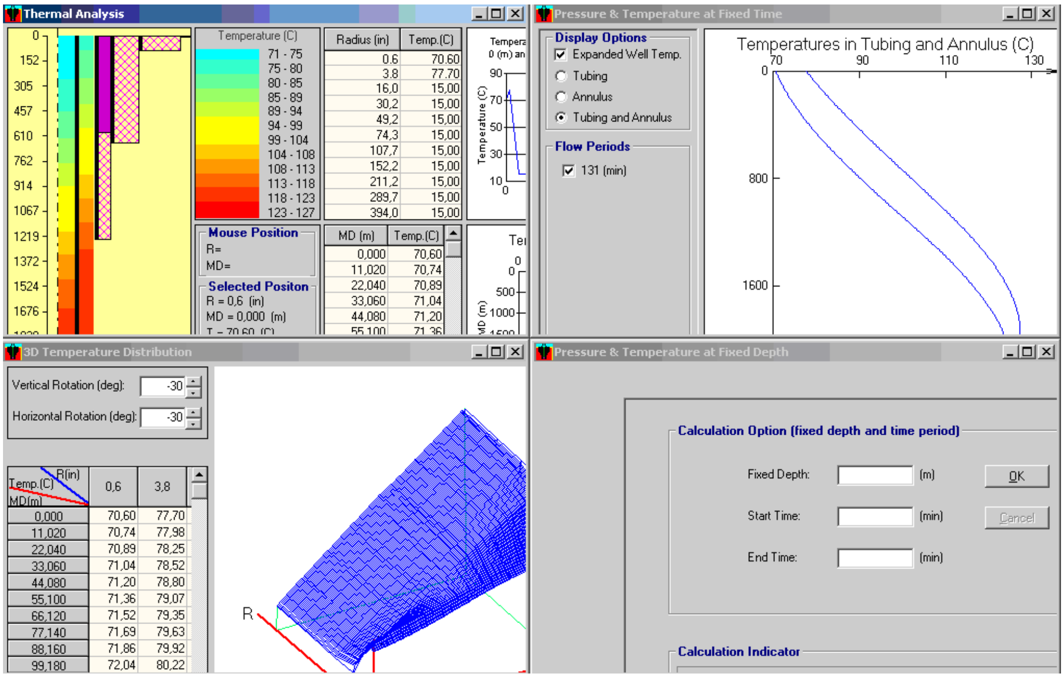


Figure 6.12. Output Window.

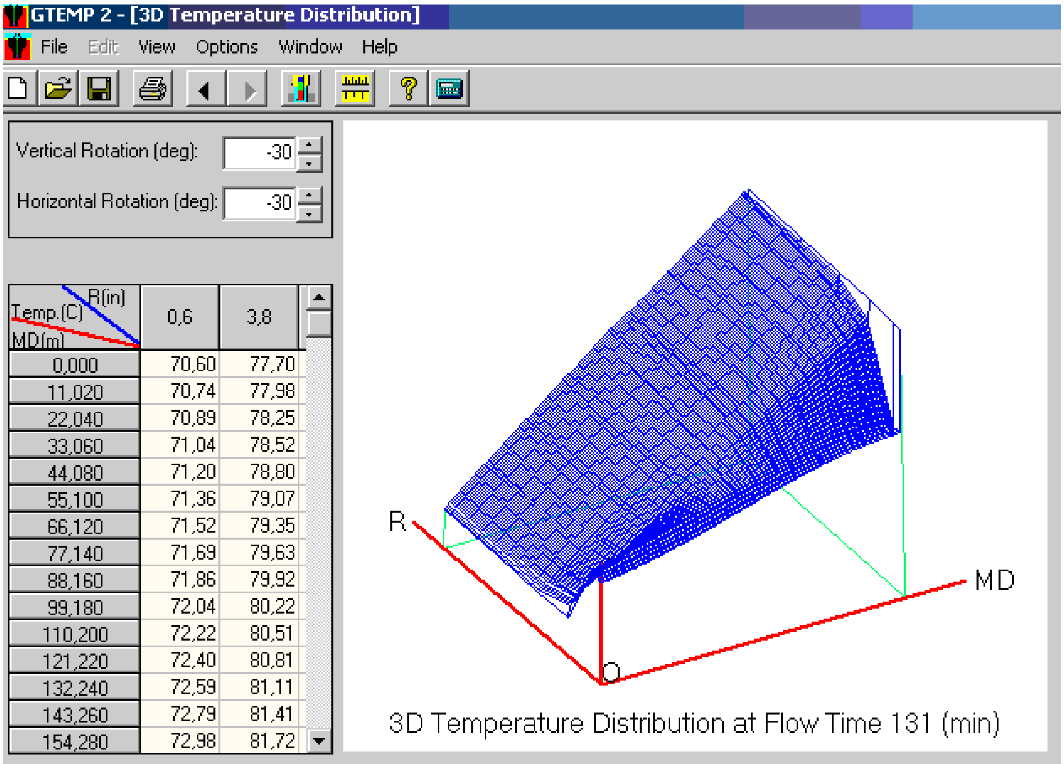
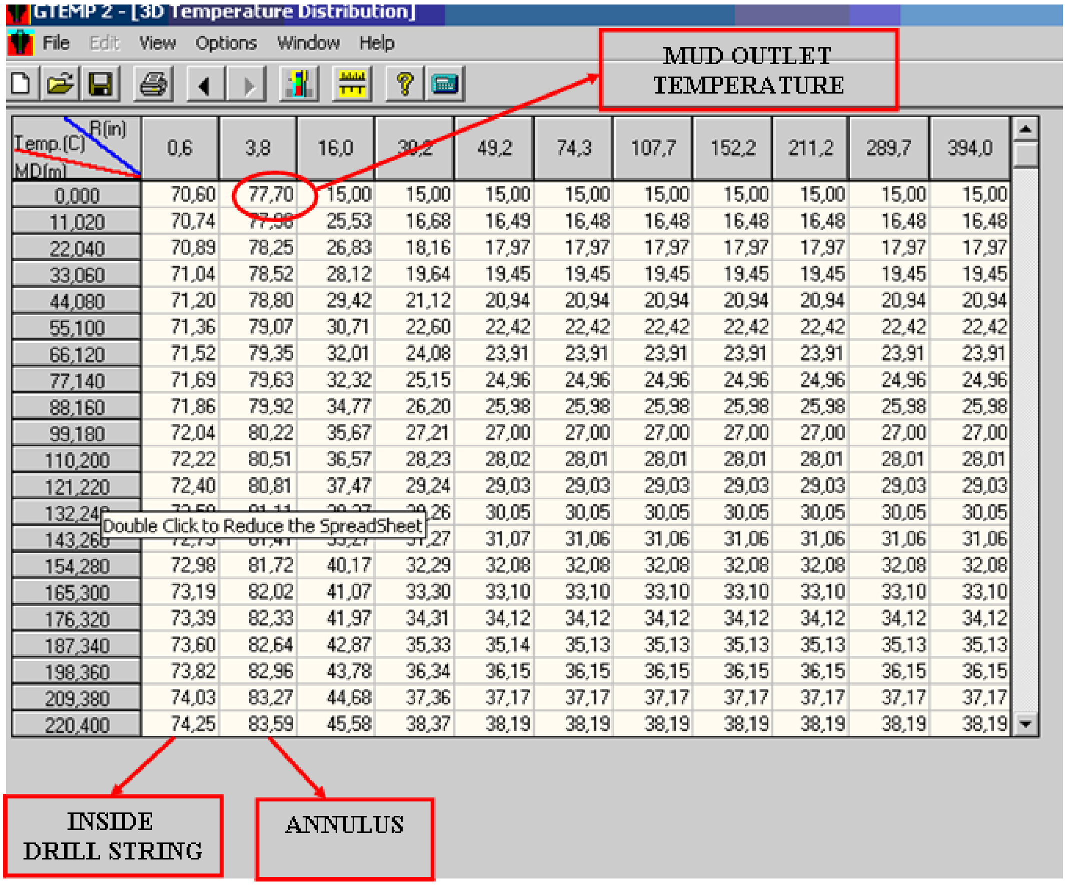
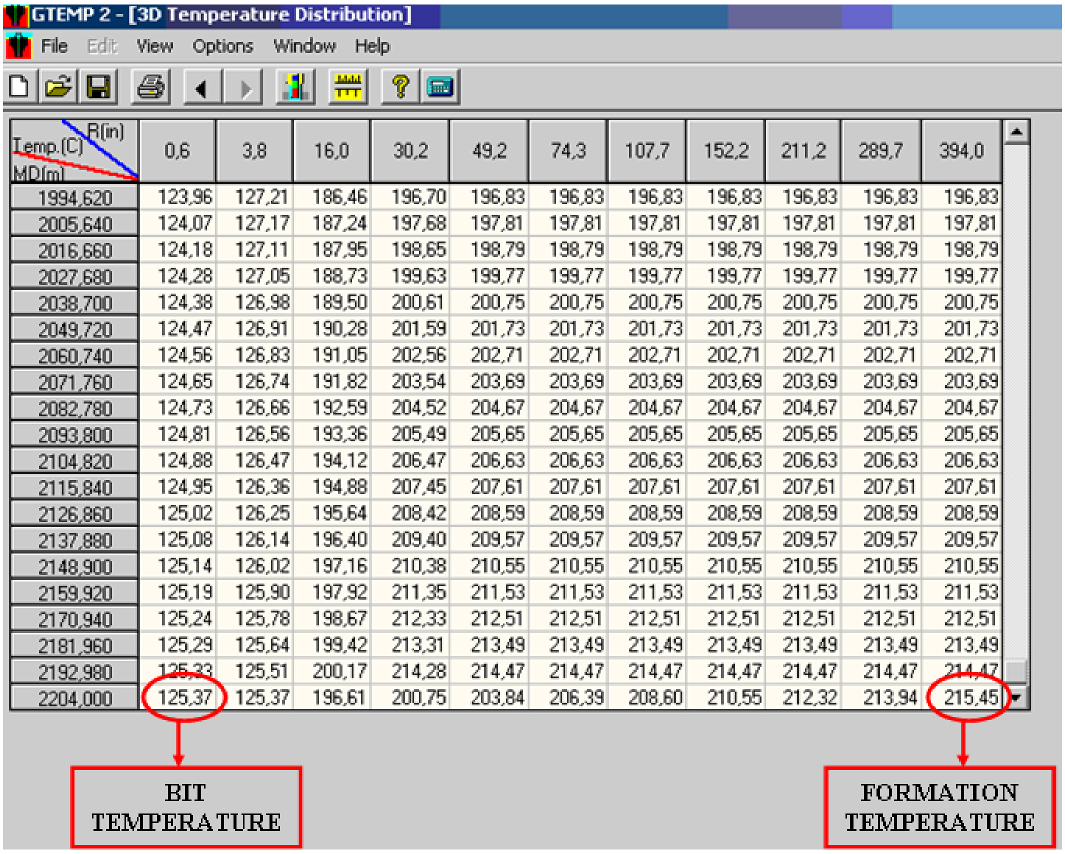


