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GEOTHERMAL EVALUATION OF THE GELDINGANES AREA IN SW-ICELAND AND PROPOSAL FOR ASSESSMENT OF THE SHIVERT HOT SPRING AREA IN MONGOLIA

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ABSTRACT

This report deals with evaluations of two geothermal fields in different parts of the world. Temperature gradient data from 16 exploration wells, and well-test results from a prospective geothermal area in SW-Iceland, the Geldinganes area, have been re-evaluated. The results indicate an up-flow of about 105°C water along a near-vertical SSW-NNW trending geological structure from depth under the southern part of Geldinganes up to shallower formations near the north coast of the peninsula. This result contradicts an earlier conceptual model of the Geldinganes field and may explain why a production well, RV-43, directionally drilled to the north-northeast in 2001 was not successful. The permeability-thickness of the Geldinganes reservoir is estimated to be 1.5-3.0 Darcy-m. Predictions by a lumped parameter model indicate that the production potential of well HS-44 in the southern part of Geldinganes is in the range of 7-20 l/s. Preliminary evaluation of the Shivert hot spring area in central Mongolia that involved temperature data from six exploration wells indicates a clear up-flow of 80-100°C water along a high-permeability vertical fracture. The Shivert area is believed to have considerable potential, but this resource needs to be carefully and thoroughly assessed. It is expected that the methods that have been successfully applied in the Geldinganes area and other low-temperature geothermal fields in Iceland are equally applicable in Mongolia. Therefore, the experience in low-temperature geothermal exploration and resource assessment, as well as the experience in geothermal development, gathered in Iceland during the last decades may be transferred to and applied in Mongolia. This will, hopefully speed up geothermal development in the country, which would benefit the Mongolian population and promote sustainable energy use in the country.

1. INTRODUCTION

An estimate of the world-wide installed geothermal power for direct use at the end of 1999 was 16,209 MWt utilizing at least 64,416 kg/s of fluid (Lund and Freeston, 2001). The thermal energy used was

162,009 TJ/yr, a 44.1% increase over the five-year period from 1995 to 2000. Geothermal energy utilization for heating and other direct uses is thus growing rapidly and a continuing increase in utilization is expected in the coming years. Iceland is one of the leading countries in both geothermal direct use, mainly used for district heating, and geothermal electric generation. Geothermal provides more than 50% of the total primary energy supply. The principal use of geothermal energy in Iceland is for space heating; about 87% of all energy used for house heating comes from geothermal resources, a world record. Total installed capacity of thermal power is 1,469 MWt (utilization 6,600 GWh/y) and electric power over 200 MWe (production is 1,433 GWh/y) or 17% of the national electrical energy total (Orkustofnun, 2004).

Low-temperature geothermal resources are known to exist in Mongolia, in particular over 43 known warm and hot springs with measured surface temperatures ranging from 20 to 90°C. In contrast to Iceland, exploration for these resources has barely started in Mongolia. Therefore, the experience in low-temperature geothermal exploration and resource assessment, as well as the experience in geothermal development gathered in Iceland during the last decades may be transferred to and applied in Mongolia. This would, hopefully, speed up geothermal development in the country. The geothermal resources of Mongolia may be used for geothermal district heating, geothermally heated swimming pools, industrial use and greenhouse heating, which would benefit the Mongolian population and promote sustainable energy use in the country.

The purpose of this report is two-fold, firstly, to re-evaluate exploration data from a specific low-temperature geothermal field in Iceland, the Geldinganes field. This re-evaluation involves interpretation of temperature gradient data from several wells in the area as well as interpretation of well-test data. Secondly it is to propose what methods should be used to assess, and consequently prepare for utilization, a specific Mongolian geothermal area, the Shivert area. The methods proposed are based on the methods that have been successfully applied in Geldinganes and other low-temperature geothermal fields in Iceland. Some exploration work, including shallow drilling, has been conducted in the Shivert area, which is believed to have considerable potential for direct utilization (Dolgorjav, 2002). Appropriate background information for both geothermal areas is also reviewed in the report.

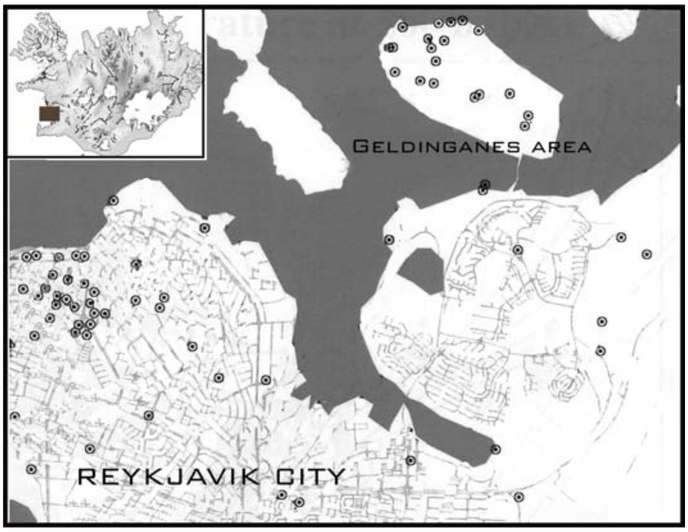

FIGURE 1: Part of the City of Reykjavik including the Geldinganes area and locations of wells

The Geldinganes geothermal field is located in the northeastern part of the City of Reykjavík in SW-Iceland (Figure 1). In the last couple of decades, Reykjavik Energy (Orkuveita Reykjavíkur) has drilled many research boreholes to establish the temperature conditions and temperature gradient (how fast the temperature changes with depth) in the bedrock at various points in Reykjavík. A total of 64 holes have been drilled (having the initials HS). When drilling hole HS-33 on the western side of Geldinganes in the spring of 1993, a high temperature gradient was discovered and at roughly 350 m depth, 100°C water was found. This was confirmed 3 years later when HS-44 was drilled to a depth of 1265 m east of HS-33. These holes can provide about 10 l/s of 100°C water at about 100 m drawdown (pressure drop). At the end of 2001, an 1832 m deep directional production well RV-43 was drilled. It turned out to be less productive than anticipated. This warranted a re-evaluation of the Geldinganes data.

Mongolia is located in the northern part of central Asia, landlocked and on a high plateau surrounded by mountain ridges with average elevation of 1580 m above sea level. The highest point is Huiten peak at 4653 m in Tavan Bogd Mountains and the lowest point is the Hoh Nuuryn depression at 532 m above sea level. Due to the distance from the sea, the climate is very continental, with hot summers (temperatures up to 41°C) and cold winters (temperatures down to –53°C). It shares a 3,005 km long border with Russia in the north, and a 4,673 km long border with China in the south. Mongolia covers a vast territory of over 1.5 million km^2 and has a population of 2.5 million.

Mongolia has 43 known hot springs, with measured surface temperatures ranging from 20 to 92°C, mainly distributed in the central and western provinces of the country. Mongolian hot springs are divided into three categories according to hydrogeological characteristics (Gendenjamts, 2003):

- Altai Soyonii area with four hot springs of sulfate-bicarbonate-sodium type, with measured surface temperature of 25-32°C and flow rate of 0.5-3 l/s;
- Khangai area with 36 hot springs of bicarbonate-sulfate-sodium type; and
- Khentii area with 3 hot springs of bicarbonate-sulfate-sodium type and temperatures in the range 67-88°C.

The Khangai hot spring region is located in the central part of Mongolia and has an area of 150,000 km^2. This study focuses on the Shivert geothermal area, which is located in the southeastern part of the Khangai area. Some geothermal exploration has been conducted since 1980 in the Shivert field.

2. BACKGROUND INFORMATION ON GELDINGANES

2.1 Introduction

Reykjavik, the capital of Iceland, is blessed with abundant geothermal resources, which were utilized to some extent, mainly for washing, since the first settlers arrived there more than 1100 years ago. Utilization for space heating started around 1930. There are three main geothermal fields inside, and around, Reykjavik (Axelsson and Gunnlaugsson, 2000). These are the Laugarnes field, which is close to the city-center, the Ellidaár field in the eastern part of the city, and the Mosfellssveit field some km northeast of the city. The reservoir temperature in these three separate systems ranges from 85 to 130°C. In resent decades, Reykjavík energy (Orkuveita Reykjavikur), which operates these three systems, has conducted geothermal exploration in-between these areas mostly with shallow exploration drilling, with the purpose of trying to locate further geothermal resources. One of the areas specially studied was the Geldinganes area where a high temperature gradient, as well as 100°C water, was discovered in 1993. Based on the results of an interpretation of data collected in the wells, as well as some geophysical data collected, an 1832 m deep directional production well, RV-43, was drilled at the end of 2001. It turned out to be less productive than anticipated.

2.2 Geological conditions

In most of the Geldinganes peninsula, solid bedrock is found at shallow depth. Unconsolidated layers are of variable thickness with sea gravel found where depth to solid rock is at a maximum, on the southernmost part of Geldinganes. The bedrock of the peninsula is almost all composed of the so-called Reykjavik olivine basalts. The northwestern side of the peninsula is composed of older rock and so is a small opening on the south coast. The basalt is divided into solid and brecciated rock with the bottom part being composed of pillow lava and breccia often with some clay-fillings. The bottom part is believed to have been formed when the basalt-lava flowed into the sea. In some places, the material is very loose and permeable. The basalt cover varies in thickness. The bottom layer of the basalt has a definite slope to the northeast and one could logically assume that it had flowed from the east through a valley or the bottom of a fjord (Steingrímsson et al., 2001).

Sedimentary layers are found underneath the basalt. This is a fine-grained sea-sediment, which appears to be very well consolidated. The sediment surface is mostly found between 15 and 40 m depth below sea level, and its thickness varies, usually only by a couple of meters, and in the boreholes in the northernmost part of the peninsula none of it is found. The sediment and the associated rock beneath it are impermeable; and below it down-flow of cold water is usually not found in the boreholes. In a small number of holes there was no sign of the sedimentary layer. Below the sediments, the rock is usually highly altered hyaloclastites and altered Tertiary basalts of low permeability. The thickness of the hyaloclastites is highly variable, the bottom depth ranging from 120 to 250 m below sea-level. Below the hyaloclastites, more permeable layers of basalt and thin interbeds are found (Steingrímsson et al., 2001).

The level of thermal alteration has not been seen as high in the Reykjavik area as in well HS-44. This did not come as a surprise since Geldinganes is much closer to the extinct central volcanic system north of Reykjavik than the production areas of Laugarnes and Elliðaár (Steingrímsson et al., 2001). Chlorite is found in a couple of places below 100 m depth indicating a past temperature of around 220-240°C or higher.

2.3 Magnetic measurements

In preparation of the drilling of hole RV-43, special attention was paid to magnetic measurements made in northern Reykjavik, since there are large changes in the magnetic and gravitational fields in the neighbourhood of Geldinganes. In Geldinganes itself, these changes in the magnetic field are small. The dominant rock types in the Geldinganes area are basalts with altered hyaloclastite below, which explains the limited magnetic variations (anomalies) in Geldinganes itself. Yet it is possible to see some negative magnetic anomalies along the coastlines (Steingrímsson et al., 2001).

The main magnetic anomaly is found ½ km to the north of Geldinganes. This is a very strong negative magnetic anomaly, almost circular in shape. A 2-dimensional model was set up arranged in a north-northeast direction, from Geldinganes to the north of the magnetic anomaly. The shape and magnetic properties of the model were adjusted until a suitable match was achieved. As expected, a good fit could be reached for various intrusions of different shapes and sizes, each being at different depth in the earth, reaching different lengths, having different thickness and differentiating in their individual magnetic strengths. The requirement must be made that the magnetic-field values are realistic; hence the upper level of the intrusions at Therney, northeast of Geldinganes, must be placed at a relatively shallow depth, probably within 100 m. The bottom of the intrusion was put at a depth of 1500 m, since the calculations were not very sensitive to that. The result was, therefore, that the main magnetic anomaly in the area north of Geldinganes demands that underneath it is a 500 m wide and 1500 m deep intrusion with unusually high magnetization, or approximately equal to the highest values encountered in rock samples in a laboratory. The south side of the anomaly has such a shape that it is not possible to simulate it with a steep wall. This intrusive body was the target for well RV-43.

3. ANALYSIS OF GELDINGANES TEMPERATURE CONDITIONS

Reservoir temperature, or formation temperature, which is the equilibrium temperature of geothermal water-rock systems, is one of the most important parameters in quantitative assessments of geothermal reservoirs (Björnsson, 2004). In most cases, the temperature information is obtained by lowering a temperature gauge into a well and measuring the temperature at specified depths, namely temperature logging (Steingrímsson, 2004). Because of the drilling operation, the original thermodynamic conditions around a well are usually disturbed (Bödvarsson and Witherspoon, 1989). This will result in the measured temperature at a certain depth in a well not necessarily being equal to the reservoir temperature. Therefore, this parameter can't always be obtained directly based on downhole temperature logging. It can, however, be estimated from careful interpretation of logging data collected during drilling and heating periods.

Commonly, there exist two major influences that complicate the interpretation of temperature logs (Stefánsson and Steingrímsson, 1990). One is internal flow within the well during and following drilling. Cooling due to drilling-fluid circulation is another main influence that should be taken into consideration during the temperature log interpretation. Therefore, information on the drilling operation and conditions of the well before temperature logging should be considered when temperature logs are interpreted. As a rule of thumb, the bottom temperature measured during drilling is usually not seriously affected by circulation. In addition, the regional mean annual temperature is also important information.

The formation temperature not only gives valuable information on aspects such as thermal gradient, actual reservoir temperature and location of feed zones, but also on the temperature distribution in the reservoir when several formation temperature profiles are available (Steingrímsson, 2004). Based on such information and additional geological data, a conceptual model of the reservoir can usually be constructed. As mentioned above, individual temperature logs don't necessarily give the actual formation temperature in the reservoir. Therefore, fundamental work involves deducing the formation temperature from temperature logs measured in each well.

