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INTERPRETATION OF TEMPERATURE MEASUREMENTS AND WELL TEST ANALYSIS AT SUMARLIDABAER AND A SIMULATION OF THE LAUGALAND GEOTHERMAL SYSTEM, S-ICELAND

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ABSTRACT

Sumarlidabaer is one of the low-temperature geothermal fields in southern Iceland, about 80 km south east of Reykjavik. Fourteen wells were drilled in the field in 1983-1987 most of them shallow exploration wells. Well SY-4 is the only production well. The water is used for chicken farming and space heating in the area. After evaluation of all available geological, geophysical and temperature data, the temperature distribution, the location of aquifers and the flow direction of the hot water as well as the inflow of cold water into the system were determined and discussed. The cooling of the water in the production well is of a particular interest. It is now believed to be mainly due to ground water down-flow through wells SY-3 and SIS-5.

Analysis of well test data from the Sumarlidabaer reservoir were made using Theis and Horner methods. The reservoir has a transmissivity of about $9x10^{-8}$ m^3/Pa-s and storativity of about $2.5x10^{-8}$ m/Pa. The estimated average thickness of the reservoir is 470 m.

The Laugaland low-temperature geothermal field (4 km northeast of the Sumarlidabaer field) was simulated by lumped parameter model using the LUMPFIT computer program. An open two tank model was used to simulate the future response of the reservoir. The results indicate that the Laugaland reservoir has a volume of 1 km^3 and is connected to an open system (possibly the ground water system in the area). An open two-tank and a closed three-tank model were used to predict the water level changes during the next ten years for different pumping rates. The optimum pumping rate from the reservoir is close to 15 l/s in order to keep the water level at the present depth.

1. INTRODUCTION

1.1 Scope of the work

The Sumarlidabaer geothermal area is a low-temperature geothermal field. Production from the field began in 1985 with about 10 l/s average pumping rate of 50°C water. A production period of 15 months caused some lowering of the water level. Also, steady cooling was observed and the water temperature at the well head was down to 39°C after the 15 months production period. Cementing of one of the wells (SG-2) reduced the observed cooling but did not stop it. The water temperature at the well head was down to 29°C on September 13th, 1994.

The purpose of this project is to estimate the temperature distribution in the field with special focus on the fractures in the area, in order to locate the aquifers and the flow direction of the hot water towards the field. Furthermore to determine the cause of cooling and hopefully to recommend a site for a new production well. The reservoir properties of the Sumarlidabaer geothermal field should also be determined by analysing pumping tests, using Theis and Horner methods. Finally the future response of a nearby reservoir, Laugaland geothermal field, was to be determined by using simple modelling technique (LUMPFIT computer programme).

This study has been carried out on the basis of the temperature measurements recorded during and after drilling, well test data, magnetic and the head-on resistivity profiling conducted at the Sumarlidabaer geothermal field, as well as the production history and the water level changes at the Laugaland geothermal field.

1.2 Location and geological setting

Iceland lies across the crest of a constructive plate boundary, the Mid-Atlantic Ridge which separates the North American plate from the Eurasian plate. This boundary is composed entirely of volcanic lavas, breccia, tuff and sediments and marked by zones of volcanic and tectonic activity. These zones are flanked by Quaternary rocks, mainly sequences of sub-aerial lava flows intercalated by hyaloclastites and morainic horizons at intervals, corresponding to glacial conditions. The Quaternary formations are bordered by Tertiary sub-aerial flood basalt. The low-temperature geothermal fields in Iceland are characterized by temperatures lower than 150°C at 1 km depth. They are located in Quaternary and Tertiary strata, mostly in the lowlands and valleys (Figure 1).

The study area is in tilted Plio-Pleistocene layers (Hreppar series). In the vicinity of Sumarlidabaer area, the Hreppar series are mainly composed of lava flows with thin, red intercalations of illites and hyaloclastites, but with little or no inter-bedding. The oldest rocks of the Hreppar series are from the Gauss magnetic epoch, but most of the series are from the Matuyama epoch. Therefore, the volcanic strata is characterized by alternating layers with normal and reversed magnetic polarity directions (Fridleifsson et al., 1980). A thin sedimentary layer (sandstone 1-5 m thick) is found below the interglacial lava flows.