Figure 6.13. 3D Temperature Distribution Window.



Temp.(C) / R(in) / MD(m)	0,6	3,8	16,0	30,2	49,2	74,3	107,7	152,2	211,2	289,7	394,0
0,000	70,60	77,70	15,00	15,00	15,00	15,00	15,00	15,00	15,00	15,00	15,00
11,020	70,74	77,98	25,53	16,68	16,49	16,48	16,48	16,48	16,48	16,48	16,48
22,040	70,89	78,25	26,83	18,16	17,97	17,97	17,97	17,97	17,97	17,97	17,97
33,060	71,04	78,52	28,12	19,64	19,45	19,45	19,45	19,45	19,45	19,45	19,45
44,080	71,20	78,80	29,42	21,12	20,94	20,94	20,94	20,94	20,94	20,94	20,94
55,100	71,36	79,07	30,71	22,60	22,42	22,42	22,42	22,42	22,42	22,42	22,42
66,120	71,52	79,35	32,01	24,08	23,91	23,91	23,91	23,91	23,91	23,91	23,91
77,140	71,69	79,63	32,32	25,15	24,96	24,96	24,96	24,96	24,96	24,96	24,96
88,160	71,86	79,92	34,77	26,20	25,98	25,98	25,98	25,98	25,98	25,98	25,98
99,180	72,04	80,22	35,67	27,21	27,00	27,00	27,00	27,00	27,00	27,00	27,00
110,200	72,22	80,51	36,57	28,23	28,02	28,01	28,01	28,01	28,01	28,01	28,01
121,220	72,40	80,81	37,47	29,24	29,03	29,03	29,03	29,03	29,03	29,03	29,03
132,240	[illegible]	[illegible]	[illegible]	[illegible]	30,05	30,05	30,05	30,05	30,05	30,05	30,05
143,260	[illegible]	[illegible]	[illegible]	[illegible]	31,07	31,06	31,06	31,06	31,06	31,06	31,06
154,280	72,98	81,72	40,17	32,29	32,08	32,08	32,08	32,08	32,08	32,08	32,08
165,300	73,19	82,02	41,07	33,30	33,10	33,10	33,10	33,10	33,10	33,10	33,10
176,320	73,39	82,33	41,97	34,31	34,12	34,12	34,12	34,12	34,12	34,12	34,12
187,340	73,60	82,64	42,87	35,33	35,14	35,13	35,13	35,13	35,13	35,13	35,13
198,360	73,82	82,96	43,78	36,34	36,15	36,15	36,15	36,15	36,15	36,15	36,15
209,380	74,03	83,27	44,68	37,36	37,17	37,17	37,17	37,17	37,17	37,17	37,17
220,400	74,25	83,59	45,58	38,37	38,19	38,19	38,19	38,19	38,19	38,19	38,19

Figure 6.14. 3D Temperature Table at Surface.



Temp.(C) R(in) MD(m)	0,6	3,8	16,0	30,2	49,2	74,3	107,7	152,2	211,2	289,7	394,0
1994,620	123,96	127,21	186,46	196,70	196,83	196,83	196,83	196,83	196,83	196,83	196,83
2005,640	124,07	127,17	187,24	197,68	197,81	197,81	197,81	197,81	197,81	197,81	197,81
2016,660	124,18	127,11	187,95	198,65	198,79	198,79	198,79	198,79	198,79	198,79	198,79
2027,680	124,28	127,05	188,73	199,63	199,77	199,77	199,77	199,77	199,77	199,77	199,77
2038,700	124,38	126,98	189,50	200,61	200,75	200,75	200,75	200,75	200,75	200,75	200,75
2049,720	124,47	126,91	190,28	201,59	201,73	201,73	201,73	201,73	201,73	201,73	201,73
2060,740	124,56	126,83	191,05	202,56	202,71	202,71	202,71	202,71	202,71	202,71	202,71
2071,760	124,65	126,74	191,82	203,54	203,69	203,69	203,69	203,69	203,69	203,69	203,69
2082,780	124,73	126,66	192,59	204,52	204,67	204,67	204,67	204,67	204,67	204,67	204,67
2093,800	124,81	126,56	193,36	205,49	205,65	205,65	205,65	205,65	205,65	205,65	205,65
2104,820	124,88	126,47	194,12	206,47	206,63	206,63	206,63	206,63	206,63	206,63	206,63
2115,840	124,95	126,36	194,88	207,45	207,61	207,61	207,61	207,61	207,61	207,61	207,61
2126,860	125,02	126,25	195,64	208,42	208,59	208,59	208,59	208,59	208,59	208,59	208,59
2137,880	125,08	126,14	196,40	209,40	209,57	209,57	209,57	209,57	209,57	209,57	209,57
2148,900	125,14	126,02	197,16	210,38	210,55	210,55	210,55	210,55	210,55	210,55	210,55
2159,920	125,19	125,90	197,92	211,35	211,53	211,53	211,53	211,53	211,53	211,53	211,53
2170,940	125,24	125,78	198,67	212,33	212,51	212,51	212,51	212,51	212,51	212,51	212,51
2181,960	125,29	125,64	199,42	213,31	213,49	213,49	213,49	213,49	213,49	213,49	213,49
2192,980	125,33	125,51	200,17	214,28	214,47	214,47	214,47	214,47	214,47	214,47	214,47
2204,000	125,37	125,37	196,61	200,75	203,84	206,39	208,60	210,55	212,32	213,94	215,45

Figure 6.15. 3D Temperature Table at Bottom.