A total of 56 temperature logs were measured in 17 wells at Geldinganes. The general characteristics of the seventeen wells on Geldinganes (Figure 2) used in this study are listed in Table 1. Based on the above, all the temperature logs have been interpreted and formation temperature for each well obtained. By comparing the temperature profiles between different wells, it was found that some profiles have similar characteristics. Generally, the temperature profiles can be divided into two types in deep and shallow wells, according to their characteristics, linear gradient-type profiles and profiles

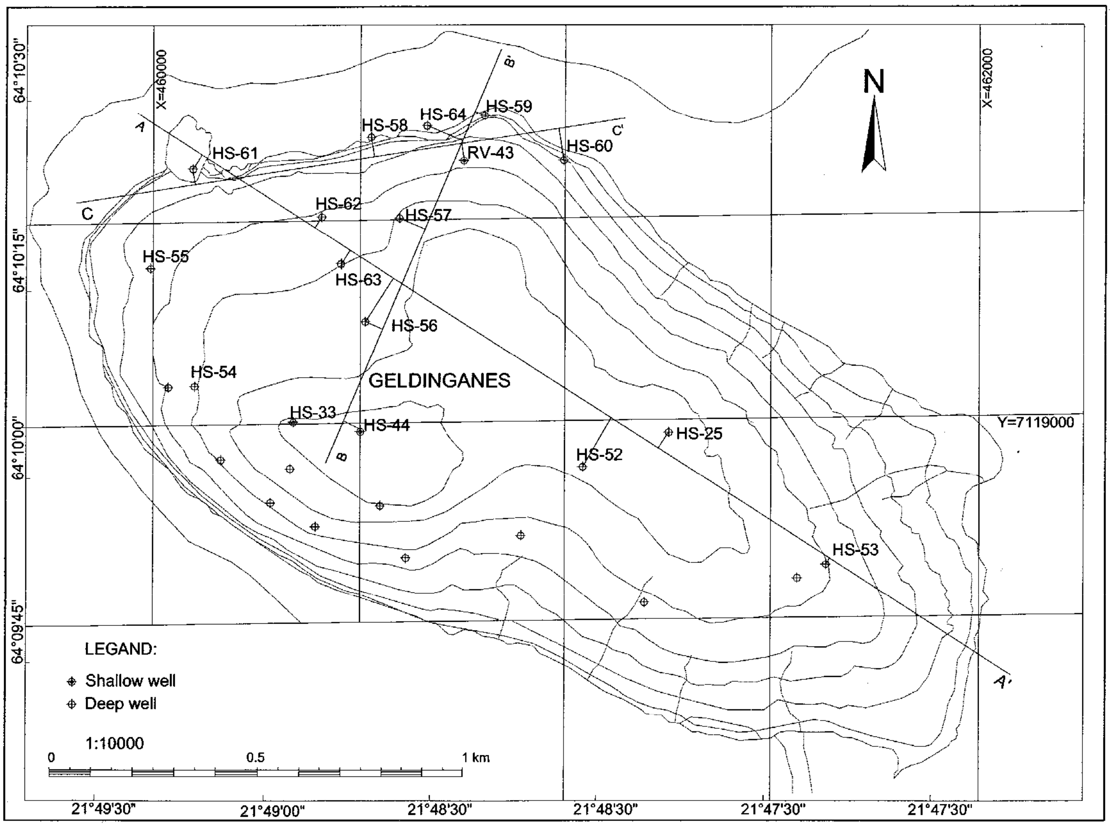

FIGURE 2: Map showing locations of wells and cross-sections in the Geldinganes area

indicating geothermal circulation. Four representative temperature profiles are presented in Figures 3-6, one from a shallow well with a profile of the former type and three profiles from the deeper wells. Other temperature logs from all the wells are presented in Appendix I.

TABLE 1: General characteristics of the wells in the Geldinganes area used in this study

Well No.	Depth (m)	Elevation (m a.s.l.)	Easting(s) (m)	Northing(s) (m)	Bottom hole temp. (°C)	Estimated temp. gradient (°C/m)	Remarks
HS-25	103	33.46	461,250	7,118,950	26.9	0.226	Exploration well
HS-33	340	35.38	460,340	7,119,000	98.0	0.266	Exploration well
HS-44	1265	37.5	460,500	7,118,970	103.3	0.252	Exploration well
RV-43	1820	21.8	460,750	7,119,620	111.2	0.231	Production well
HS-52	122	31.25	461,045	7,118,870	32.8	0.151	Exploration well
HS-53	100	26.43	461,645	7,118,625	19.1	0.292	Exploration well
HS-54	117	18.18	460,100	7,119,090	38.8	0.331	Exploration well
HS-55	102	16.77	460,000	7,119,385	38.4	0.335	Exploration well
HS-56	98	28.56	460,510	7,119,250	38.3	0.416	Exploration well
HS-57	102	23.60	460,595	7,119,500	44.5	0.406	Exploration well
HS-58	103	8.63	460,595	7,119,700	47.9	0.408	Exploration well
HS-59	103	9.61	460,800	7,119,750	47.8	0.334	Exploration well
HS-60	124	10.85	460,995	7,119,640	46.0	0.284	Exploration well
HS-61	123	12.94	460,170	7,119,620	39.8	0.363	Exploration well
HS-62	123	17.85	460,455	7,119,510	50.2	0.356	Exploration well
HS-63	117	23.2	460,450	7,119,385	46.2	0.428	Exploration well
HS-64	125	9.1	460,665	7,119,725	60.0	0.311	Exploration well

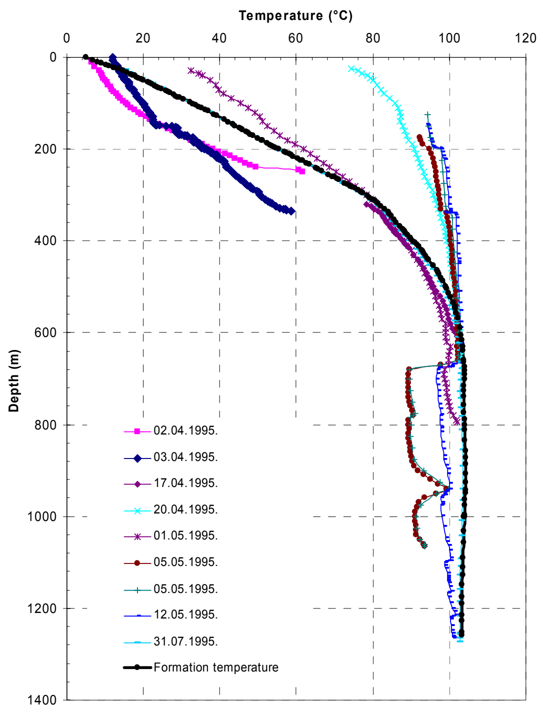

FIGURE 3: Temperature profiles for well HS-

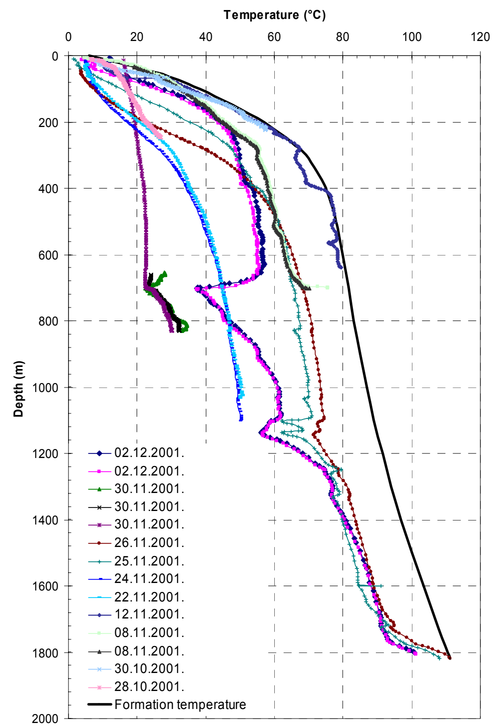

FIGURE 4: Temperature profiles for well RV-43

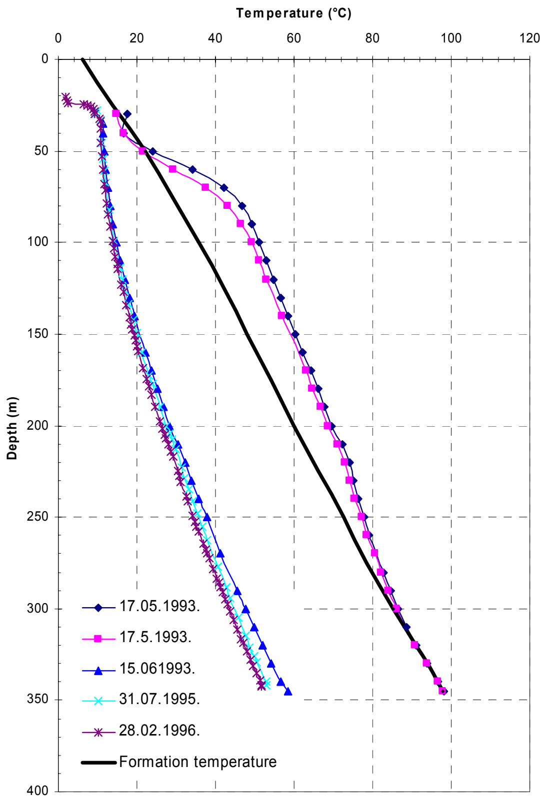

FIGURE 5: Temperature profiles for well HS-33

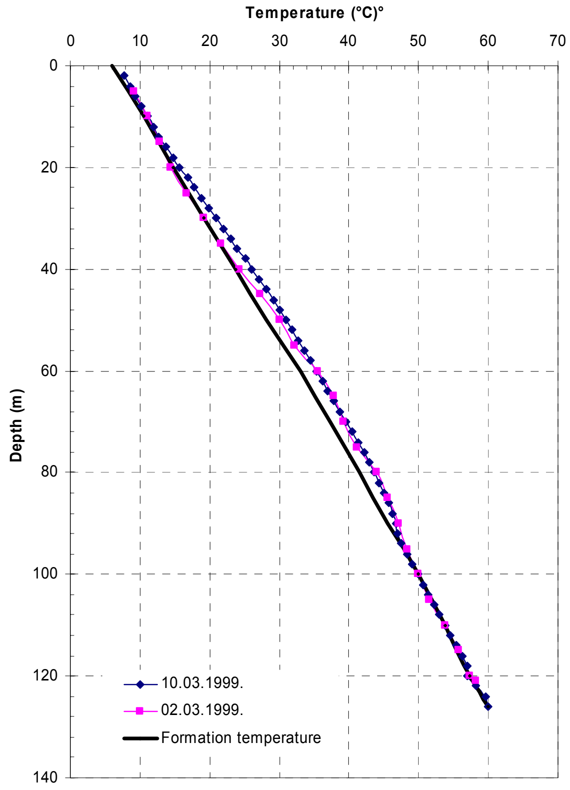

FIGURE 6: Temperature profiles for well HS-64

In order to delineate hot water flow paths in the Geldinganes reservoir, three temperature cross-sections were generated by using the estimated formation temperature profiles from the wells along each cross-section (Figures 7-9). Locations of the cross-sections are shown in Figure 2. Four temperature contour maps at 50, 100, 150 and 200 m depth were also generated for this purpose (Figures 10-13). A temperature gradient map at 200 m depth was also generated (Figure 14).