The Sumarlidabaer low-temperature geothermal field is located in southern Iceland (Figure 1), about 80 km southeast of Reykjavik and about 25 km east of the town Selfoss. The stream Mjoilaekur forms the eastern boundary of the geothermal area, which covers about 0.03 km^2 and is almost flat at an elevation of 40 m a.s.l. Several warm springs and seeps were found in the area prior to production (Figure 2).

The Hreppar series have been much affected by dyke intrusions and faulting. The general trend of the dykes is NE-SW, while the normal faults generally trend N15-30°E with down throw of several tens of meters. In the region near Sumarlidabaer three directions of faulting are seen: N0-10°E, N60°E, N20-40°E. Most of the faults are arranged in a step-fault pattern with the down throw side on the east towards the axis of the Hreppar anticline (Ignacio, 1982).

Several low-temperature areas are found in the region, such as; Laugaland, Sumarlidabaer, Harlaugsstadir, and Skammbeinsstadir. Experience in the low-temperature areas in Iceland shows that aquifers are commonly connected with fractures, faults and dykes cutting the lava formations (Fridleifsson, 1979).

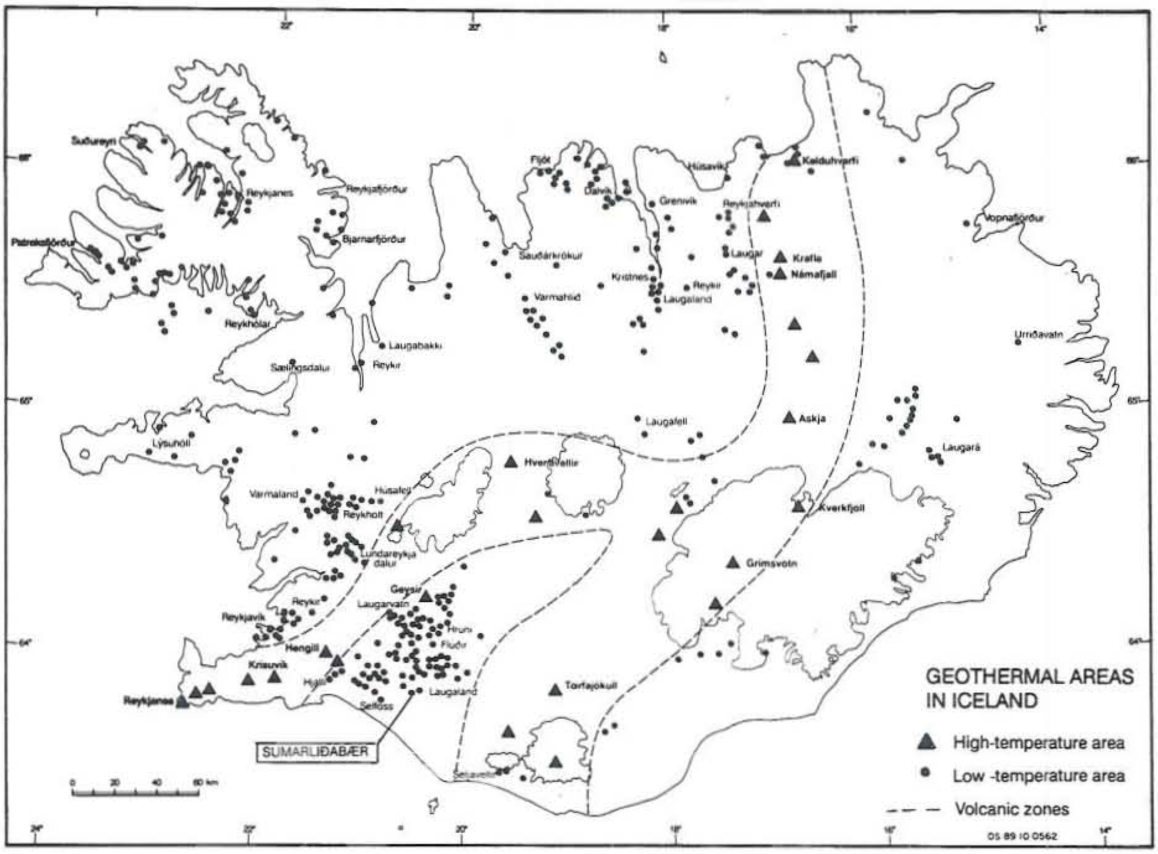

FIGURE 1: Geothermal areas in Iceland

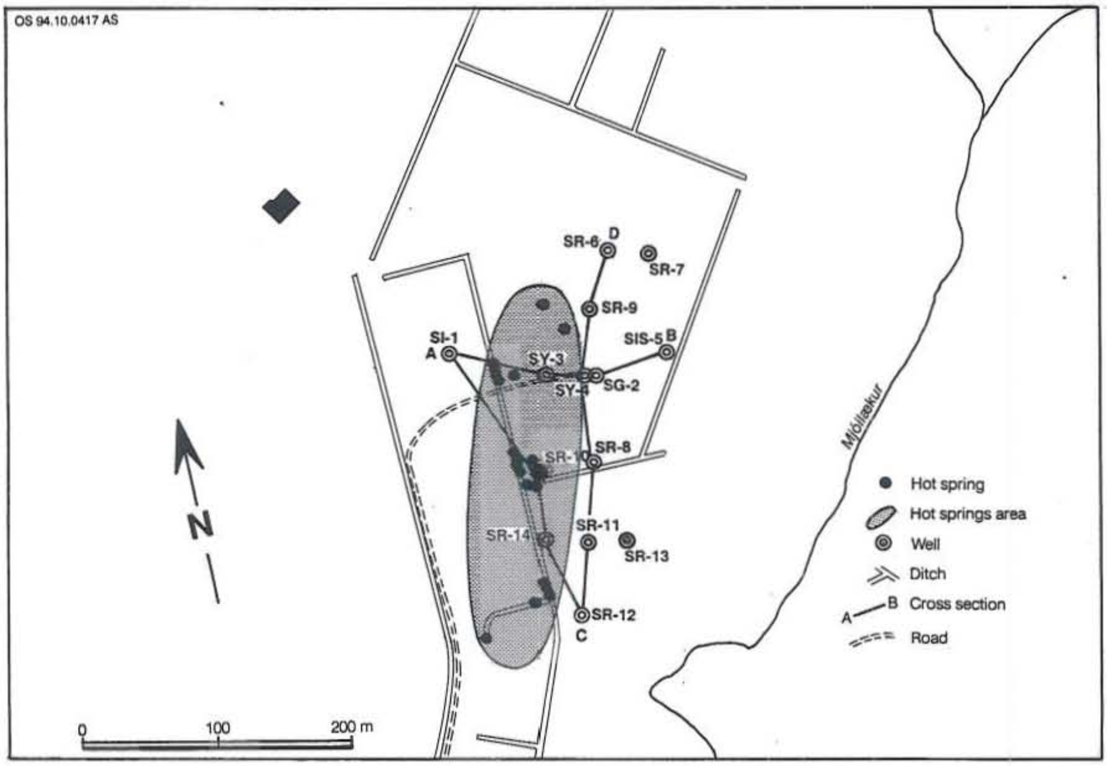

FIGURE 2: Location of hot springs, wells and temperature cross-sections at the Sumarlidabaer geothermal field

1.3 Geophysical studies in the area

Geothermal studies at Sumarlidabaer began in 1982, apart from one Schlumberger sounding carried out in 1976. Ignacio (1982), carried out a magnetic survey in the area as a project work for the UNU Geothermal Training Programme. The geothermal field was mapped and a 300 x 400 m^2 area was covered. Figure 3 shows the magnetic map. The main results of the study show two major anomalies, one was interpreted as a reversely magnetized dyke, trending N25-30°E, the other as a fault structure, trending N30-40°E.

In 1982, a search for fractures was also conducted in quite a big area around the geothermal field without success. Results of the geothermal and magnetic mapping indicated that the geothermal springs were located on a fracture, with a direction of N20-30°E.