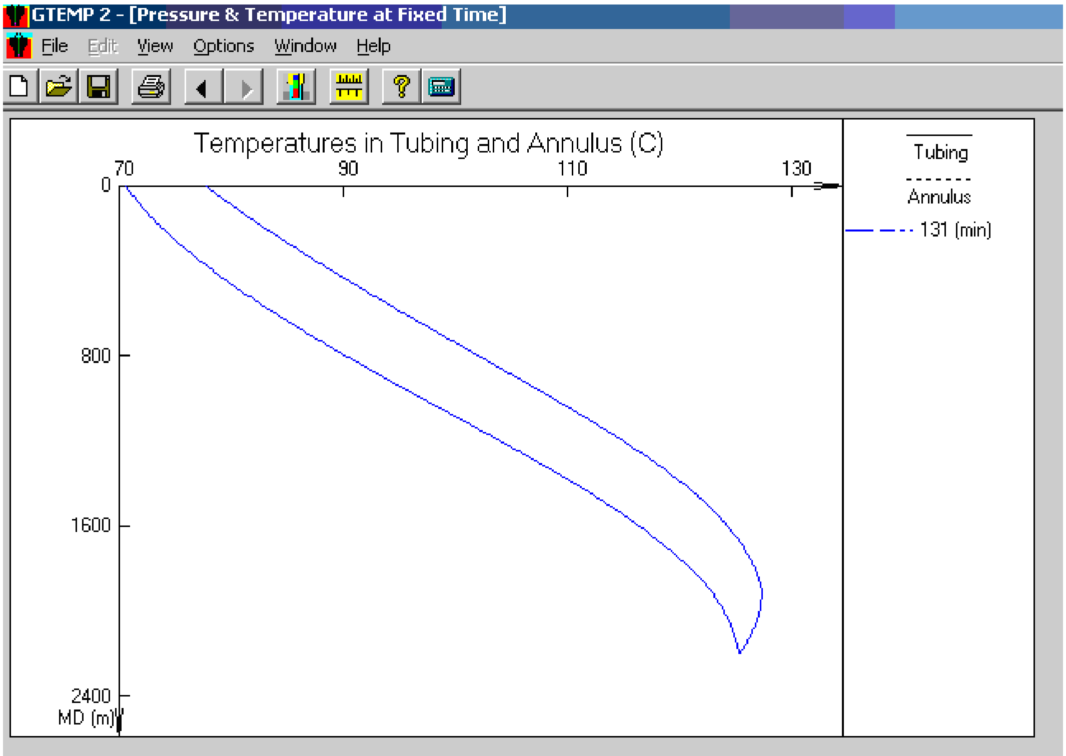


Figure 6.16. Temperature at Fixed Time Window.

6.5 Case Definition

This study is performed in two different cases for every five well concerning cooling tower effect to mud temperatures.

6.5.1 Case 1

In Case 1, cooling tower effect is neglected and no modification is conducted through the input parameters except the bottom temperature modification explained in Figure 6.2.

6.5.2 Case 2

In Case 2, cooling tower effect is taken into account and the field parameters of mud inlet and mud outlet temperatures are modified as if the cooling tower is not used. For this modification, mud outlet temperature of the first depth is decreased according to Table 6.2 and corrected mud inlet temperature of the first depth is obtained. Corrected mud outlet temperature of the second depth is 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 as shown in Equations 7 and 8. Moreover an example for the depth couple 2196-2204 m is shown in Figure 6.17.

$$\mathrm{MIT}_{n}^{cor.} = \mathrm{MOT}_{n} - \mathrm{deg.} \quad (7)$$

$$\mathrm{MOT}_{n+1}^{cor.} = \mathrm{MIT}_{n}^{cor.} + \left(\mathrm{MOT}_{n+1} - \mathrm{MIT}_{n}\right) \quad (8)$$

where;

MIT_{n} = Mud inlet temperature of first depth

$\mathrm{MIT}_{n}^{cor.}$ = Corrected mud inlet temperature of first depth

MOT_{n} = Mud outlet temperature of first depth

MOT_{n+1} = Mud outlet temperature of second depth

$\mathrm{MOT}_{n+1}^{cor.}$ = Corrected mud outlet temperature of second depth

deg. = Temperature value according to Table 6.2

Depth Couple	MIT (°C)	MOT (°C)	Corrected MIT (°C)	Corrected MOT (°C)
First Depth 2196 m	55,90	77,50	= 77,5 - 9 = 68,5	
Second Depth 2204 m		77,70		= 68,5 + 21,8 = 90,3

Temperature increase of 21,8 °C through circulation

Cooling according to Table 6.2

Figure 6.17. Corrected MIT and MOT Calculation.

CHAPTER 7

RESULTS AND DISCUSSION

7.1 Well #3

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 778-965 m right after marble-schist formation. 32 computer runs are conducted throughout the well for each case. The formation temperature of the final depth is estimated with 769-777 m depth couple and computer run for total loss section is conducted with water.

Temperatures vs. depth graphs of Well #3 for Case 1 and 2 are shown in Figures 7.1 and 7.2. Comparison of the temperature differences between Case 1 and 2 and the match of the calculated formation temperature with the reservoir temperature for Well #3 can be seen in Figure 7.3.

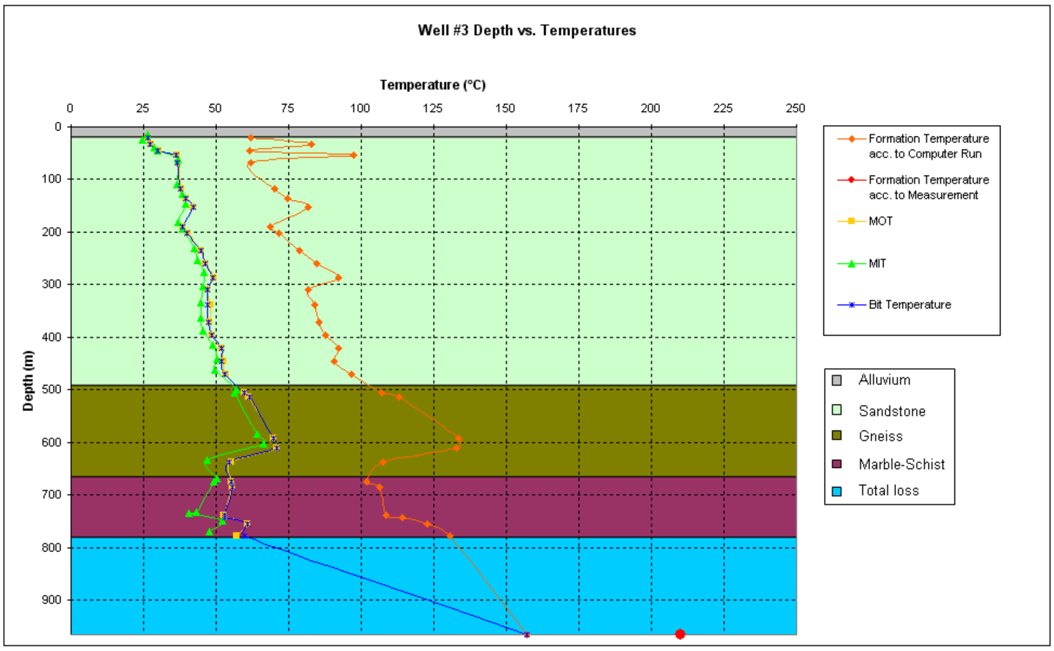


Figure 7.1. Temperatures vs. Depth Graph of Well #3 for Case 1.