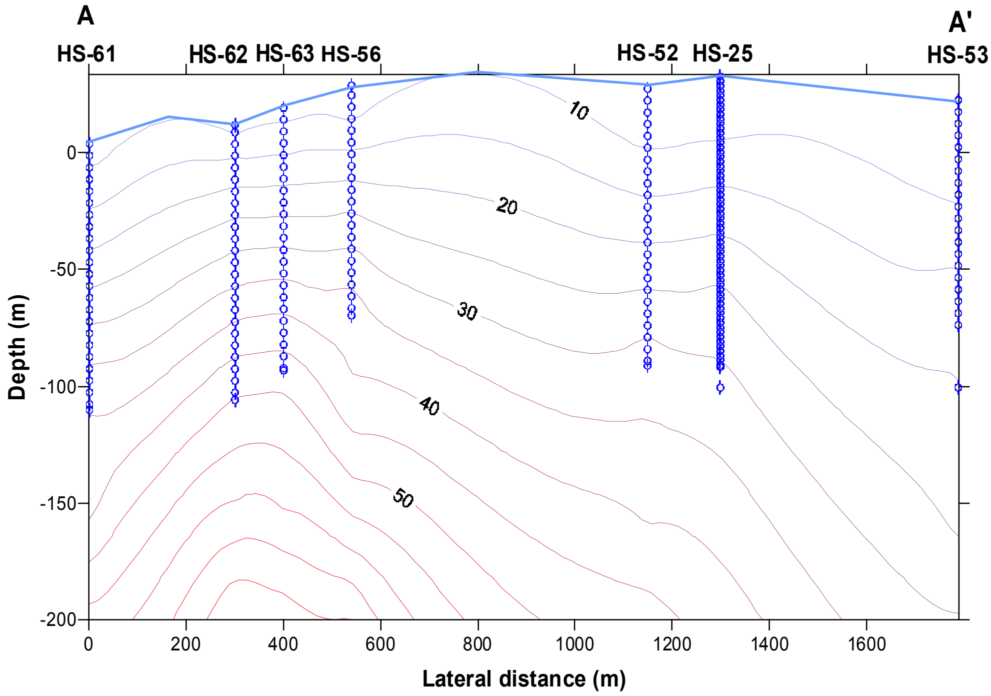

FIGURE 7: Temperature cross-section A-A′

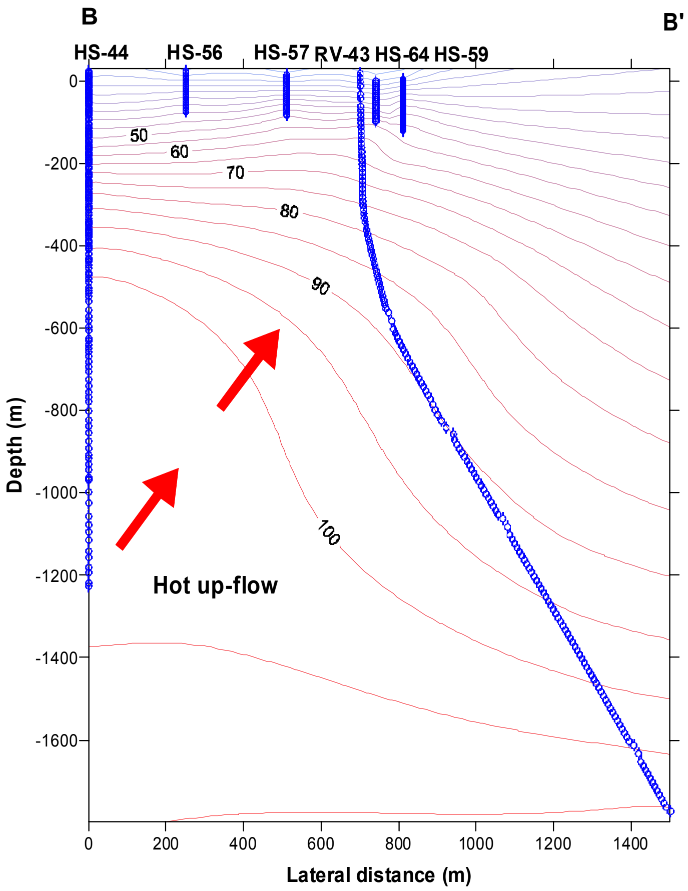

FIGURE 8: Temperature cross-section B-B´

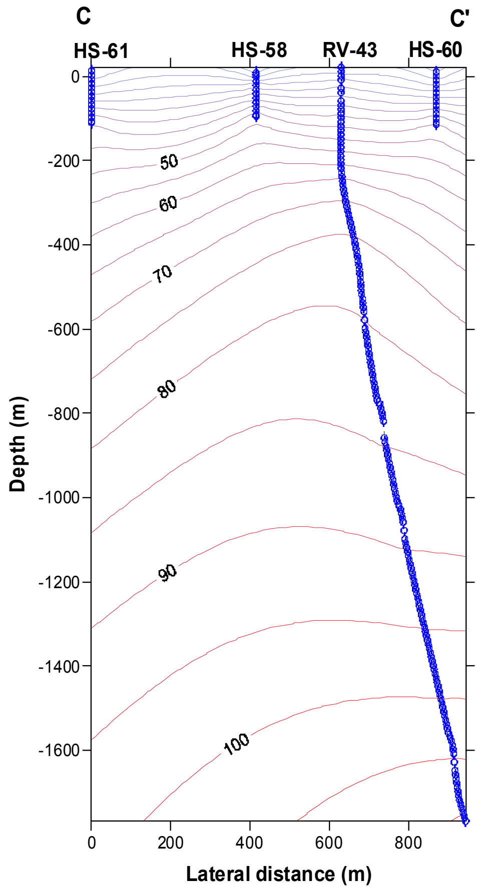

FIGURE 9: Temperature cross-section C-C´

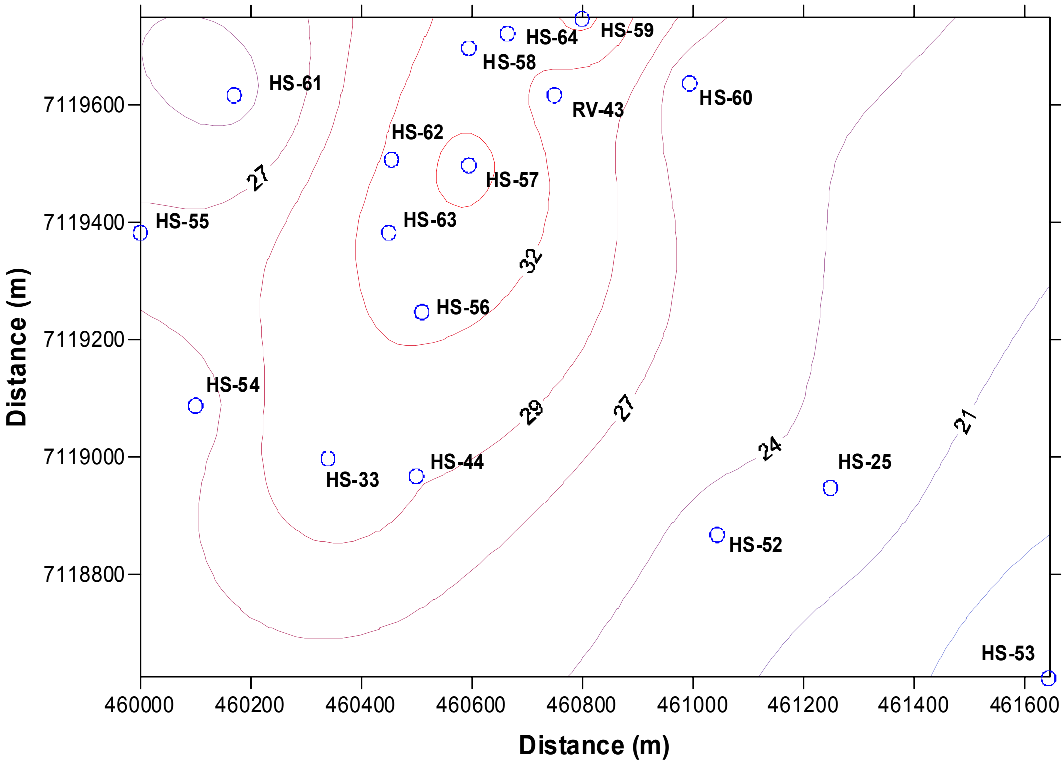

FIGURE 10: Temperature contour map at 50 m depth

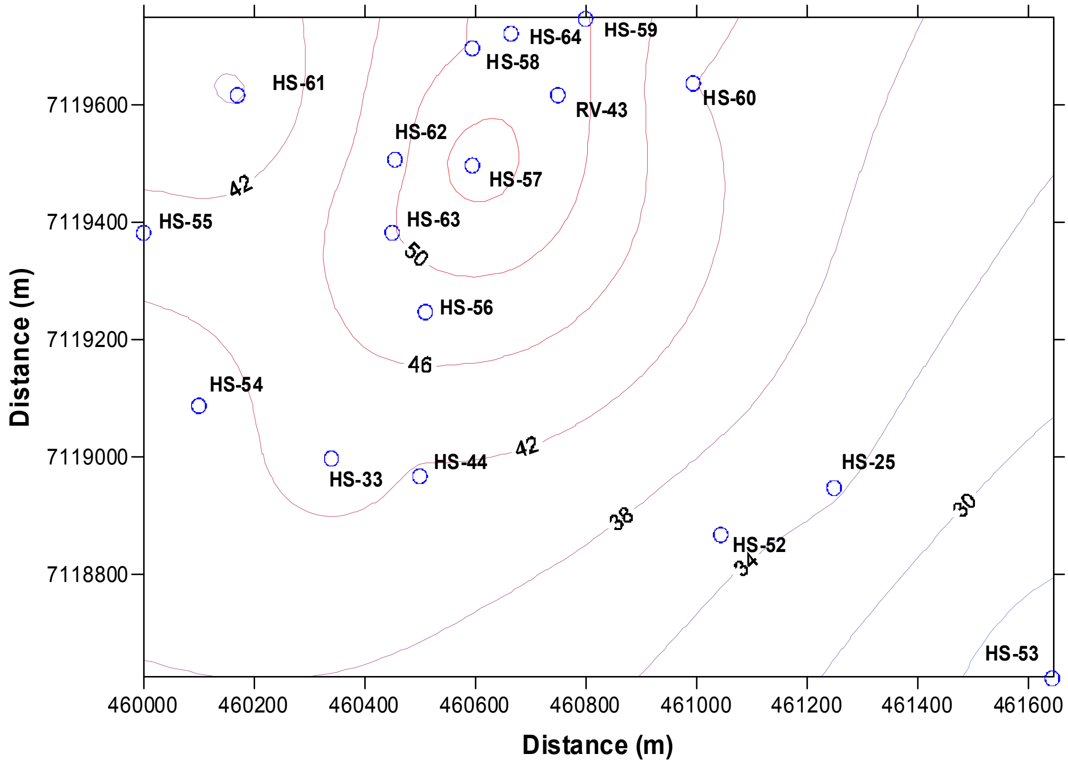

FIGURE 11: Temperature contour map at 100 m depth

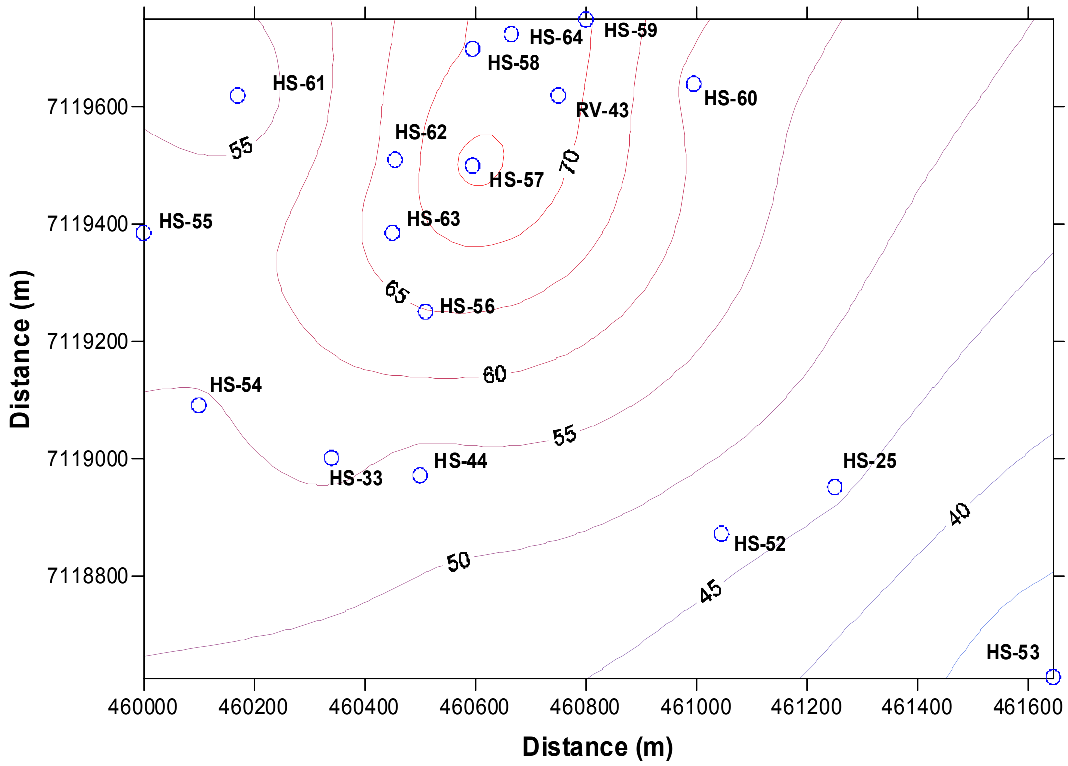

FIGURE 12: Temperature contour map at 150 m depth

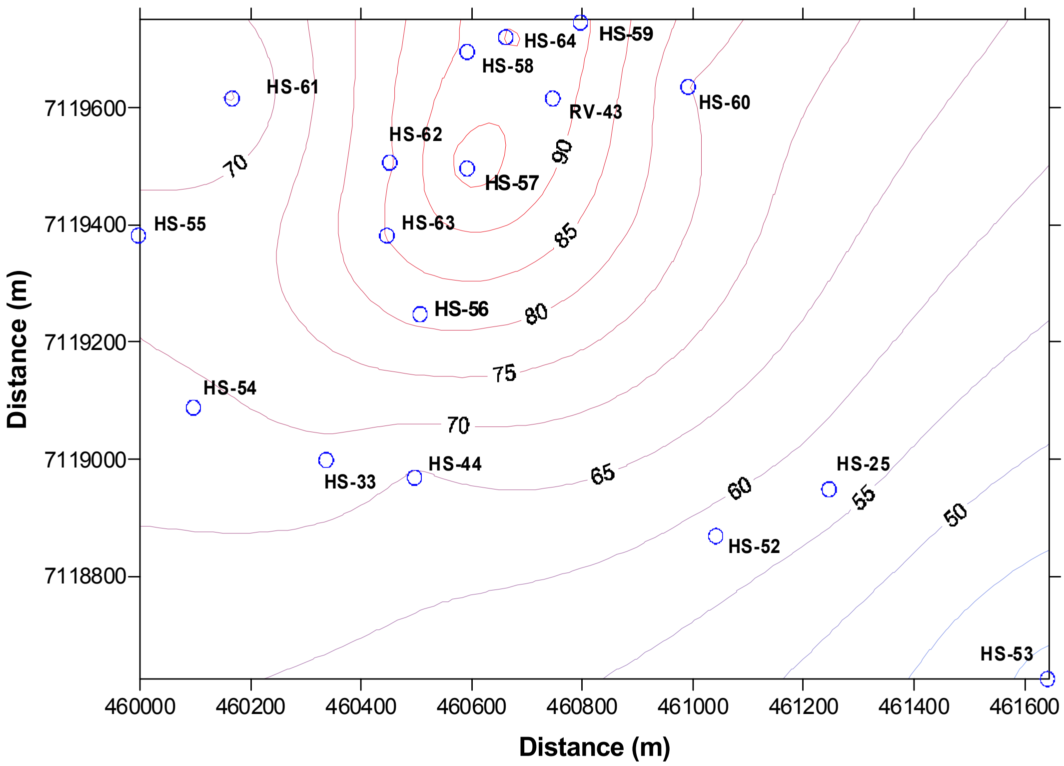

FIGURE 13: Temperature contour map at 200 m depth

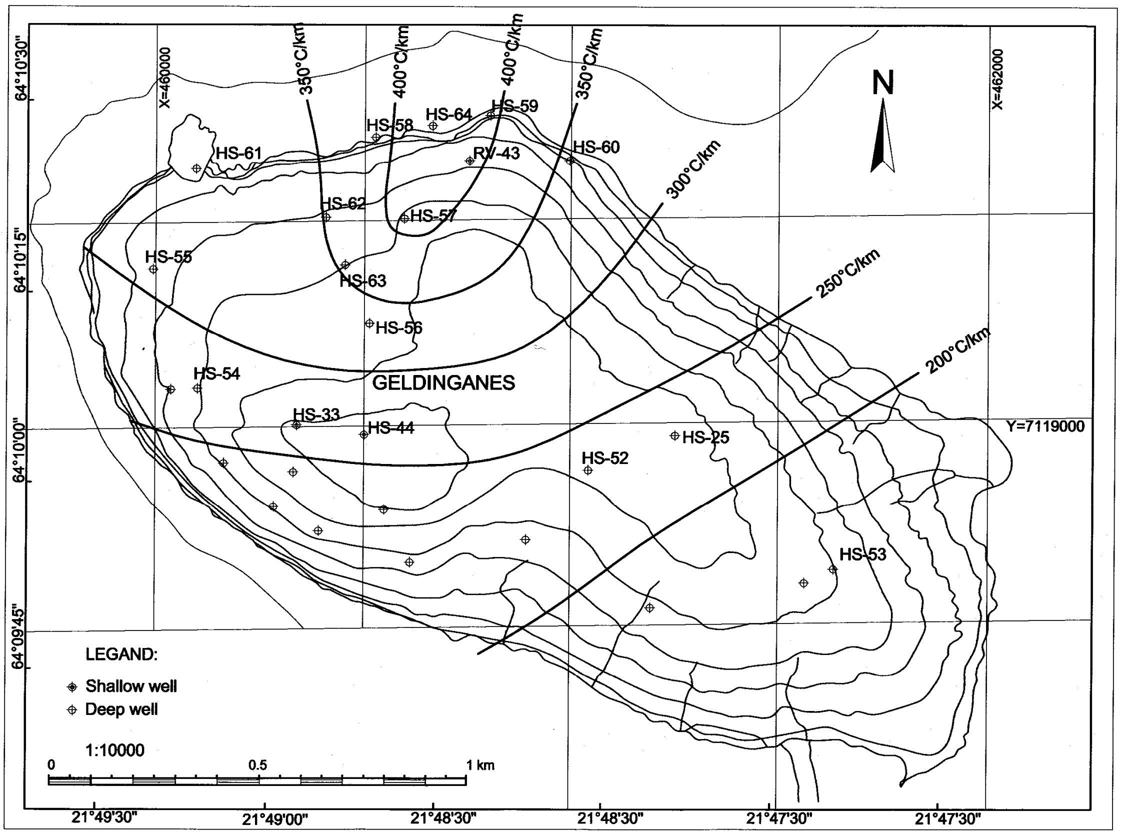

FIGURE 14: Temperature contour gradient map in the Geldinganes area at 200 m depth

Both the temperature cross-sections and temperature contour maps indicate an up-flow directed from south-southwest to north-northeast. The up-flow appears to flow from depth in the southern part of Geldinganes near well HS-44 and flow up to shallower formations near well HS-57. The temperature of the up-flow is about 105°C at 1200 m depth. The up-flow may be along a near-vertical geological structure, such as a fracture zone. This result contradicts the earlier conceptual model of the Geldinganes field.

4. WELL TEST ANALYSIS

A well test is usually the most important tool available for estimating hydrological parameters in geothermal and other hydrological systems (Axelsson, 2004; Bödvarsson and Witherspoon, 1989). According to the interpretation of temperature conditions and the purpose of a study, different well test methods are selected and used. Pressure transient methods have been used extensively as important well test methods, to evaluate the parameters of geothermal reservoirs. In most cases, the parameters obtained from such well tests are the formation permeability (or transmissivity) and the storage coefficient. Sometimes, the characteristics of a well, such as well bore storage, skin factor and turbulence factor, can also be estimated by analyzing well test data.