In 1986, a head-on resistivity profiling survey was performed. Seven profiles of different lengths were measured. Figure 4 shows the position of the profiles. A preliminary interpretation on the profiles shows low resistivity fractures, the most important trending N10-15°E. The head-on profiles, however, need to be interpreted with 2-dimensional computer programmes in order to get better and more reliable results. No obvious effect is seen from the proposed dyke. The warm springs at Sumarlidabaer appear to emerge on a fracture trending N25°E. Compared to the distribution of the hot springs on the surface, the location of the fracture at about 200 m depth (according to the head-on profiling) indicates that close to the surface it is inclined 60-70° to the east (from horizontal) (Georgsson, 1986). The interpretation of the head-on resistivity profiling is shown in Figure 5.

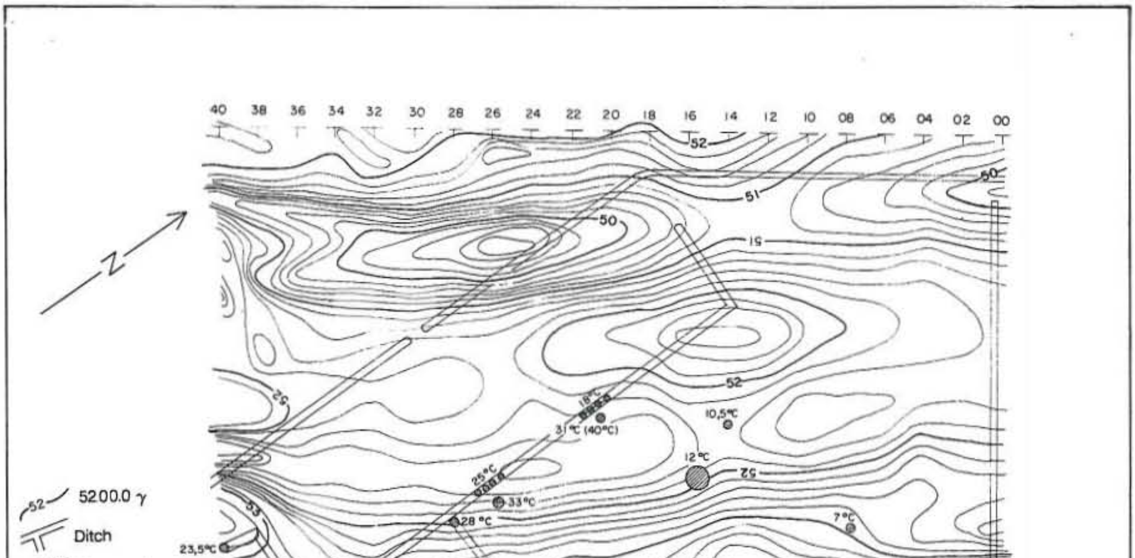

FIGURE 3: The magnetic map of the area (Ignacio, 1982)