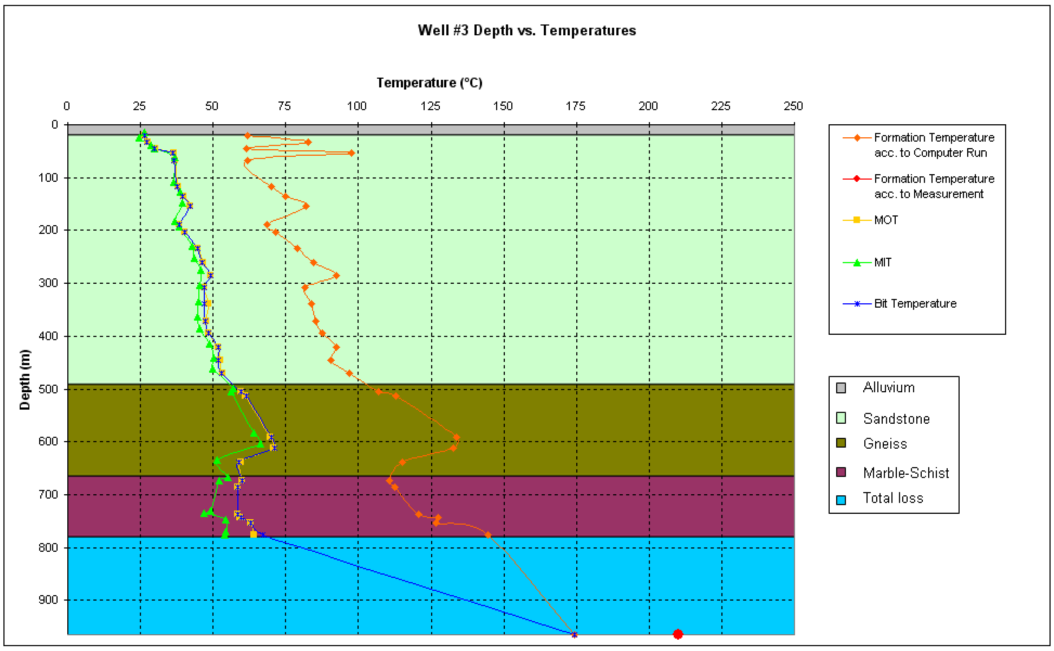


Figure 7.2. Temperatures vs. Depth Graph of Well #3 for Case 2.

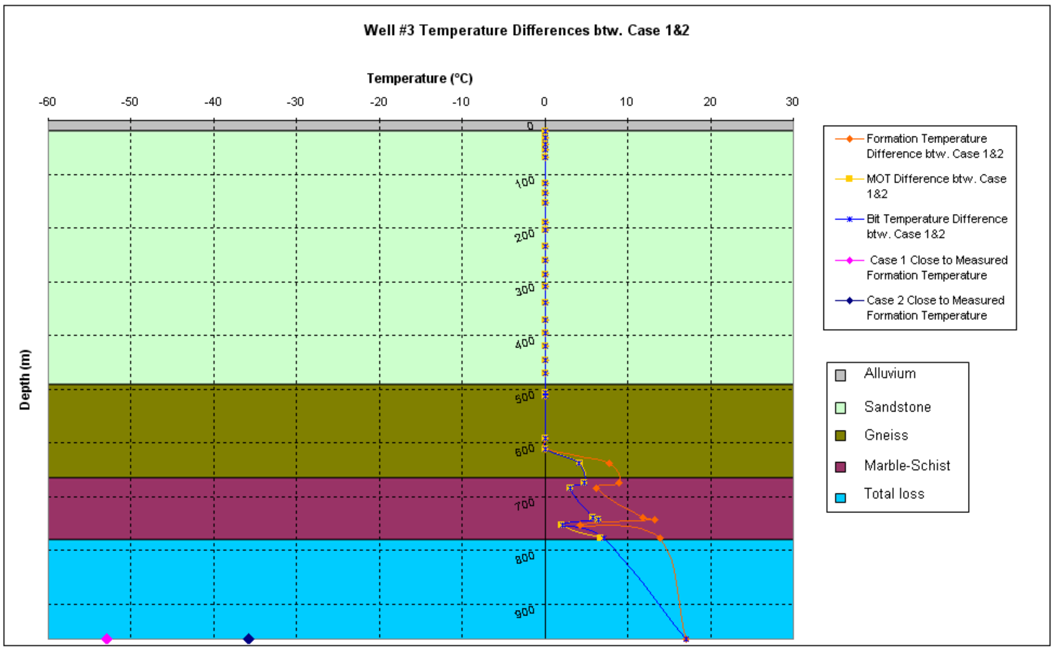


Figure 7.3. Comparison of Cases 1 and 2 for Well #3.

In Well #3, correction of mud temperatures in Case 2 give higher results in MOT between 2,00-6,70 °C, in bit temperature between 2,10-22,27 °C and in formation temperature between 4,17-22,27 °C compared to Case 1.

For the comparison of formation temperature estimation of the final depth to the reservoir temperature; 157,11 °C is estimated with % 25,2 deviation in Case 1 and 174,22 °C is estimated with % 17,0 deviation in Case 2.

7.2 Well #4

The final depth of Well #4 is 2260 m and the reservoir temperature is 205 °C. Cooling tower was used after 858 m. Total loss was encountered between 2205-2260 m right after marble-schist formation.

34 computer runs are conducted throughout the well for each case. The formation temperature of the final depth is estimated with 2196-2204 m depth couple and computer run for total loss section is conducted with mud.

Temperatures vs. depth graphs of Well #4 for Cases 1 and 2 are shown in Figures 7.4 and 7.5. Comparison of the temperature differences between Case 1 and Case 2 and the match of the calculated formation temperature with the reservoir temperature for Well #4 can be seen in Figure 7.6.

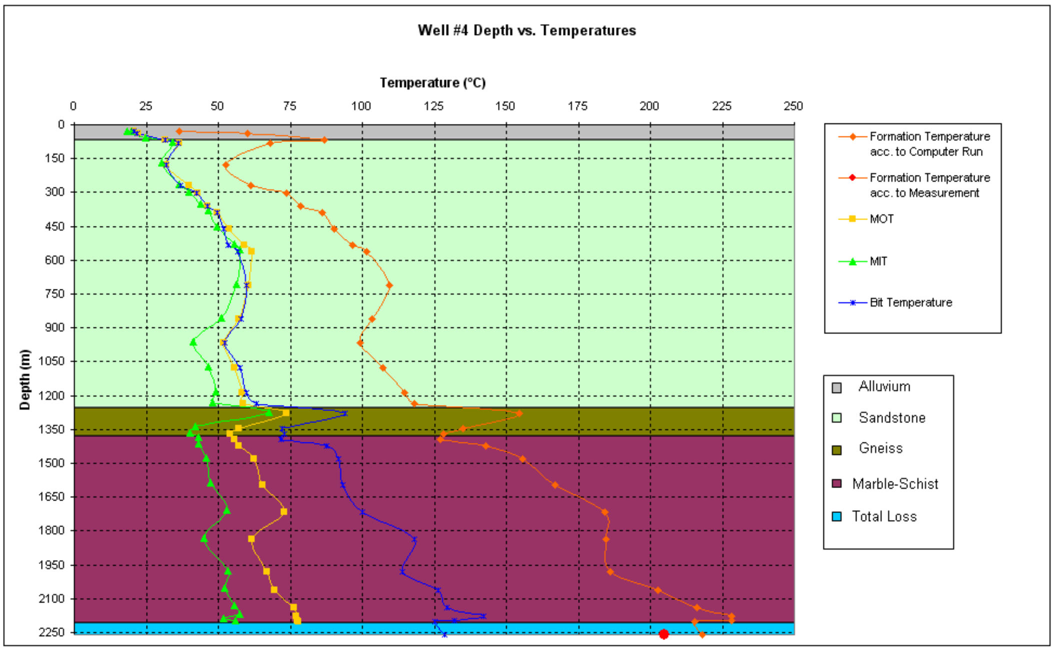


Figure 7.4. Temperatures vs. Depth Graph of Well #4 for Case 1.