A rather long well test using a down-hole pump was carried out in well HS-44, from August 31 through November 11, 1995, with a total duration of about 17 days, or about 410 hours. Pressure changes were measured in the well itself during the test, and they are presented as water level changes in Figure 15 along with the pumping rate.

By plotting water level versus flow-rate, and using a polynomial regression equation (Bödvarsson and Witherspoon, 1989), the pressure loss caused by turbulent flow can be estimated. The water level changes, H, in a well area are described by:

$$H = H_o + BQ + CQ^2 \tag{1}$$

where Q = Flow-rate (l/s);
H_o = Water level in the production well at zero flow (m);
BQ = Linear drawdown in the reservoir, caused by Darcy (laminar) flow (m);
CQ^2 = Pressure loss caused by turbulent flow at the location of inflow into the well and inside the well (m).

Figure 16 shows the relationship between water level and flow rate in well HS-44.

4.1 Semi-logarithmic well test analysis

The so-called Theis model, which assumes that a reservoir is homogeneous, isothermal, isotropic, horizontal, of uniform thickness and infinite in radial extent, and that the fluid follows Darcy's law, is the model most commonly used to analyze pressure transient well test data (Horne, 1995). The Theis model solution can be approximated as:

$$P_i - P(r,t) = \frac{2.303q\mu}{4\pi kh} \cdot \left[\log\left(\frac{4k}{\mu c_t r^2}\right) - \frac{\gamma}{2.303}\right] + \frac{2.303q\mu}{4\pi kh}\log(t) \tag{2}$$

The above equation is of the form $\Delta P = A + m \log t$, which is a straight line with the slope m on a semi-logarithmic graph, where:

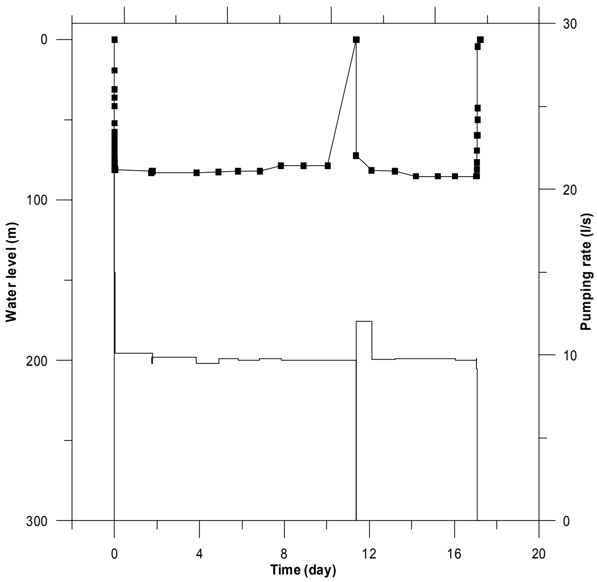

FIGURE 15: Water level changes and pumping rate during the HS-44 well test

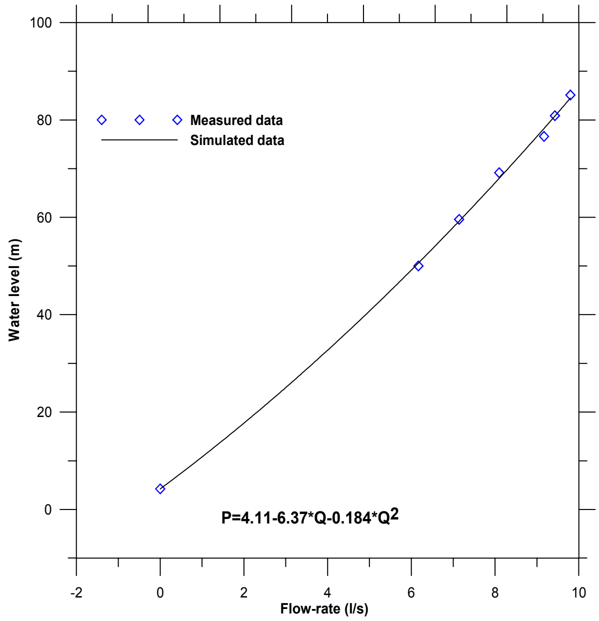

FIGURE 16: Relationship between water level and flow rate in HS-44

$$\Delta P = P_i - P(r,t); \quad A = \frac{2.303 q\mu}{4\pi kh}\left[\log\left(\frac{4k}{\mu c_t r^2}\right) - \frac{\gamma}{2.303}\right]; \quad \text{and} \quad m = \frac{2.303 q\mu}{4\pi kh}\log(t) \tag{3}$$

The formation transmissivity, T, can be calculated from the slope of the semi-log straight line by:

$$T = \frac{kh}{\mu} = \frac{2.303 q}{4\pi m} \tag{4}$$

If the temperature is known, then the dynamic viscosity, μ, can be inferred from steam tables, and thus the permeability thickness, kh, can be calculated as follows:

$$kh = \mu\frac{2.303 q}{4\pi\, m} \tag{5}$$

The formation storativity or storage coefficient, $S = c_t h$, is then obtained from the intercept with the ΔP axis when the permeability thickness is known. The Theis solutions can then be written as:

$$\frac{\Delta P}{m} = \left[\left[\log\left(\frac{4kh}{\mu}\right)\left(\frac{1}{S}\right)\left(\frac{t}{r^2}\right)\right] - \frac{\gamma}{2.303}\right] \tag{6}$$

or

$$10^{+\frac{\Delta P}{m}} = \left(\frac{kh}{\mu}\right)\left(\frac{1}{S}\right)\left(\frac{t}{r^2}\right)\left(4\times 10^{\frac{-\gamma}{2.303}}\right) \tag{7}$$

And the storage coefficient can be obtained by:

$$S = 2.25\left(\frac{kh}{\mu}\right)\left(\frac{t}{r^2}\right)\times 10^{\frac{-\Delta P}{m}} \tag{8}$$

Since, the transmissivity, $T = kh/\mu$, then:

$$S = 2.25T\left(\frac{t}{r^2}\right)\times 10^{\frac{-\Delta P}{m}} \tag{9}$$

These equations imply that the skin factor equals zero. Thus, a plot of ΔP vs. log t gives a semi-log straight line response for the infinite acting radial flow period of a well, and is referred to as semi-log analysis. The semi-log analysis is based on the location and interpretation of the semi-log straight line response that represents the infinite acting radial flow behaviour of the well. However, as the wellbore has finite volume, it becomes necessary to determine the duration of the wellbore storage effect, or the time at which the semi-log straight line begins (Hjartarson, 2004).

The semi-log method was used to analyze the pressure changes data from the well HS-44, with corresponding permeability thickness and storage coefficient estimated. The results are presented in Table 2. It should be mentioned here that only the first 10 minutes, or so, of the data set from well HS-44 were used when applying the semi-log method (Figure 17). After that the effect of a constant pressure boundary or increased recharge dominated the pressure changes.

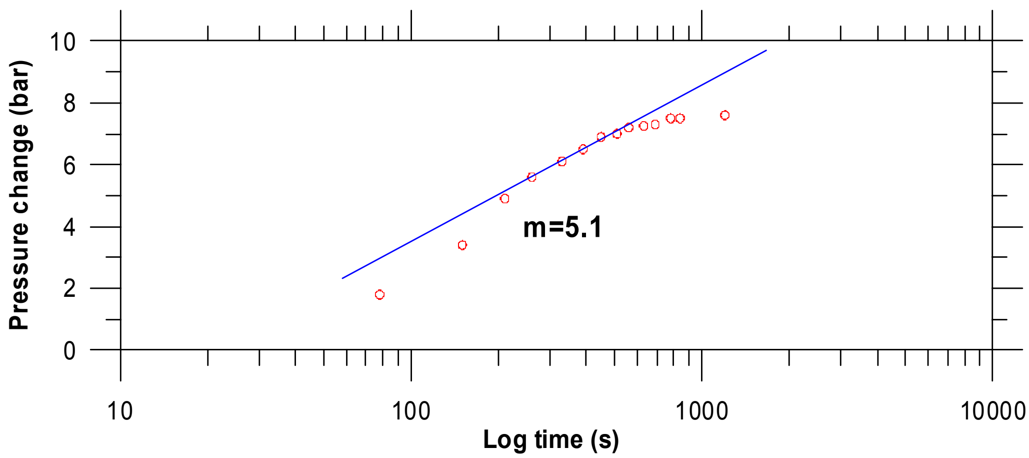

FIGURE 17: Plot of pressure changes vs. logarithmic time in well HS-44

4.2 Dimensionless variables and type curve well test analysis

Well test analysis often makes use of dimensionless variables in order to simplify the reservoir models by embodying reservoir parameters, thereby generating the pressure equations and solutions (Hjartarson, 2004). They have the advantage of providing model solutions that are independent of any particular unit system. Different reservoir models may have different boundary conditions giving rise to different solutions of the pressure diffusion equation. Some of the solutions are mathematically complicated, and are therefore expressed as type curves that are dimensional solutions associated with a specific reservoir model. An appropriate reservoir model for a specific well test is found by plotting pressure transient data from a well test on a log-log graph and comparing it with various type curves. The following dimensionless variables are substituted in the pressure diffusion equation:

Dimensionless pressure

$$P_D = \frac{2\pi kh}{q\mu}\left(P_i - P(r,t)\right) \tag{10}$$

Dimensionless time

$$t_D = \frac{kt}{c_t \mu r^2} \tag{11}$$

Dimensionless radius or distance

$$r_D = \frac{r}{r_W} \tag{12}$$

Generally, the procedure for type curve analysis is as follows:

- The data is plotted as log ΔP vs. log Δt on the same scale as that of the type curve.
- The curves are then moved, one over the other, by keeping the vertical and horizontal grid lines parallel until the best match is found.
- The best match is chosen and the pressure and time values are read from fixed points on the graphs, ΔP_M, P_{DM}, Δt_M, and t_{DM}.
- For an infinite acting system (Theis-model), the transmissivity, T, is evaluated from:

$$T = \frac{kh}{\mu} = \frac{q}{2\pi} \frac{P_{DM}}{\Delta P_M} \tag{13}$$

- And the storativity, S, is calculated by:

$$S = c_t h = \frac{kh}{\mu r_w^2} \frac{\Delta t_M}{t_{DM}} \tag{14}$$

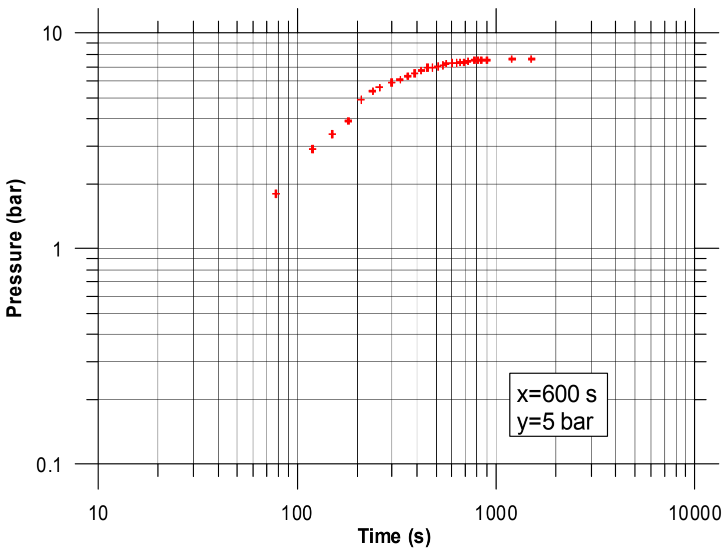

FIGURE 18: A log-log plot of pressure draw-down vs. time, type curve method

The type curve method was used to analyze the pressure draw-down data from well HS-44 (Figure 18) with corresponding permeability thickness and storage coefficient estimated. The results are presented in Table 2, along with the results from the semi-log method.

Table 2 shows that the results obtained with the two different methods are quite comparable. In addition, the permeability-thickness, which is estimated to be of the order of 1.6 Dm, is rather low. The storativity value is realistic.

TABLE 2: Results of well test analysis for well HS-44

Well number	Transmissivity, kh/μ (10^{-9} m^3/Pa-s)		Permeability thickness, kh (Dm)		Storativity, $c_t h$ (10^{-5}m/Pa)	
	Type curve	Semi-log	Type curve	Semi-log	Type curve	Semi-log
HS-44	4.22	4.77	1.54	1.74	2.01	1.88

5. SIMPLE LUMPED PARAMETER MODELLING

The three-dimensional, numerical reservoir simulators which have been developed to date, are complicated tools which require substantial man-time and computer power. These are generally applied during the last stage of a geothermal exploration phase, for example when the decision to construct a new power plant is taken. One alternative to the detailed numerical modelling of complex fluid rock systems is lumped parameter modelling (Axelsson, 1989). Lumped modelling is probably the most powerful of the simple modelling methods. In lumped models, the hydrological properties of a reservoir are lumped together in one or two quantities for several sub volumes of a reservoir. This is analogous to the methods used for system analysis in electrical and mechanical engineering. Simple lumped parameter models can be used to predict responses of a reservoir to different future production schemes and the model gives some insight into the properties of a reservoir being simulated. In this chapter, the method of lumped parameter modelling of Axelsson (1989) is applied for the interpretation of water level and production data from the Geldinganes geothermal area (well HS-44).

5.1 The LUMPFIT computer program

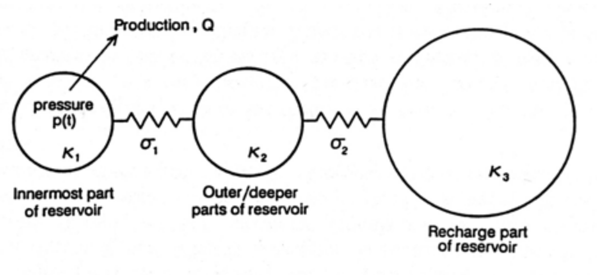

FIGURE 19: A three-tank closed lumped parameter model (Axelsson, 1989)

The lumped model, applied in this work, consists of a few capacitors or tanks that are connected by resistors (Figure 19). The program LUMPFIT, which employs a non-linear, iterative, least-squares procedure, is used (Axelsson and Arason, 1992). The tanks simulate the storage of different parts of the reservoir in question, whereas the resistors simulate the permeability. A tank in a lumped parameter model has a mass storage coefficient κ. The tank responds to a load of liquid mass m with a pressure increase given by $p=m/\kappa$. The mass conductance of a resistor in a lumped model is σ when it transfers $q=\sigma\Delta p$ units of liquid mass per unit time at the impressed pressure differential, Δp. The pressures in the tanks simulate the pressures in different parts of the reservoir, whereas production from the reservoir is simulated by withdrawal of water from one of the tanks (Axelsson, 1989). Lumped models can either be open or closed. The open models are connected by a resistor to an infinitely large imaginary reservoir, which maintains a constant pressure. On the other hand, closed, lumped models are isolated from any external reservoir. Actual reservoirs are most generally represented by a two- or three-tank closed or open lumped parameter model (Axelsson, 1989).

Different lumped parameter models were used to simulate the water level response data for well HS-44 from August 31 and November 11, 1995, with a total duration of about 17 days. A two-tank closed model and a two-tank open model both yield similarly good fits. The results are shown in Table 3. The comparison between observed and simulated water level data is shown in Figures 20 and 21.