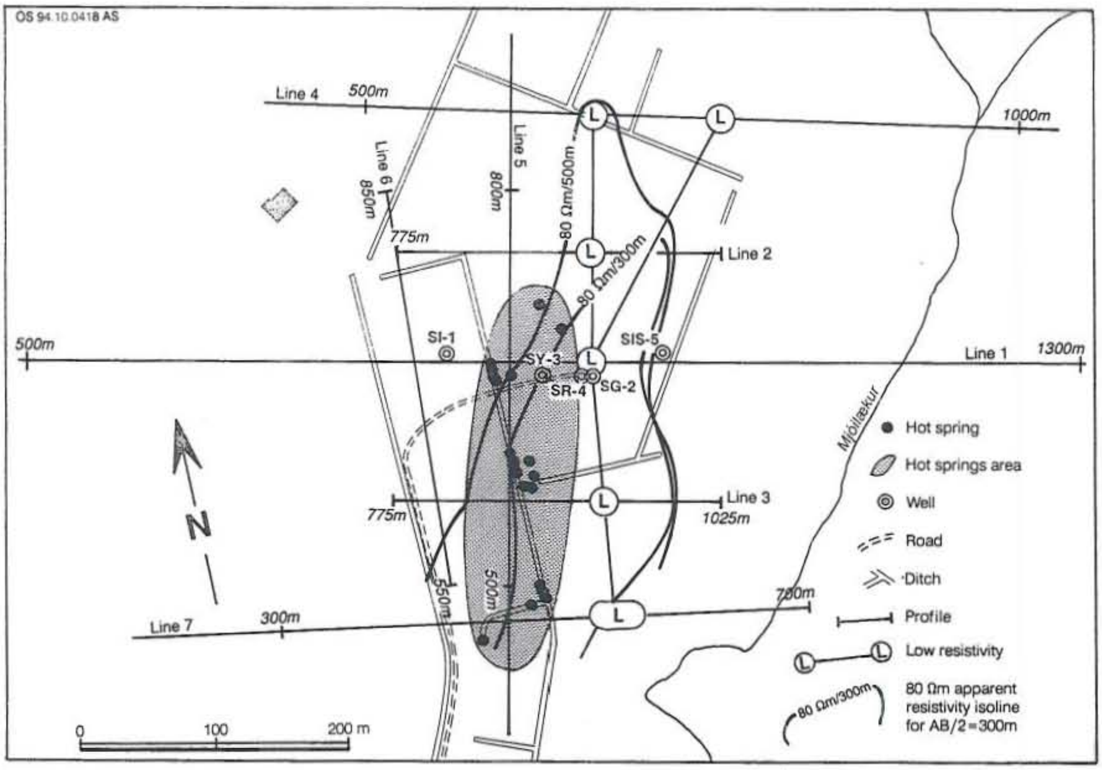

FIGURE 4: The location of the head-on profiles and the low-resistivity structure (Georgsson, 1986)

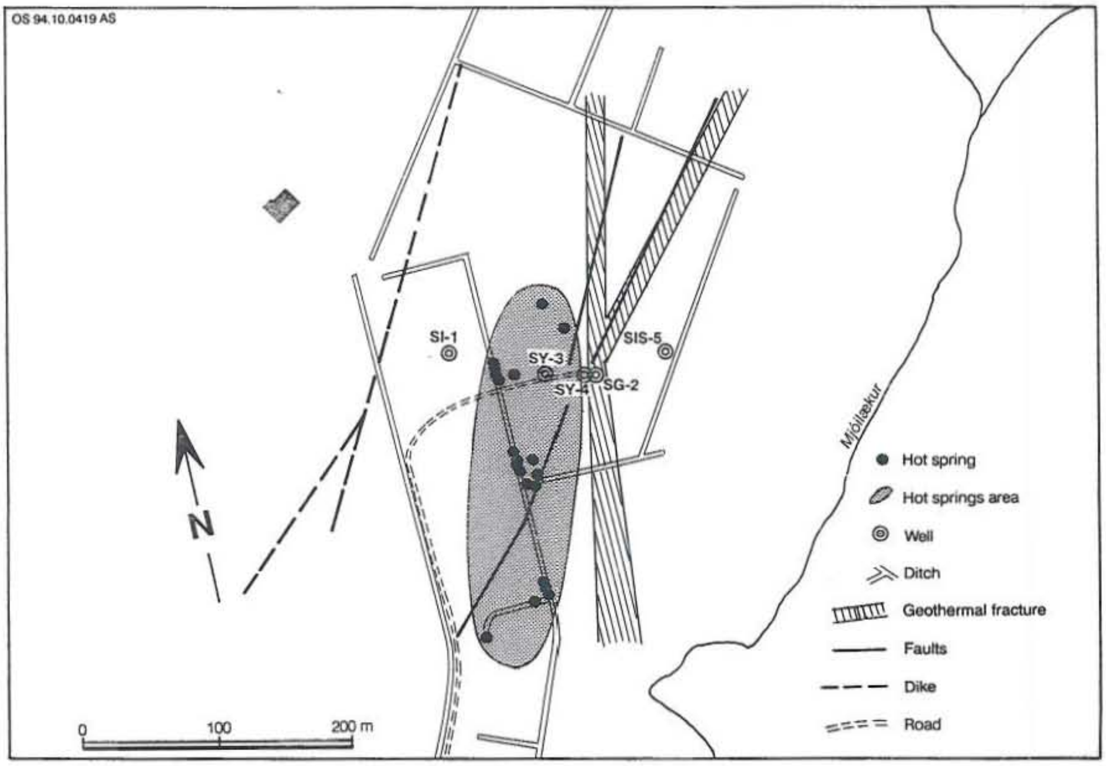

FIGURE 5: The interpretation of the head-on profiling (Georgsson, 1986)