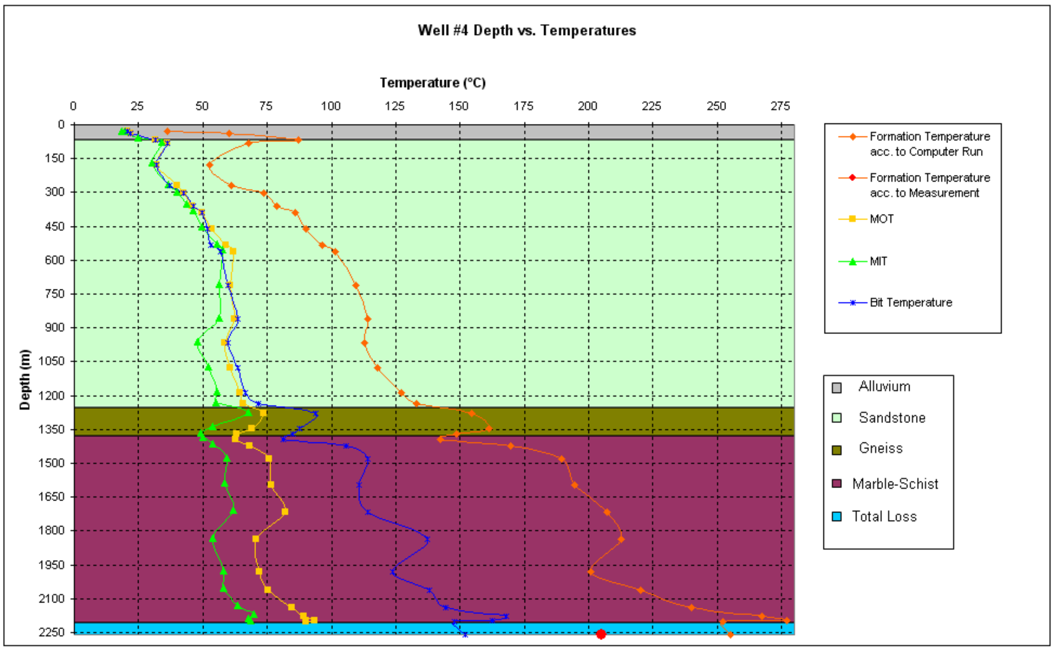


Figure 7.5. Temperatures vs. Depth Graph of Well #4 for Case 2.

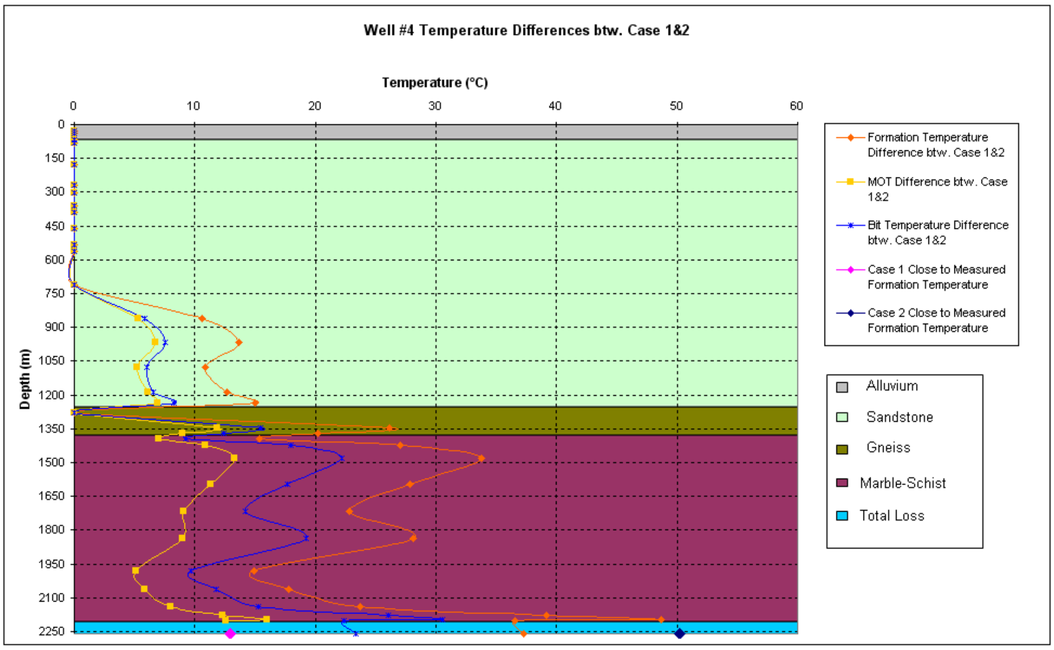


Figure 7.6. Comparison of Cases 1 and 2 for Well #4.

In Well #4, correction of mud temperatures in Case 2 give higher results in MOT between 5,10-16,00 °C, in bit temperature between 5,87-30,53 °C and in formation temperature between 10,57-48,67 °C compared to Case 1.

For the comparison of formation temperature estimation of the final depth to the reservoir temperature; 217,94 °C is estimated with % 6,3 deviation in Case 1 and 255,25 °C is estimated with % 24,5 deviation in Case 2.

7.3 Well #5

The final depth of Well #5 is 1838 m and the reservoir temperature is 191 °C. Cooling tower was used after 1098 m. Total loss was encountered between 1765-1838 m right after marble formation. 28 computer runs are conducted throughout the well for each case. The formation temperature of the final depth is estimated with 1733-1743 m depth couple and computer run for total loss section is conducted with water.

Temperatures vs. depth graphs of Well #5 for Cases 1 and 2 are shown in Figures 7.7 and 7.8. Comparison of the temperature differences between Case 1 and Case 2 and the match of the calculated formation temperature with the reservoir temperature for Well #5 can be seen in Figure 7.9.

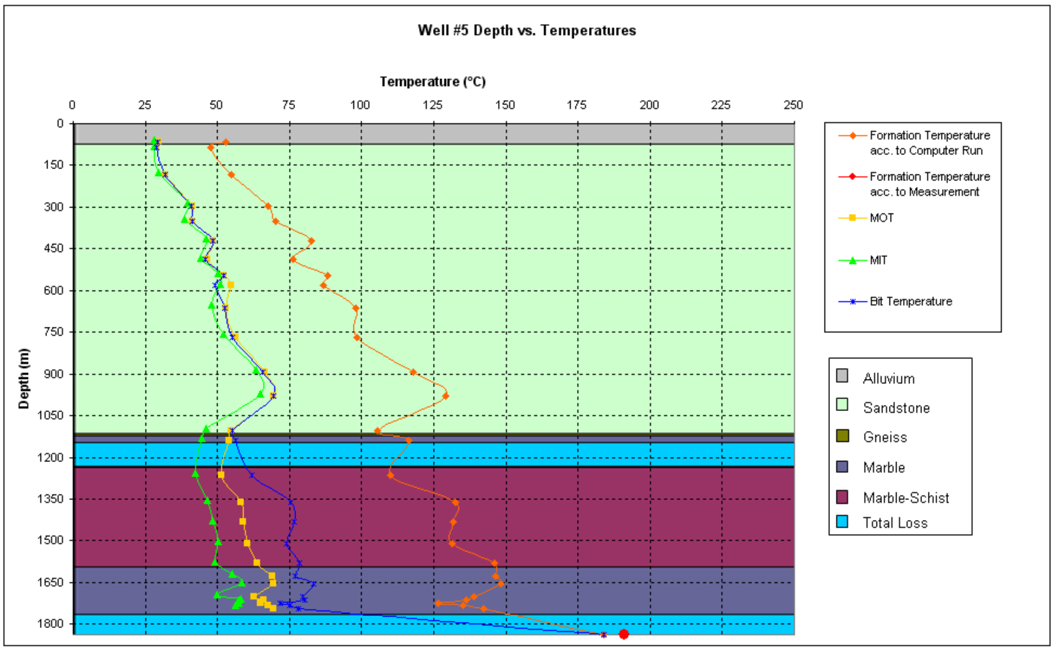


Figure 7.7. Temperatures vs. Depth Graph of Well #5 for Case 1.