TABLE 3: Estimated reservoir properties for the Geldinganes system according to lumped parameter models (the thickness is assumed to be 800 m)

Model	Parameter	Value
Two-tank closed model	Volume (km^3) Surface area (km^2) Permeability (m^2)	6.75 13.5 6.6×10^{-15}
Two-tank open model	Volume (km^3) Surface area (km^2) Permeability (m^2)	1,68 3.4 6.3×10^{-15}

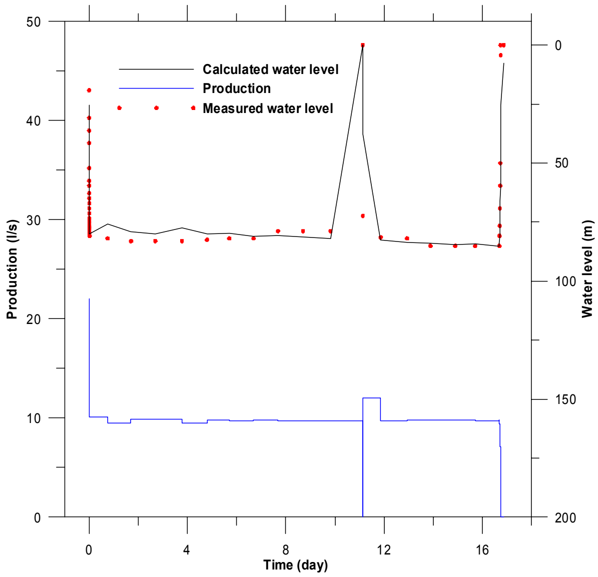

FIGURE 20: Water level changes in well HS-44 simulated by LUMPFIT with a two-tank closed model

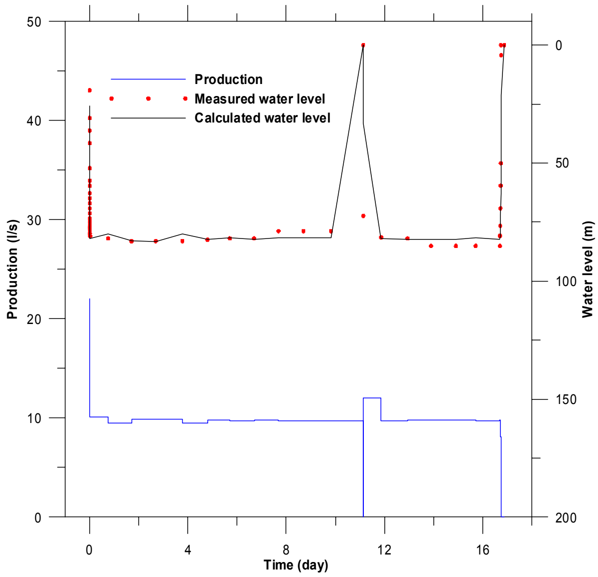

FIGURE 21: Water level changes in well HS-44 simulated by LUMPFIT with a two-tank open model

The results in Table 3 indicate a system surface area in the range of 3.4-14 km^2, which corresponds to a radius of 1-2 km, if a circular area is assumed. This appears to be realistic since the surface area of Geldinganes itself is about 2 km^2. The permeability values in the table correspond to a permeability-thickness of the order of 3 Dm. This is only slightly higher than the value presented in Table 2, 1.6. Dm.

5.2 Predicted water level changes

One of the main purposes of modelling is to use calibrated models for prediction. By calculating predictions based on a reliable model, responses of a reservoir to production loads, both favourable and unfavourable, can be forecasted. This will, in turn, help investors to better manage the geothermal resource and avoid or reduce financial risks. This is also the main reason why modelling plays an important role in successful geothermal resource management. As mentioned previously, both of the lumped parameter models can simulate the water level monitoring data equally well. Hence, the two models were both used to predict the water level changes under different production scenarios for 1 year (October 1995-October 1996).

- Scenario I: Production of 7 l/s from October, 1995 to October, 1996;
- Scenario II: Production of 12 l/s from October, 1995 to October, 1996;
- Scenario III: Production of 20 l/s from October, 1995 to October, 1996.

The predicted water level drawdown for each of the scenarios is shown in Figures 22-24, as well as in Table 4. The figures show that the predicted water levels, according to the two different models, are quite different for the same scenario. This is because open models give optimistic predictions (minimum draw-down) and closed models pessimistic ones (maximum draw-down) and the divergence between the two is quite great when the underlying data-series is short (only 17 days in this case). The actual response of this well to long-term production may be expected to lie somewhere between these two extremes, which also may be looked upon as giving an estimate of the uncertainty in the predictions. These predictions show that if one allows for a maximum draw-down of the order of 200 m, then the production potential of well HS-44 is in the range of 7-20 l/s for a pessimistic and optimistic estimate, respectively.

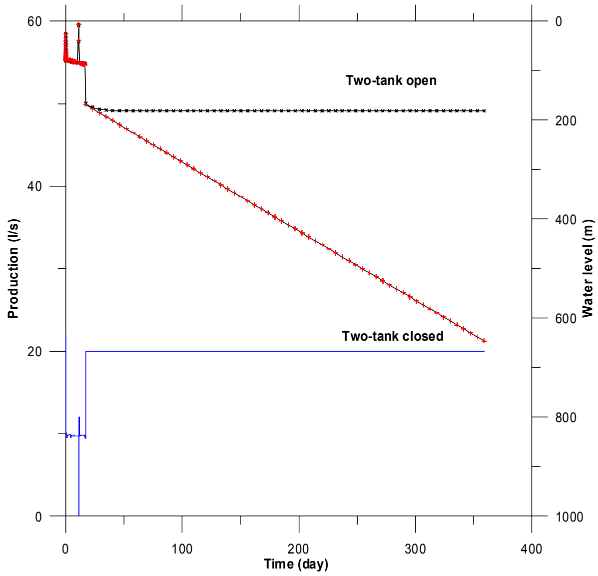

FIGURE 22: Predicted water level changes in well HS-44, scenario I

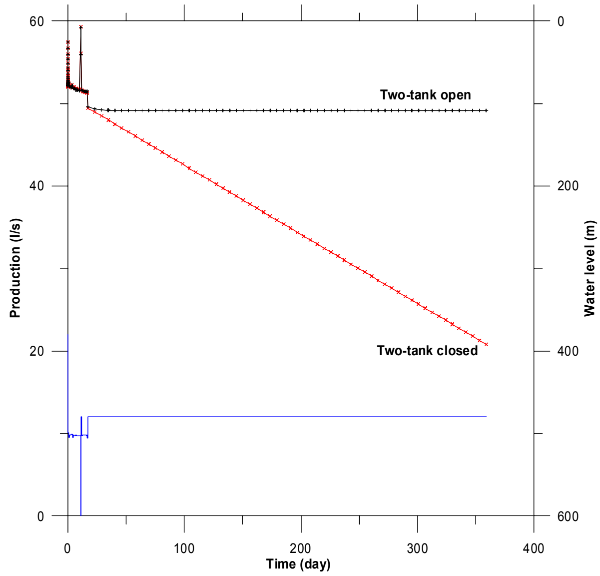

FIGURE 23: Predicted water level changes in well HS-44, scenario II

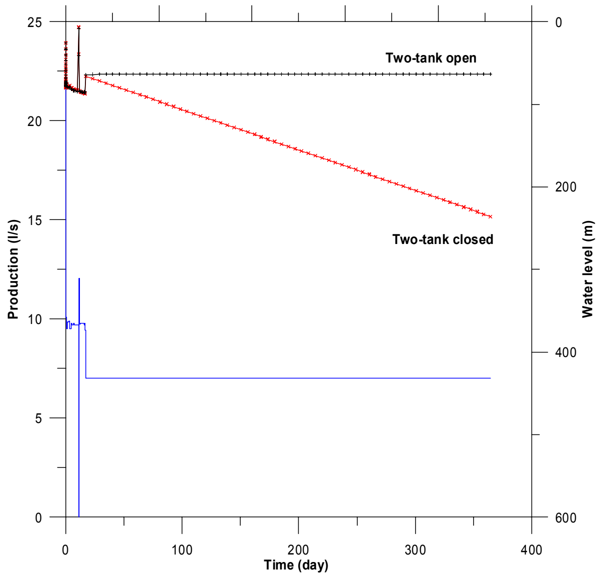

FIGURE 24: Predicted water level changes in well HS-44, scenario III

At the end of drilling of well RV-43 in November 2001, it was clear that the well was not very productive. A few hour airlift test yielded only 2-3 l/s with a water level draw-down of about 180 m. Therefore, it was attempted to try to simulate the well through high-pressure well-head injection. Simulation attempts were conducted at variable flow-rate for about 64 hours, with the maximum flow-rate being 60 l/s at which the well-head pressure reached about 101 bar. Following the simulation attempts, the well was airlift tested again for a few hours yielding about 8 l/s with a draw-down of about 210 m. Thus it is clear that the simulation has been partly successful. Well RV-43 turned out to be considerably less productive than had been anticipated, however, and it was clear that the well had not intersected any good fractures, or feed-zones. Well RV-43 is, in fact considerably less productive than well HS-44 (see above).

TABLE 4: Lowest water levels (m) predicted by two lumped parameter models, at the end of the 1 year prediction period for scenarios I-III

Model	Scenario I	Scenario II	Scenario III
Two-tank closed model	645	390	235
Two-tank open model	181	108	63

6. THE SHIVERT HOT SPRING AREA

6.1 General background

The Shivert hot spring area is located in the Khangai area in central Mongolia (Figure 25). The Khangai region has wide open valleys with huge rounded mountains, the highest reaching an altitude of 3905 m. The Khangai mountain range is over 750 km long, stretching from west to southeast in the central portion of Mongolia, with peaks of 3200-3500 m. The main mountain range has several big branch ranges. The elevation of the hot springs in the Khangai region is in the range of 1335-2500 m.

The latest active tectonic period in Mongolia started at the end of the Mesozoic and beginning of the Oligocene, due to the simultaneous development of the south Siberian plate (mountain part) and Baikal Lake region. At that time, intense tectonic development caused an accumulation of "thermal energy sources" (magma intrusions) located near the surface under the Khangai and Khentii mountain regions. Geothermal resources in Mongolia are mainly distributed in the Khangai and Khentii regions. They are also found in the Khovsogol region and in the Altai Mountains as well as in the Dornod-Dariganga area in eastern Mongolia and the Orkhon-Selenge area in N-Mongolia. Their existence is the result of development during the second geodynamic Cenozoic age. The Khangai geothermal area has attracted the interest of researchers, and its location is favorable with regards to social and economic conditions (Ministry of Agriculture and Industry of Mongolia, 1999). Figure 26 shows a map of hot springs and main faults in the Khangai area (Jamyandorj et al., 1990).

Mongolia consists of 21 provinces (approx. 50,000-110,000 people in each province), and each province consists of 12-22 "soums" (administration units comparable to villages, each "soum" has approx. 4,000-5,000 inhabitants). The Khangai geothermal region covers 4 provinces in the central part of Mongolia and has an area of about 150,000 km^2, which is slightly greater than the surface area of Iceland.

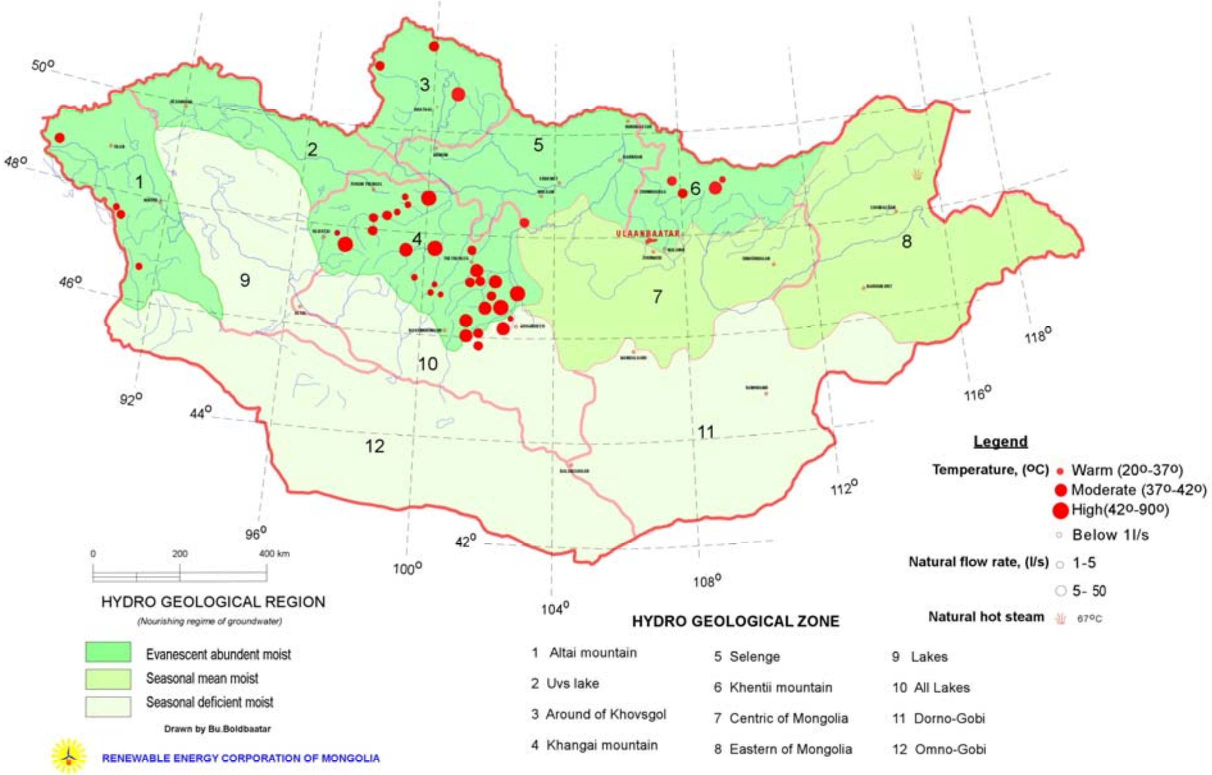

FIGURE 25: Hydrogeological regions and location of hot springs in Mongolia

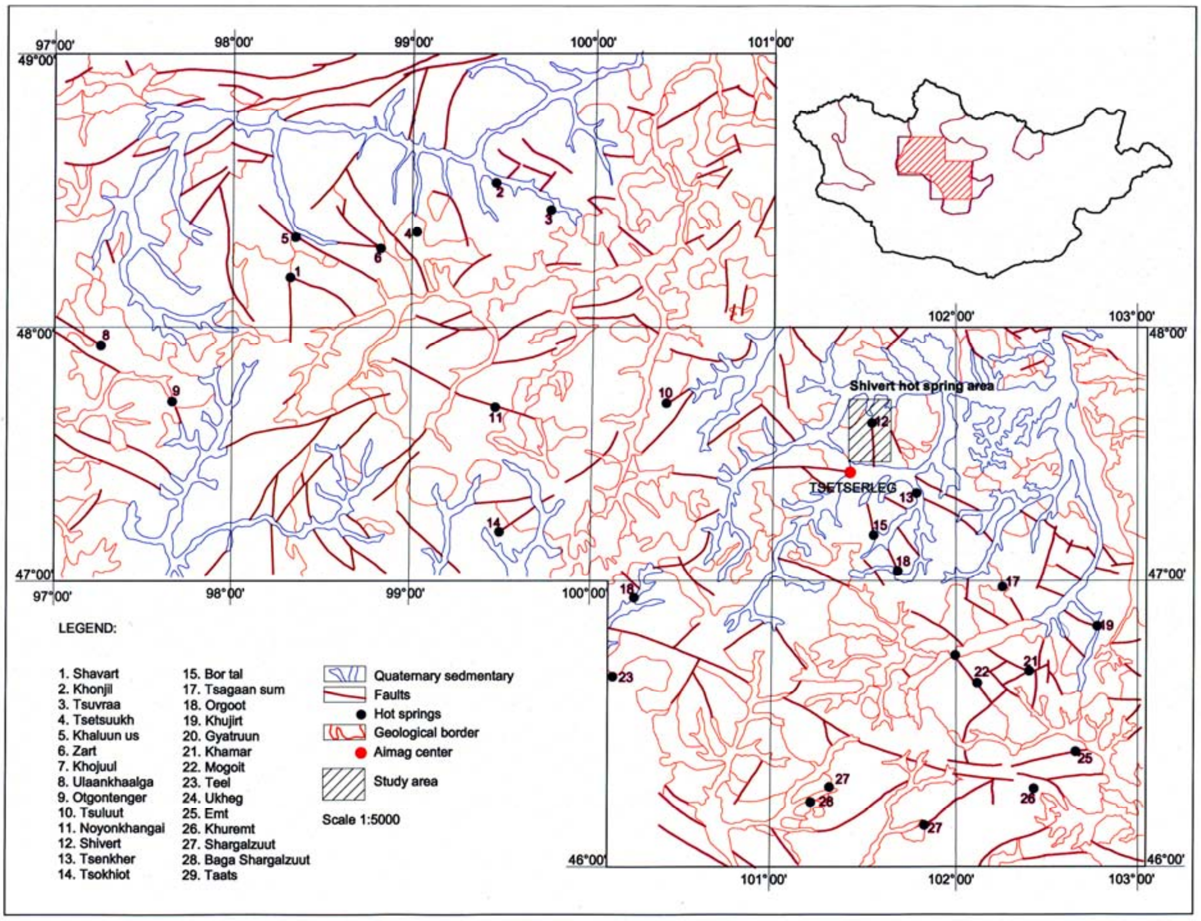

FIGURE 26: Map of hot springs and main faults of the Khangai geothermal region

A recent pre-feasibility study "Geothermal project in Tsetserleg, Mongolia" was written in cooperation by ISOR Iceland Geosurvey, Fjarhitun Geothermal Consultants, and Rafhönnun Consulting Engineers on behalf of the Icelandic side; and the Renewable Energy Corporation on behalf of the Mongolian side (Elíasson et al., 2004). The report concludes that there are clear indications that geothermal energy can be economically developed in Tsetserleg in the Khangai region, and in several other towns in the Khangai area where the main geothermal activity is (Elíasson et al., 2004).

6.2 Hydrological conditions in Mongolia

There are more than 3,800 rivers and streams with regular run-off in Mongolia. The total length of the river network is about 6,500 km. There are 186 glaciers with a total volume of 62.5 km^3 and 3500 large lakes covering a total surface area of 15,600 km^2 (surface area of each exceeding 0.1 km^2) with a total volume of 500 km^3 and 8,000 river outlets (Table 5). There are three major drainage basins in Mongolia (details see Table 6):

- Rivers in the west drain to the enclosed Basin of Central Asia;
- Rivers in the north drain to the Arctic Ocean;
- Rivers in the east drain to the Pacific Ocean.

The territory of Mongolia is also divided into three main hydro-geological zones, based on availability of moisture in the earth (Figure 25), (Geodesy and Cartographical Institute, 1990). Subsequently, the hydro-geological regions are subdivided into twelve sub-zones. Most of the hot springs in Mongolia are located in the region of evanescent abundant moisture as Figure 25 demonstrates.

The potential water resources of the country are estimated to be about 36.4 km^3. Of this, the surface water resources are 22.0 km^3 and the usable groundwater resources are 12.6 km^3. About 78% of the river run-off is formed on 36% of the territory in the northern, western, and northeastern mountainous areas, and 22% per cent is formed on 64% of the territory in the south of the country.

TABLE 5: Types of surface water in Mongolia (UNEP, 2002)

Surface water	Number	Length (km)	Area covered (km^2)
Rivers	3,811	67,080	
Lakes	3,500		15,640
Glaciers	187		540
Springs	6,899		
Mineral waters	250		

TABLE 6: Watershed distribution in Mongolia (UNEP, 2002)

Name of drainage basin	Area (10^3 km^2)
Arctic Ocean	320
Pacific Ocean	197
Enclosed basin,	
with permanent run off	426
with permanent flow	621
Total	1564

TABLE 7: Water balance in Mongolia (UNEP, 2002)

Item	Volume (km^3)
Total annual precipitation	360
Total annual run-off:	36.6
surface run-off	24.6
ground water flow	12
Total soil moisture	202
Total evaporation	190

If one considers that the total evaporation is 190.0 km^3, on the average, the annual amount of water resources available per capita is 17,300 m^3. However, it ranges from 4,500 m^3 per capita in the Gobi area to 46,000 m^3 per capita in northern and central areas. The total mean annual precipitation over Mongolia is estimated to be 360 km^3 (Table 7) of water, or 230 mm per year (nationwide average). About 90% of this is lost through evapotranspiration, 4% infiltrates to aquifers, and 6% contributes to surface flow. At present, there are 107 observation guards and 17 stations in operation at 70 rivers, 1 spring and 9 lakes. The guards and stations undertake studies on water regime, quality and composition, including water biology samples. Statistically, the probability that Mongolia's total yearly surface run-off reaches 69.5 km^3 is about 5% (high flow) and the probability that it is above 23 km^3 is about 75%. In 2000, 19 km^3 of water originated in the territory of Mongolia. Mongolia's annual surface run-off has been increasing since 1988 and it reached its maximum of 78.4 km^3 in the year 2002. Water quality is found to be good in the mountainous areas of Mongolia and the rivers and surface streams originating in high mountain areas carry very clean water. It may also be mentioned that Mongolia is a country through which the world's main watershed line crosses (UNEP, 2002).

6.3 Previous work in the Shivert hot spring area

6.3.1 General information on the Shivert hot spring area

The Shivert hot springs area is located at 47°11’49”N and 101°30’54”E northeast from Tsetserleg, the province centre of Arkhangai province in the Khangai low-temperature region (Figure 27). The Shivert area is at an elevation of 1710 m a.s.l. (Namnandorj et al., 1966) and consists of 5 known hot springs and six wells. Data from 6 shallow exploration wells is available in the Shivert area, 5 of which were drilled by Mongolian and Russian scientists in 1980 (Dorj et al., 2003). General characteristics of the six wells are listed in Table 8. The borehole depths are in the range of 19-40 m. The average surface temperature of the hot springs is 55°C, and artesian flow rate of the hot springs is 4 l/s (Tseesuren, 2001). According to Dolgorjav (2003), the average surface temperature of the hot springs was 57.5°C in 2002.

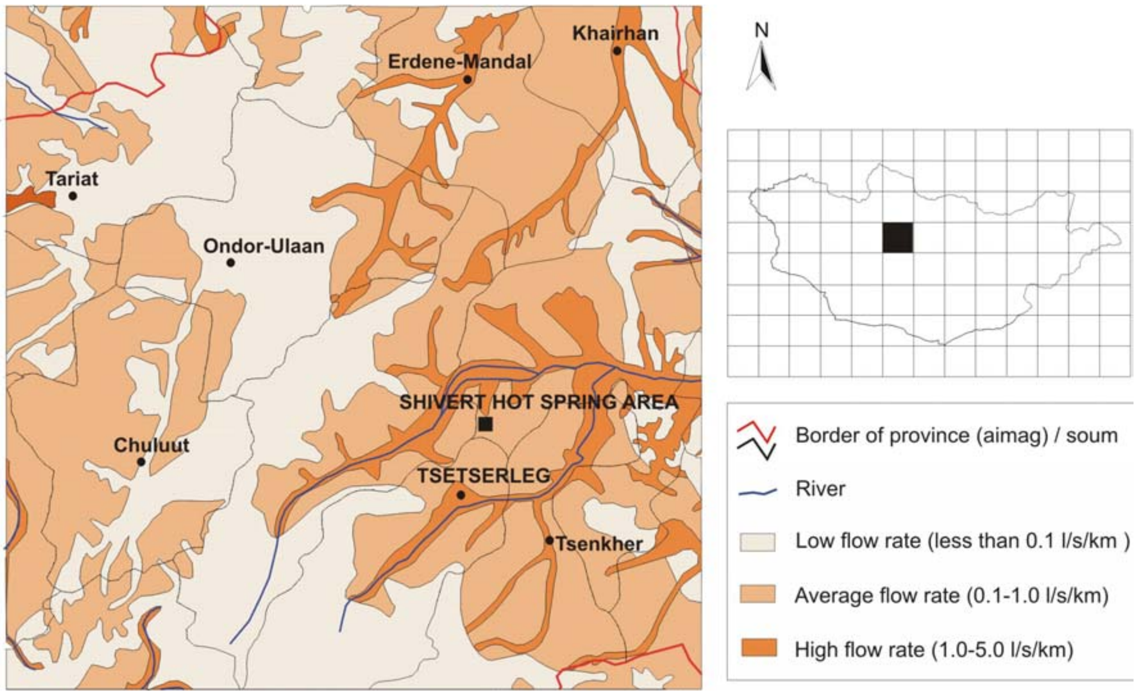

FIGURE 27: Ground water resources of the Khangai geothermal region

TABLE 8: General characteristics of wells in the Shivert hot spring area

Well No.	Depth (m)	Eastings	Northings	Max. well temperature (°C)	Bottom hole temperature (°C)	Temperature gradient (°C/m)	Remarks
SH-01	19	93.5	31.5	19	40	1.1	Exp. well
SH-02	40	89	34.5	25	57	0.8	Exp. well
SH-03	31	135	63	22	55	1.06	Exp. well
SH-04	26	0.0	0.0	6	16	0.38	Exp. well
SH-05	30	121	2.0	10	30	0.6	Exp. well
SH-06	36	100	120	7.63	12	0.12	Exp. well

6.3.2 Geological conditions in the Shivert area

The geological structure of the Shivert geothermal system is characterized by a Paleozoic rock formation and “fourth age” sedimentation (Dorj et al., 2003). It can be divided into two structural units in terms of lithology and tectonics. The deeper structure is composed of Paleozoic granites while the upper one is composed of continental sedimentary deposits. The boundary between the two is sharp and clear.

The Paleozoic group (Pz) formation is the older of the two units. It lies everywhere at the depth of 24-50 m. It is composed of pink granites, densely fissured in the zone of main weathering. At the site, the Paleozoic layer is completely covered by continental sediments, already mentioned. They can be classified into three generic types:

- Lake type sediment (dQ_{III-IV}), forming the central part of the area, lies at 10-20 m depth. It is composed of green gray clays, thin and fine green gray sand and middle-fine gray sand with a mixture of thin layers of clay. Total thickness of this sediment cover is no more than 10 m;
- Alluvial type (Q_{III-IV}) beds are found at 20-28 m depth and between 2 and 19 m depth. Both of these beds include gravel and boulders filled with dark brown sandy material. The thickness of the beds is between 7 and 9 m, respectively.
- Modern sedimentation (Q_{IV}^4) that may be divided into non-sorted sand and gravel found locally in the bed of the Shivert river with a thickness of 2-3 m and more widespread yellow-gray sandy layer with a thickness of 2.5-5.0 m.

6.3.3 Hydrogeological conditions in the Shivert area

The hydrogeological conditions in the area under study involve a complex system of artesian basins and intermountain depressions. The underground water is believed to accumulate in the weathered zone of the crust as well as in porous layers in the sediment cover. In addition, fracture zones provide channels for water accumulation and flow, in particular intersections of structures of different orientation. It should be noted that fissures and fractures cause specific hydrogeological conditions and play a key role in the geothermal activity.

Palaeozoic group fissure-vein water (Pz). Three separate fissure/fracture systems exist that carry the thermal water (30-57°C) which is mainly of the hydrocarbon-sulphuric type with mineralization of 0.35-0.36 g/l. The water ascends along the above-mentioned fractures playing the role of “donors” while the upper permeable beds play the role of “recipient”.

Water bearing complex of fourth sedimentation (Q_{IV}). This water bearing sediment complex is partly composed of not fully mature beds of sand and gravel, with some hydraulic connection between them. It contains hydrocarbon-sulphuric water with mineralization of 0.39-0.45 g/l. At a depth of 25-30 m, the water temperature reaches 12-14°C in general, while at the centre of the hot water up-flow (thermal water “dome”), the water temperature reaches 49°C at a depth of 19 m as measured in well SH-1. The free flow from this well varies greatly, from 0.8 to 4.7 l/s.

An analysis of the hydrogeological structures discussed above provides the basis for understanding the geothermal activity in the Shivert area. Obviously, the geothermal water originates in the Paleozoic granites and consequently rises up to the sediment cover where it converges in the hot-water up-flow ”dome” due to special geological conditions (network of fractures/fissures).

Boreholes in the centre of the up-flow “dome” (SH-02 and SH-03), have water with chemical content corresponding to the chemical content of water in the Paleozoic granites. Wells on the flanks of this region (boreholes SH-03-SH-06) have lower temperature and higher mineralization. The reason for the high mineralization is believed to be mixing with inflowing ground-water.

At last it should be mentioned that analysis of the hydrogeological conditions in the Shivert area indicates that the prospects of geothermal utilization are quite good. Reasonable output (mass-flow) is expected, and at temperatures considerably higher than encountered so far once deeper wells have been successfully drilled into the geothermal up-flow zone.