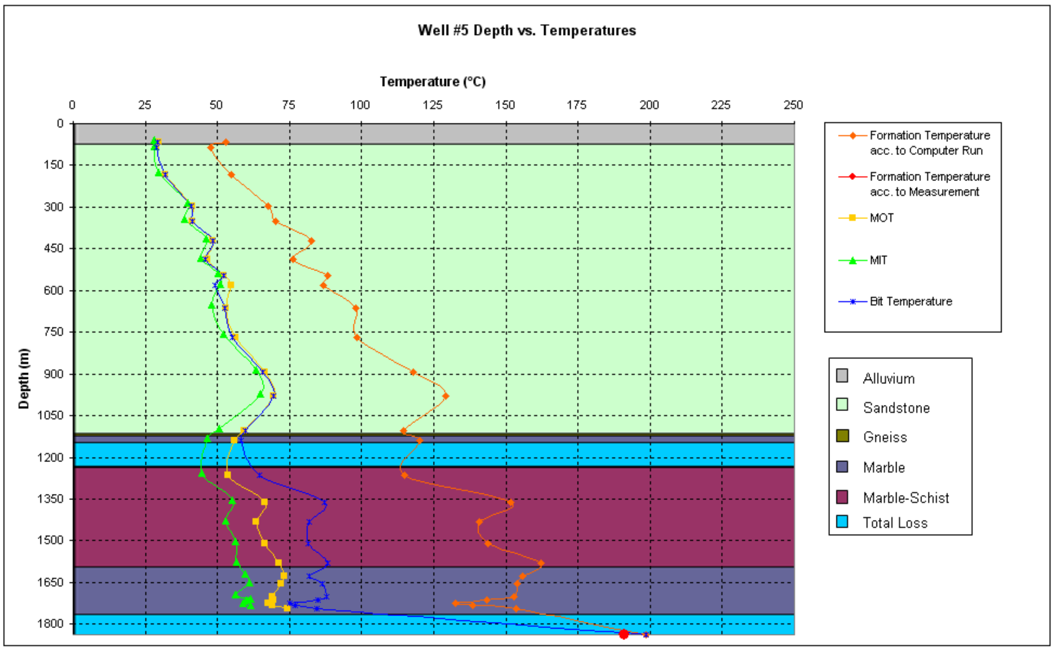


Figure 7.8. Temperatures vs. Depth Graph of Well #5 for Case 2.

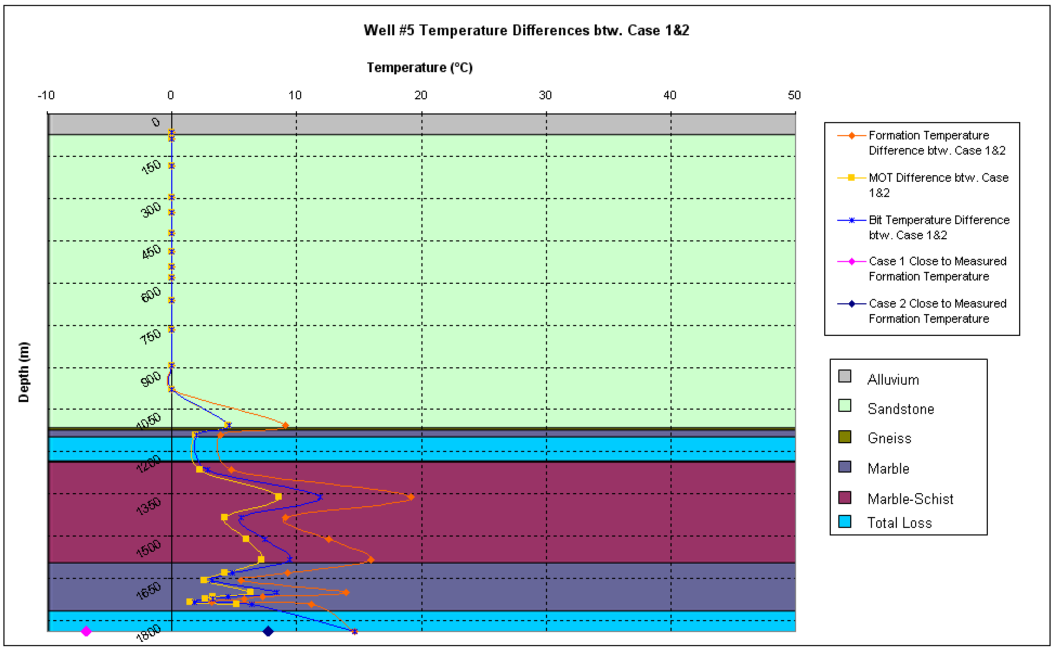


Figure 7.9. Comparison of Cases 1 and 2 for Well #5.

In Well #5, correction of mud temperatures in Case 2 give higher results in MOT between 1,50-8,60 °C, in bit temperature between 1,83-11,98 °C and in formation temperature between 3,23-19,20 °C compared to Case 1.

For the comparison of formation temperature estimation of the final depth to the reservoir temperature; 184,09 °C is estimated with % 3,6 deviation in Case 1 and 198,72 °C is estimated with % 4,0 deviation in Case 2.

7.4 Well #7

The final depth of Well #7 is 1252 m and the reservoir temperature is 199 °C. Cooling tower was used after 950 m. Total loss was encountered between

1121-1252 m right after marble-schist formation. 26 computer runs are conducted throughout the well for each case. The formation temperature of the final depth is estimated with 1111-1117 m depth couple and computer run for total loss section is conducted with water.

Temperatures vs. depth graphs of Well #7 for Cases 1 and 2 are shown in Figures 7.10 and 7.11. Comparison of the temperature differences between Case 1 and Case 2 and the match of the calculated formation temperature with the reservoir temperature for Well #7 can be seen in Figure 7.12.

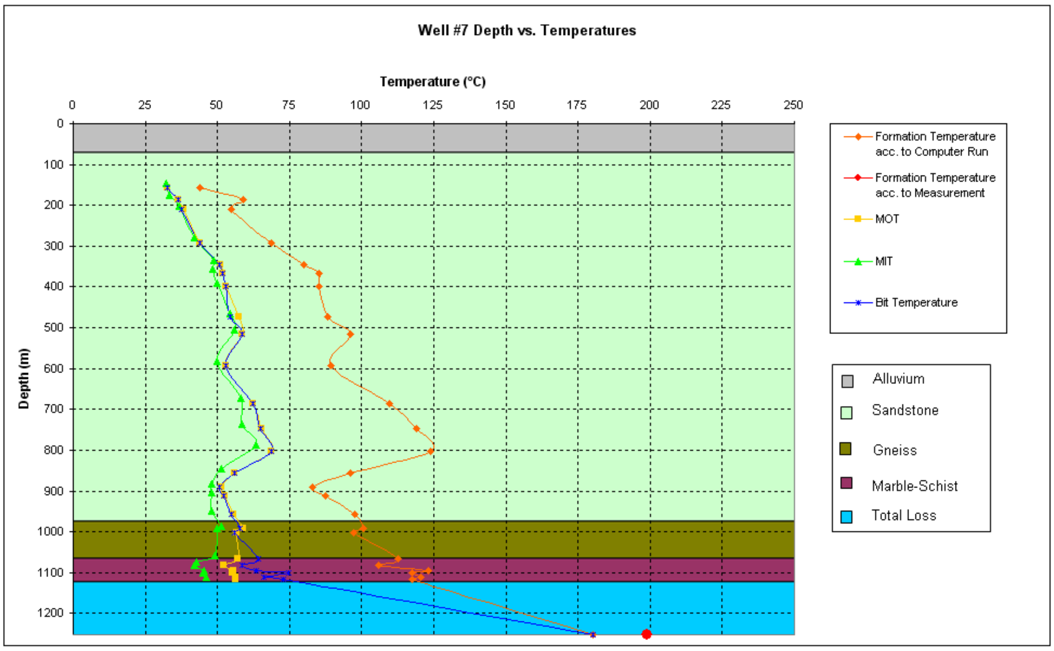


Figure 7.10. Temperatures vs. Depth Graph of Well #7 for Case 1.