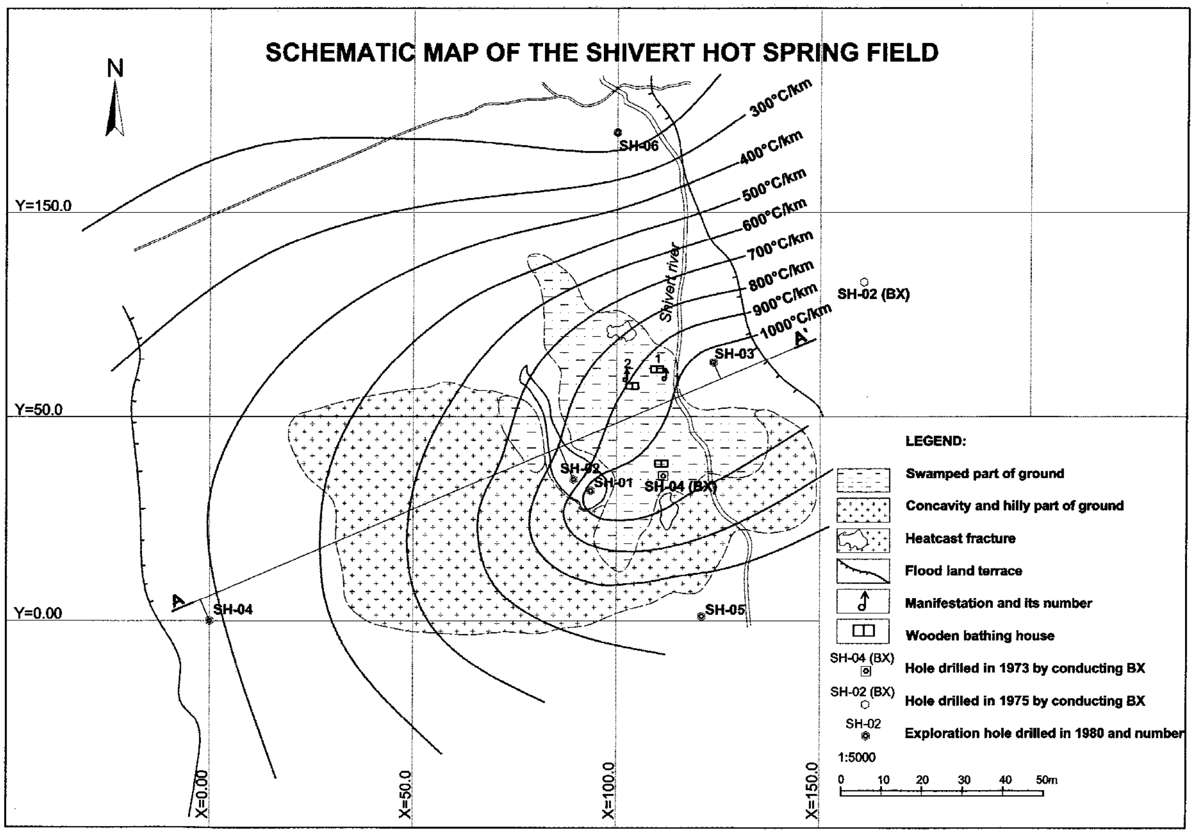

FIGURE 28: The Shivert geothermal field with hot springs and wells and a temperature gradient map

6.4 Analysis of temperature conditions

Figure 28 shows a map of the area with the location of the hot springs and wells, and a contour map of the temperature gradient. In order to delineate the hot water flow paths in the Shivert reservoir, temperature cross-sections were generated based on the available temperature profiles (see Figure 29). Two temperature contour maps, at 50 and 100 m depth were, furthermore, generated for this purpose (see Figures 30 and 31). The gradient maps and the temperature cross-sections, clearly indicate an up-flow from the east-northeast. The up-flow temperature appears to be about 100°C at 100 m depth.

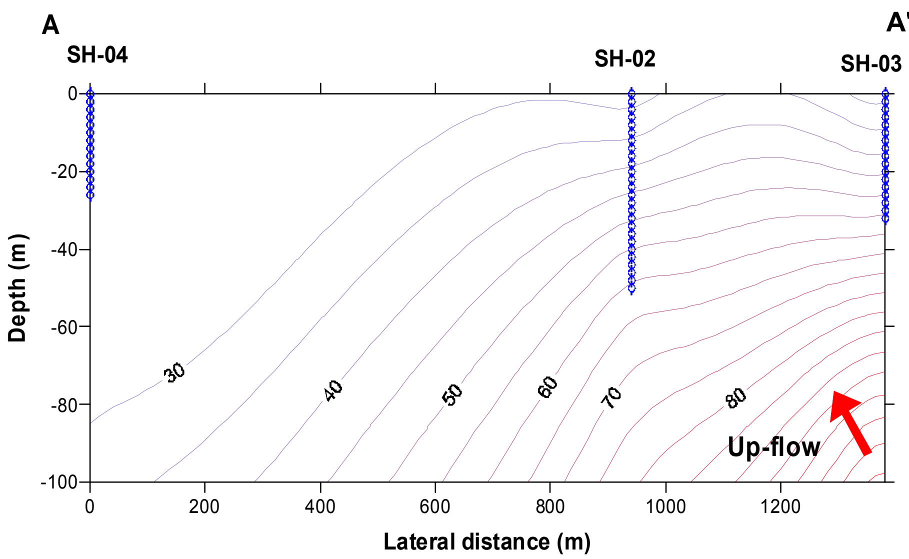

FIGURE 29: Temperature cross-section in the Shivert area

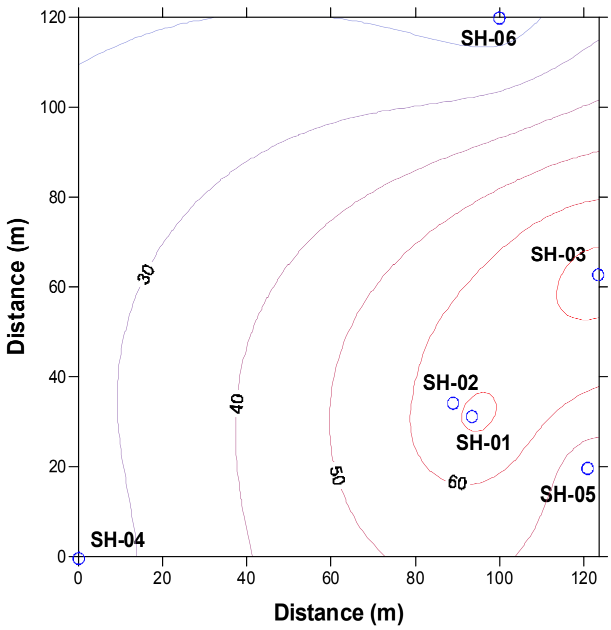

FIGURE 30: Temperature contour map at 50 m depth in the Shivert area

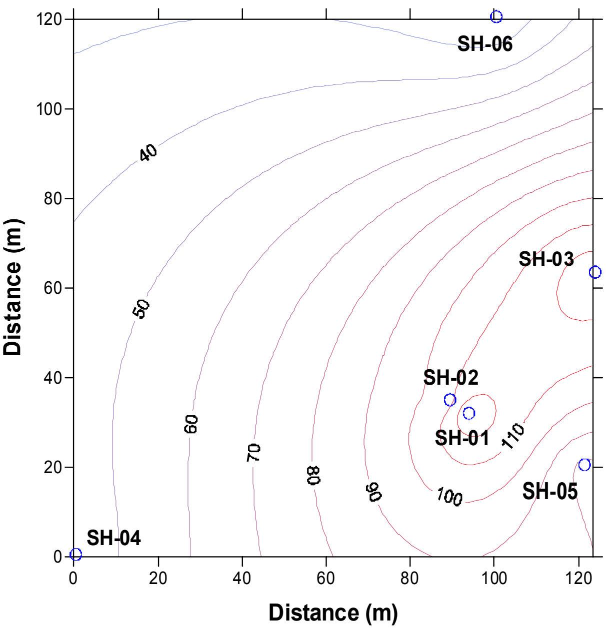

FIGURE 31: Temperature contour map at 100 m depth in the Shivert area

7. PROPOSAL FOR ASSESSMENT OF THE SHIVERT AREA

Exploration of the Shivert geothermal area in Mongolia has barely started but the main characteristics of the system are presented above. It is clear that the area has good geothermal resources but further exploration is required before the potential of the system is known, i.e. how much geothermal energy may be produced in the long-run. The methods used in low-temperature exploration and assessment in Iceland, such as for the Geldinganes area, discussed above, are fully applicable in Mongolia. It is, therefore, suggested that the following steps be taken in order to implement an assessment of the Shivert geothermal area:

- **More temperature gradient drilling:** More gradient wells need to be drilled, in particular to the northeast of the current wells to try to close the open temperature contours and have a finer delineation of the temperature anomaly apparent in the current data set. After that, some deeper exploration wells may be needed.
- **Geophysical exploration:** Geophysical exploration methods have not yet been applied in the Shivert area field. It will be of interest to carry out resistivity, gravity and even seismic studies in the area. In particular, resistivity findings at shallow depth should be compared to the shallow temperature conditions obtained from the gradient wells. Deep probing of the formation by using either the MT or TEM method should be applied to delineate the deep reservoir prior to deep well drilling.
- **Geological exploration:** For geology, most of the surface manifestations have been identified and the structures that may be controlling the hydrology of the area have been identified. Borehole geology which has not been studied in the region is recommended once deep wells are drilled in the area.
- **Drilling of exploration well(s):** Most of the wells drilled in this area are shallow, hence exploring a very small part of the reservoir. Deep drilling needs to be done in order to explore the deep formation of the area. This will determine the alteration minerals present in the Shivert reservoir and give a history of the reservoir in terms of temperature evolution as well as give information on the properties and characteristics of the reservoir conditions beneath.

- **Well testing:** As soon as one, or more, productive exploration/production wells have been drilled in the Shivert area these need to be tested for several months. This would involve producing (e.g. pumping) from one or more wells and monitoring of the response of the system. Well test data can be interpreted to give information on reservoir properties, such as permeability and storage, as well as forming the foundation of mathematical models developed to simulate the reservoir and estimate its capacity, which is based on its potential response to future fluid extraction scenarios.
- **Chemical sampling and analysis:** The Shivert area needs more chemical sampling and analysis. Water samples collected from hot springs or wells as well as gas samples should be analyzed carefully and subjected to various evaluations that concern the age of fluid, reservoir temperature and reservoir potential.
- **Simple modeling:** A simple pre-exploitation model of the Shivert area needs to be developed. From the gradient wells, the area enclosed by the 400°C/km contour can be used to define the reservoir boundary. The depth is still in question due to lack of deep wells in the area. By assuming a conservative value of 1 km common with most geothermal wells, a simple assessment of the resource can be made. Also a simple model, perhaps a lumped parameter model, should be developed on the basis of eventual well test data, mentioned above.
- **Model predictions and production potential assessment:** The simple model(s) can be used to predict the response of the Shivert reservoir to future production for 10-30 years, for various relevant scenarios (different rates of production). This applies, in particular to pressure or water level decline but also to changes in temperature (energy-content). This decline, in conjunction with the production technology used, will consequently determine the production potential of the Shivert area.

8. SUMMARY AND CONCLUSIONS

The purpose of this study was twofold. First, to re-evaluate data from the Geldinganes low-temperature geothermal field in Reykjavik, SW-Iceland; secondly, to evaluate limited data on temperature conditions in the Shivert low-temperature field in Central Mongolia and to propose what methods should be used to assess, and consequently prepare the field for utilization.

The following concludes the present analysis of the Geldinganes area.

- The Geldinganes area is located on a small peninsula having an elevation between 0 and 35 m a.s.l. The area is devoid of surface manifestations but an exploration well drilled in 1993 discovered 100°C water in the area. Following that, a number of exploration wells were drilled on the peninsula.

- Temperature logging data from 16 exploration wells, ranging from 98-1265 m in depth, and one deep (1820 m) production well, were analyzed. The results indicate an up-flow directed south-southwest - north-northeast, which appears to flow from depth in the southern part of Geldinganes near well HS-44 and up to shallower formations near well HS-57. The temperature of the up-flow is about 105°C at 1200 m depth. The up-flow may be along a near-vertical geological structure, such as a fracture zone.

- By analyzing data collected during a 17 day well test of well HS-44, which is 1265 m deep in the south part of Geldinganes, the formation permeability and storativity of the Geldinganes reservoir were estimated as well as the turbulence coefficient of the well. The results indicate that the permeability thickness is rather low near the well, or about 1.6 Darcy-m.

- Two lumped parameter models of the Geldinganes reservoir were set up on the basis of the well test data, using the LUMPFIT program. Two-tank closed and two-tank open models simulate the data equally well and indicate a permeability thickness of the Geldinganes reservoir of about 3.0 Darcy-m. The lumped models were used to predict water level changes for one year, for different production scenarios. The results indicate that the production potential of well HS-44 is in the range of 7-20 l/s, according to pessimistic and optimistic predictions, respectively.

- The results of the re-evaluation presented here contradict the earlier conceptual model of the Geldinganes field. That may explain why the only production well in the field, RV-43, which was directionally drilled to the north-northeast to a depth of about 1800 m in 2001 was not successful.

The following concludes the present analysis on the Shivert hot spring area.

- The Shivert area is located on a plateau at 1650-1655 m a.s.l., and is characterized by active tectonic faults. Hot springs are found on the surface, usually in conjunction with the intersection of different fault zones.

- A preliminary evaluation of temperature data from six exploration wells indicates a clear up-flow of 80-100°C water along a high-permeability vertical fracture zone.

- The Shivert area is believed to have considerable potential, but further exploration and consequent assessment is needed before successful utilization can start. It is proposed that the methods that have been successfully applied in the Geldinganes area and other low-temperature geothermal fields in Iceland should be equally applicable in Mongolia.

- The following methods or steps are proposed as tools for a comprehensive assessment of the Shivert hot spring area:

  - More temperature gradient drilling;
  - Geophysical exploration;
  - Geological exploration, including borehole geology;
  - Drill deeper exploration well(s);
  - Well testing (several months);
  - Chemical sampling and analysis;
  - Simple modelling;
  - Model predictions;
  - Production potential assessment.

- The experience in low-temperature geothermal exploration and resource assessment, as well as the experience in geothermal development gathered in Iceland during the last decades may be transferred to and applied in Mongolia. This would, hopefully, speed up geothermal development in the country, which could involve utilization for district heating, to name one possibility. This would benefit the Mongolian population and promote sustainable energy use in the country.

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APPENDIX I: Temperature logs from shallow exploration wells in Geldinganes, SW-Iceland

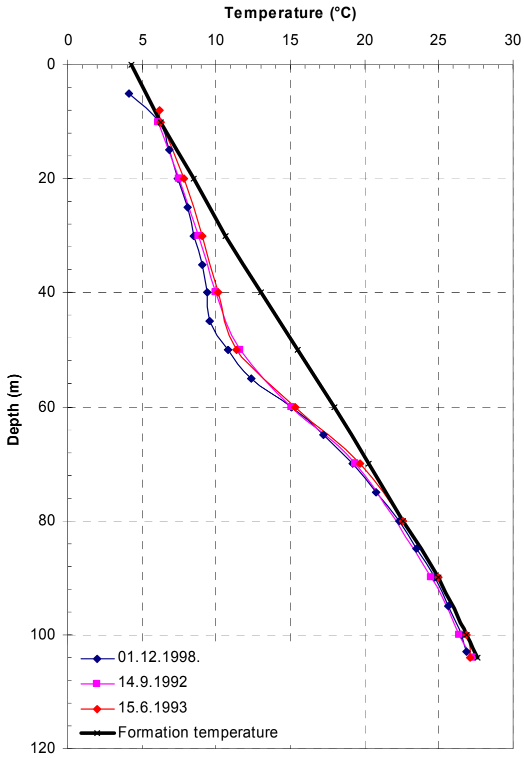

FIGURE 1: Temperature profiles for well HS-25

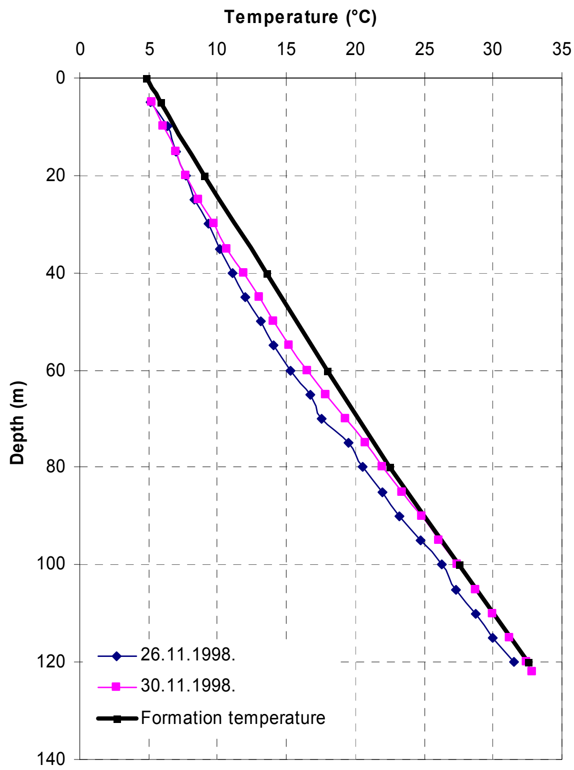

FIGURE 2: Temperature profiles for well HS-52

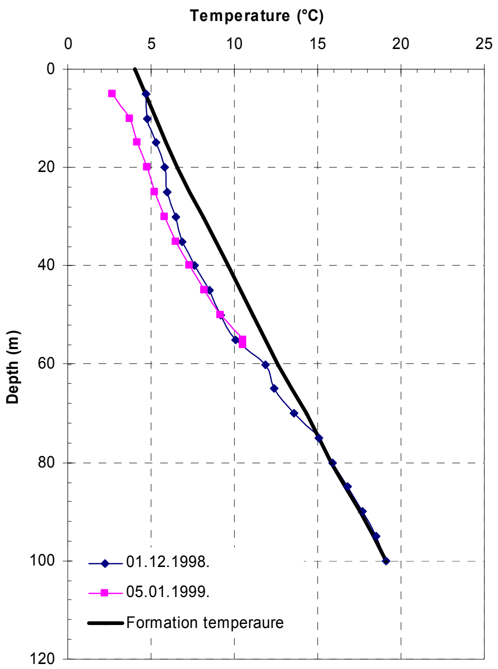

FIGURE 3: Temperature profiles for well HS-53

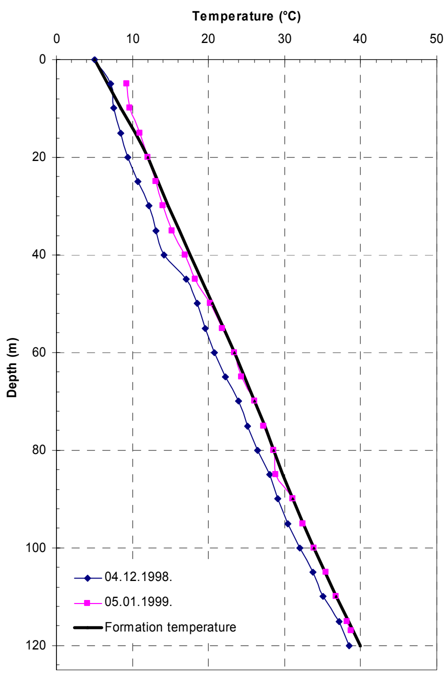

FIGURE 4: Temperature profiles for well HS-54

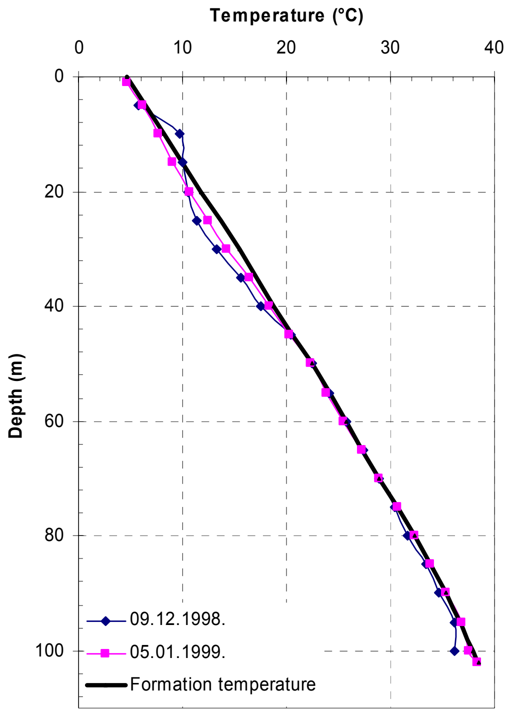

FIGURE 5: Temperature profiles for well HS-55

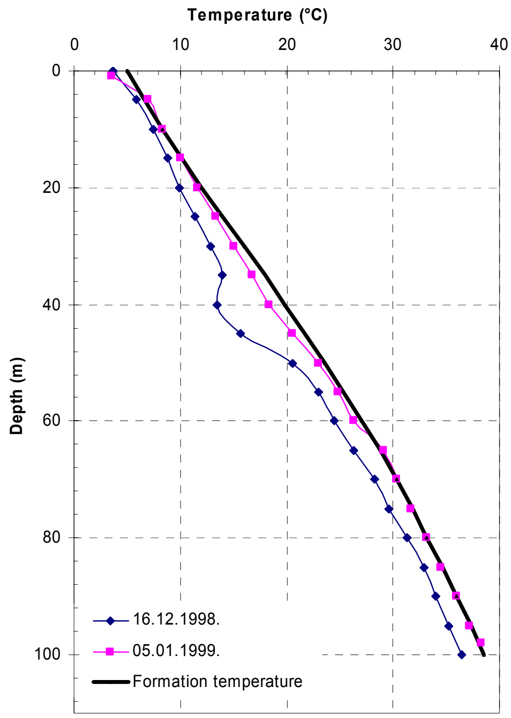

FIGURE 6: Temperature profiles for well HS-56

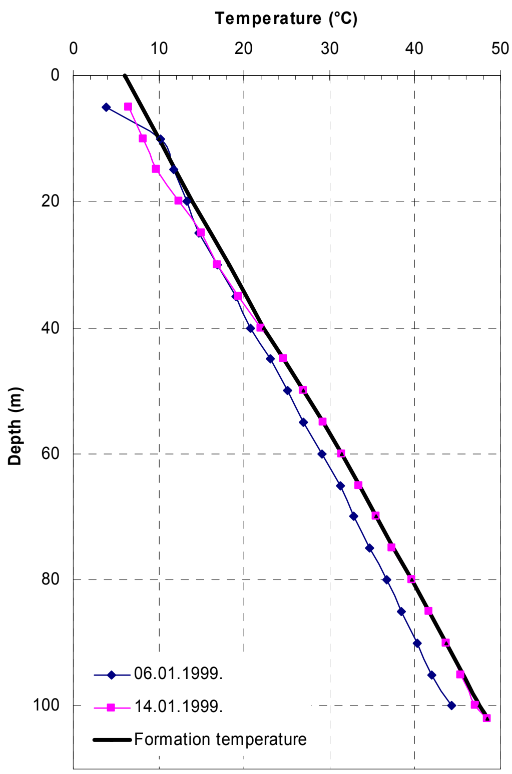

FIGURE 7: Temperature profiles for well HS-57

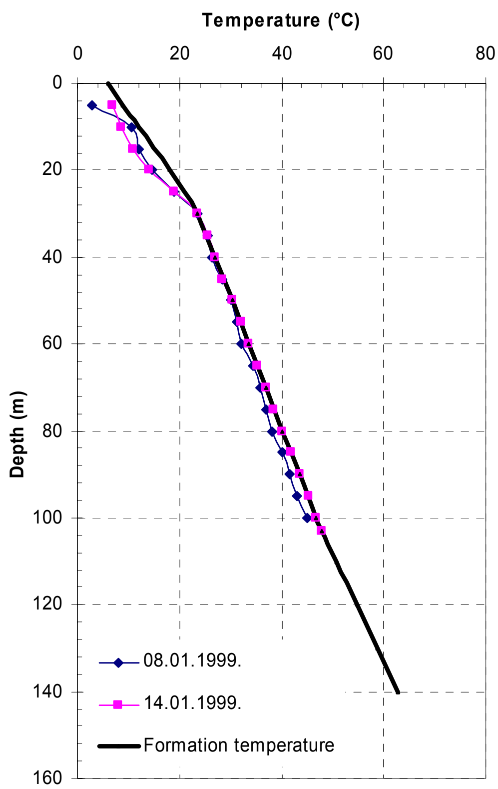

FIGURE 8: Temperature profiles for well HS-58

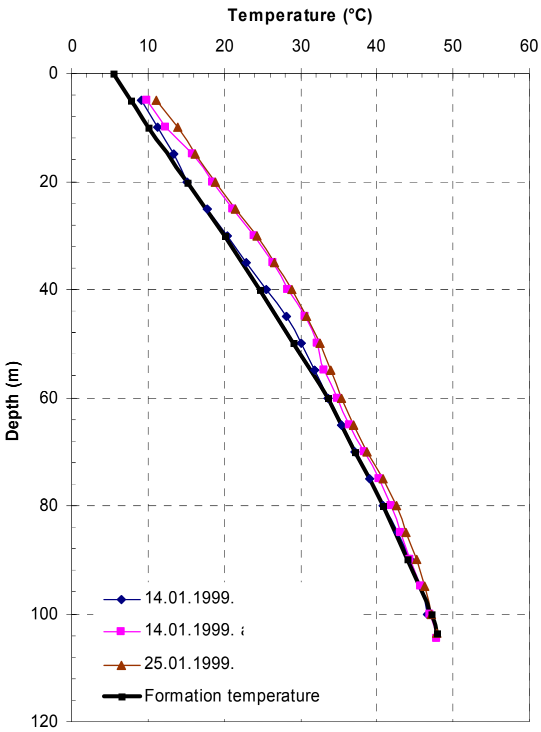

FIGURE 9: Temperature profiles for well HS-59

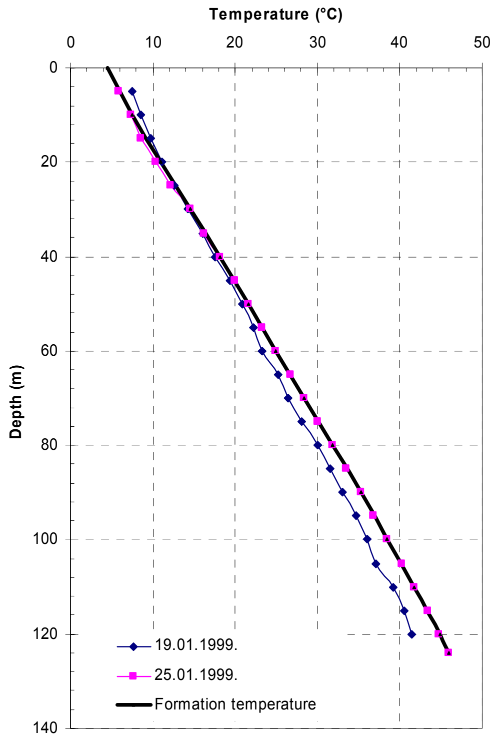

FIGURE 10: Temperature profiles for well HS-60

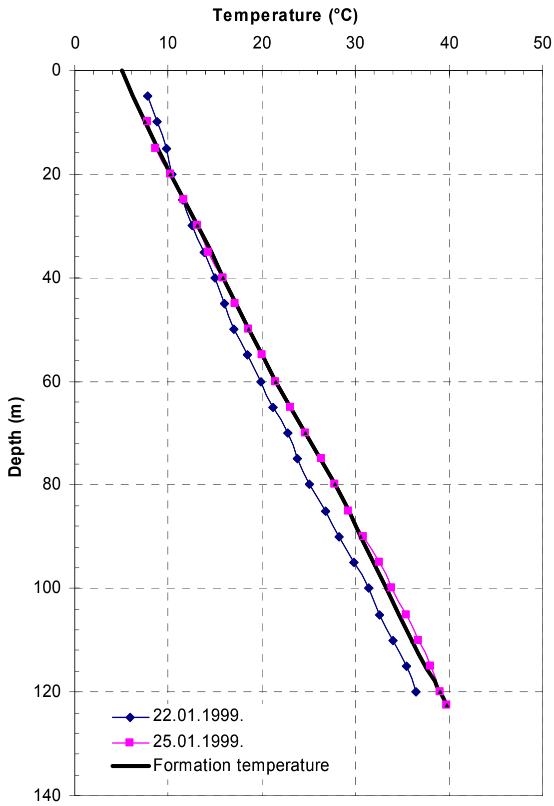

FIGURE 11: Temperature profiles for well HS-61

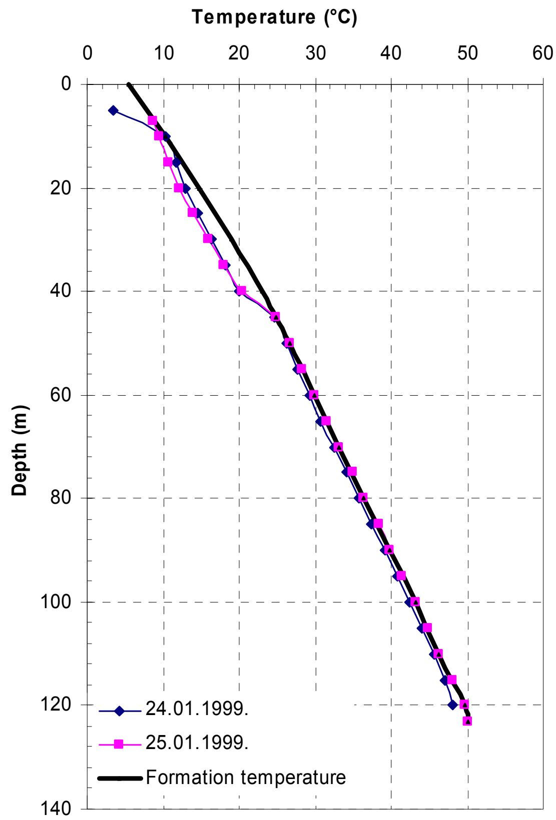

FIGURE 12: Temperature profiles for well HS-62

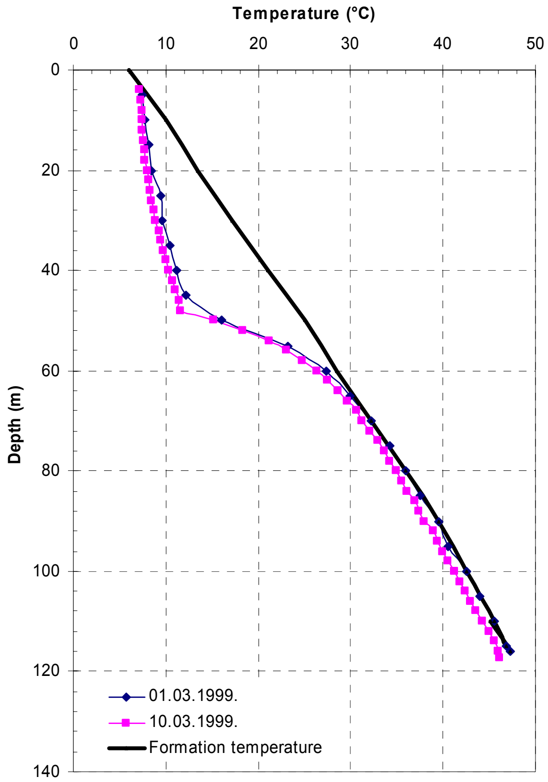

FIGURE 13: Temperature profiles for well HS-63