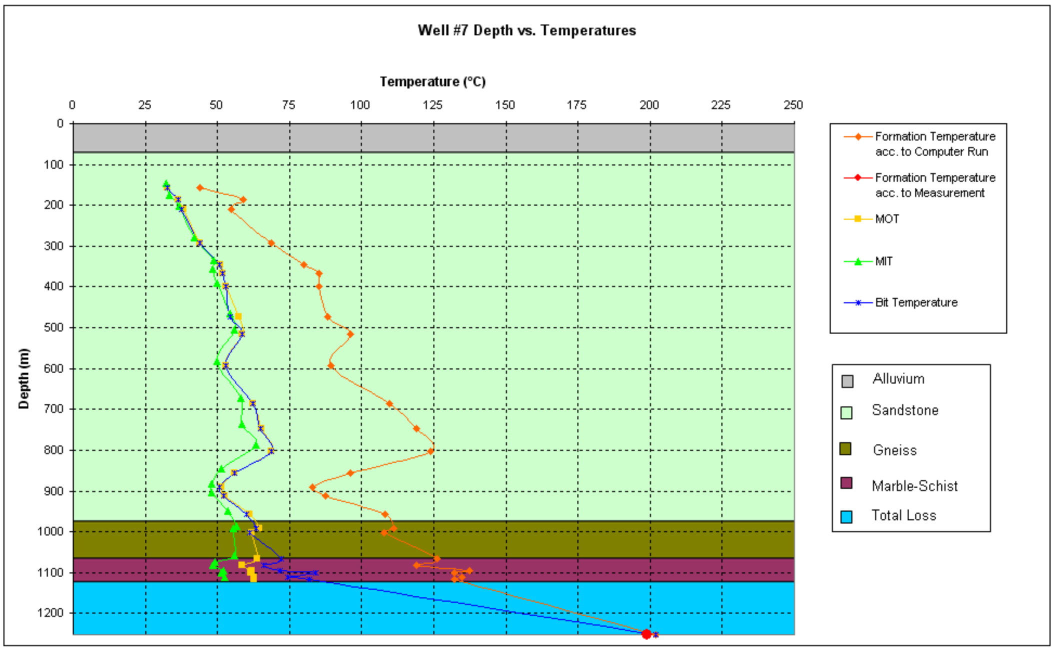


Figure 7.11. Temperatures vs. Depth Graph of Well #7 for Case 2.

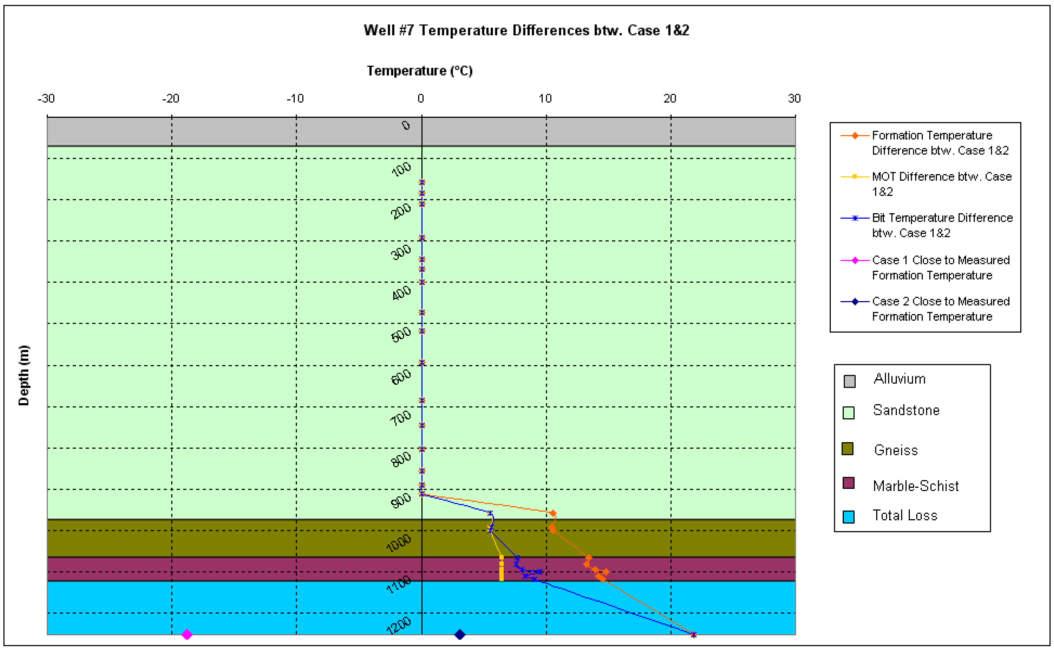


Figure 7.12. Comparison of Cases 1 and 2 for Well #7.

In Well #7, correction of mud temperatures in Case 2 give higher results in MOT between 5,50-6,50 °C, in bit temperature between 5,48-21,86 °C and in formation temperature between 10,46-21,86 °C compared to Case 1.

For the comparison of formation temperature estimation of the final depth to the reservoir temperature; 180,22 °C is estimated with % 9,4 deviation in Case 1 and 202,08 °C is estimated with % 1,5 deviation in Case 2.

7.5 Well #9

The final depth of Well #9 is 1651 m and the reservoir temperature is 227 °C. Cooling tower was used after 721 m. Total loss was not encountered in this well. 31 computer runs are conducted throughout the well for each case. The formation temperature of the final depth is estimated with 1635-1641 m depth couple.

Temperatures vs. depth graphs of Well #9 for Cases 1 and 2 are shown in Figures 7.13 and 7.14. Comparison of the temperature differences between Case 1 and Case 2 and the match of the calculated formation temperature with the reservoir temperature for Well #9 can be seen in Figure 7.15.

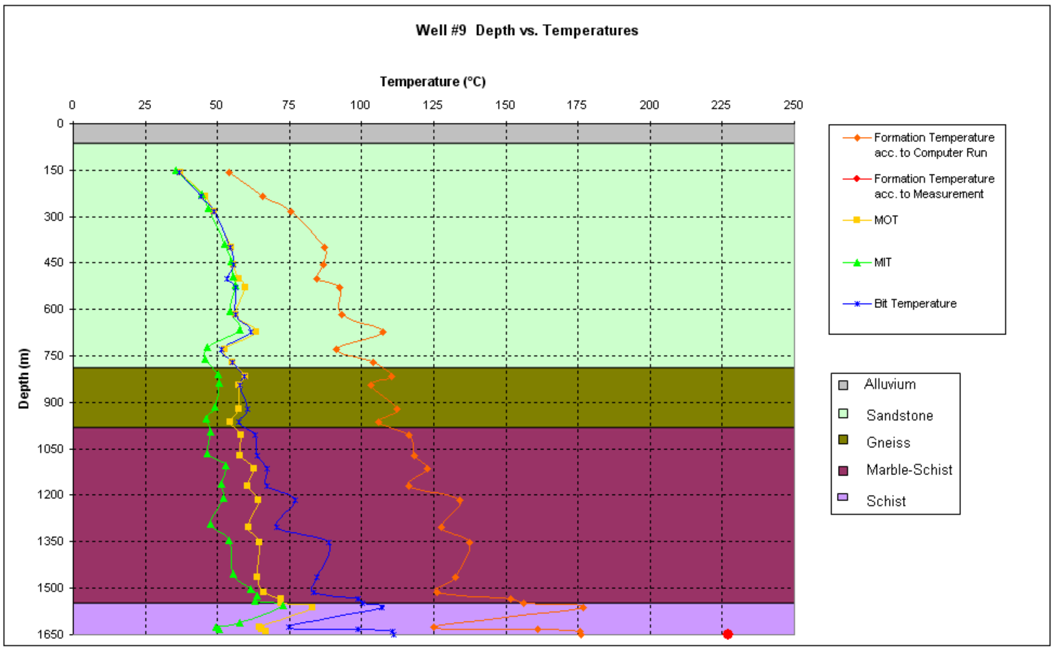


Figure 7.13. Temperatures vs. Depth Graph of Well #9 for Case 1.

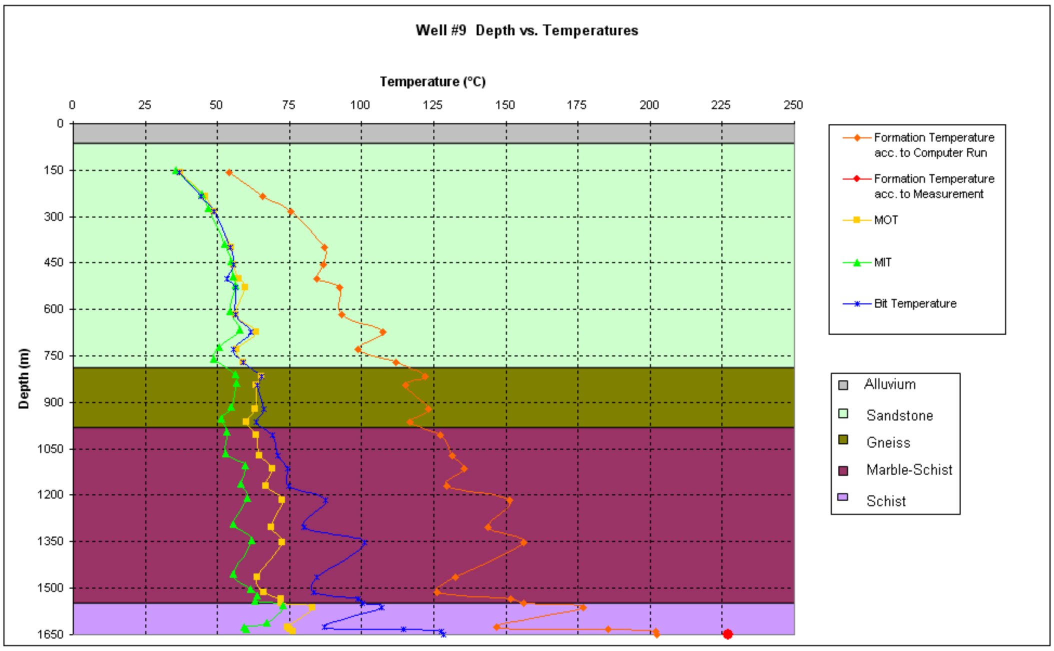


Figure 7.14. Temperatures vs. Depth Graph of Well #9 for Case 2.

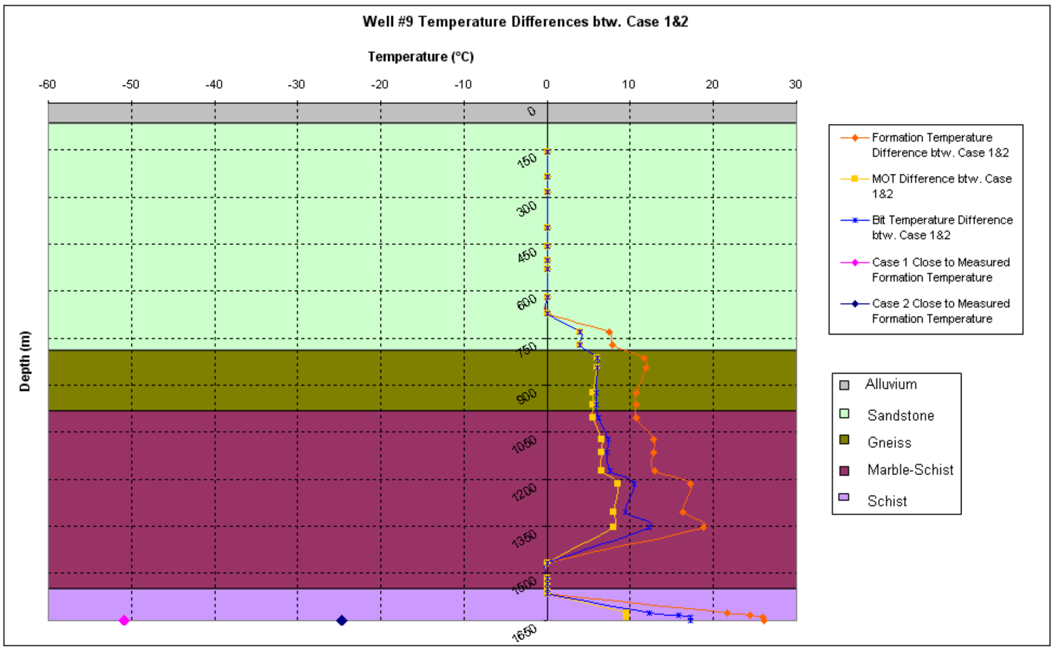


Figure 7.15. Comparison of Cases 1 and 2 for Well #9.

In Well #9, correction of mud temperatures in Case 2 give higher results in MOT between 4,00-9,50 °C, in bit temperature between 3,90-17,25 °C and in formation temperature between 7,53-26,13 °C compared to Case 1.

For the comparison of formation temperature estimation of the final depth to the reservoir temperature; 176,16 °C is estimated with % 22,4 deviation in Case 1 and 202,29 °C is estimated with % 10,9 deviation in Case 2.

7.6 Discussion

The deviations of the estimated formation temperatures of the final depth to reservoir temperature for five wells are shown in Table 7.1. In Well #5, almost the same deviation is obtained with the results of Cases 1 and 2. In Wells #3, #7 and #9, deviations of the results are decreased in Case 2 compared to Case 1.

Moreover, formation temperature estimation is more approximate in Case 1 rather than Case 2 for Well #4 which is the deepest well in this study.

Table 7.1. Comparison of Cases 1 and 2 for Five Wells.

Well No	Case 1		Case 2		Reservoir Temperature (°C)	Depth (m)
	Value (°C)	Deviation (%)	Value (°C)	Deviation (%)		
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

Estimation of formation temperature with GTEMP is observed as more successful in wells with medium depth like Wells #5, #7 and #9. Besides, for the shallow and deep wells like Wells #3 and #4, less accurate results are obtained. This situation is related with the ability of the program to simulate the fractured and faulted characteristics of the formation as the way they exist in reality.

Bit temperatures show near values to mud outlet temperatures until 1050-1250 m. After these depths, the formation changes to gneiss or marble-schist and significant difference occurs between bit temperatures and mud outlet temperatures. However, in total loss sections of Wells #3, #5 and #7, estimated bit temperature values are the same with the formation temperatures due to the reason that in these sections, the final depth is extrapolated and the program assumes these zones as not drilled and therefore not affected by circulation. For Wells #4 and #9, since the extrapolated section is shorter, this zone is considered as affected by circulation.

In general, significant changes at mud and formation temperatures are observed through the depths where lithology changed.

CHAPTER 8

CONCLUSION

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

The estimated formation temperatures of the final depth of five wells are compared with reservoir temperature data. Estimations are obtained with % 3,6-25,2 deviation in Case 1 and % 1,5-24,5 deviation in Case 2. The best matches are mostly obtained with Case 2 where cooling tower effect is taken into account.

Moreover, significant differences observed between bit and mud outlet temperatures after 1050-1250 m when the formation changes to gneiss or marble-schist. In addition to this, fluctuations in mud inlet and outlet temperatures are quite relevant with formation temperature and also indicate lithology variations.

Besides, this study is found useful in many different aspects:

- Formation and bit temperatures can be estimated while drilling. This information is especially important during drilling total loss sections since no cuttings can be observed at the surface and no temperature measurements can be conducted.

- A decision can be made on the final depth of the well by comparing the formation temperature estimation of the current depth with the target.
- Project cost can be optimized in many ways regarding drilling operations and temperature limits of the down hole equipment.

CHAPTER 9

RECOMMENDATIONS

GTEMP has provided approximate results for the formation temperature of the final depth with regards to reservoir temperature. However, several recommendations can be made to obtain more optimized match results.

Although using cooling tower during drilling has significant effect on mud temperatures, GTEMP does not include this effect in its model. It is recommended to reflect cooling tower effect at mud temperatures in a more efficient way either by simulating this effect in another model and using the results as mud temperatures or by modifying the tank surface area part in GTEMP in a consistent way.

Currently, little or no data is available regarding the heat conductivity, heat capacity and density of the formations encountered during drilling. It is recommended to obtain a more detailed geologic study in terms of rock heat properties.

It is also recommended to apply this study simultaneously with drilling operation at field by obtaining more accurate mud temperature and cooling tower information.

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