1.4 History of the field development and drilling

After the magnetic survey, it was recommended that an inclined exploration well be drilled for further understanding of the geothermal system and to search for fractures in connection with the geothermal system in the area. Well SI-1 was drilled during the period March 11-April 13, 1983. It was located about 50 m west of the warmest spring and drilled diagonally 42° (from horizontal), underneath the spring field. The well was 100.6 m long and intersected an open fracture at 100 m (at a depth of 65 m). Water flowed from the fracture and was measured to be 52°C warm at the aquifer.

A production well was located 30 m east of the fracture, close to the hottest spring. The goal was to intersect the geothermal fracture at 400-500 m, assuming that the fracture had an inclination of 86° to the east. The drilling of well SG-2 began on June 2 and ended September 6, 1983. The drilling was difficult in the beginning, as the rock was very fractured and collapsible in the uppermost 400 m. About 10 l/s of water entered the well in the top 200 m, but it was not warmer than that in the diagonal well (SI-1), only 52-54°C. The well was even colder (<45°C) below 200 m. The drilling was, therefore, continued in order to try to intersect a better aquifer at deeper levels. Below 450 m the drill rig had drilled through the fractured rocks and after that drilling was easier. The temperature increased again, to over 65°C at 600 m. The well was drilled to a depth of 1169 m. However, the results were not as good as hoped for and no usable aquifers were found below 200 m. Later it became evident that the geothermal fracture was intersected at a too shallow level, probably at about 200 m depth.

The results of the drilling of well SG-2 were a disappointment and it was evident that hotter water than 50-55°C would be difficult to obtain. The owners opinion was that it would be better to have 50-55°C water than no water. It was not feasible to get this water from well SG-2, because the aquifer in the top 200 m had been cemented many times, therefore, it was decided to drill a new production well, SY-3. The well was located directly over the place where well SI-1 was thought to have intersected the geothermal fracture, about 25 m east of the hottest warm spring. The drilling started on June 5 and ended June 13, 1984. It was drilled down to 222 m depth, and cased down to 21 m with 7 5/8" casing. Much water flowed into the well but it was a few degrees colder than that in well SG-2 or just below 50°C. Below 150 m it was much colder like SG-2 and here the temperature was measured to be 45°C or lower.

According to the drilling results of well SY-3 and due to the value of each degree when relatively cold water (<60°C) is utilized, it was decided to drill one more well, between wells SY-3 and SG-2 hoping to get the same water as in well SG-2. Well SY-4 was located about 12 m to the west of SG-2. The drilling began on June 14 and the well was completed on June 29, 1984. The well was drilled down to a depth of 145.2 m. There were some problems in drilling due to water flow and collapses. It was cased by a 8 5/8" casing down to 62 m. A long-term test was performed in the well after drilling, 16.5 l/s were pumped from the well for 7 days. This pumping rate caused a draw-down in the water level of about 8 m. It was thought that this result would allow a long-term pumping of 10-12 l/s from the well with small draw-down. In the summer of 1985, production from the well started with an average pumping rate of 10 l/s, which caused some draw-down. The water level dropped from 8 to 12 m after 15 months of production and the surface activities were reduced. At the same time cooling occurred and a steady temperature drop was observed. After 15 months of production the temperature at the well head was down to 39°C from over 50°C.

In the autumn of 1986 the head-on resistivity profiling was carried out to determine the position and the slope of the geothermal fracture in order to locate a new production well. Based on these results, it was recommended to drill a new well further to the east in order to reach the water at a greater depth and hopefully hotter. Well SIS-5 was drilled for this purpose during the period January 21 to February 4,1987 (Figure 5). It was drilled to 330 m and cased down to 5 m only. The well did not of intersect the geothermal fracture.

The latest development and drilling activity at Sumarlidabaer was in 1987, when nine shallow exploration wells (20-60 m deep) were drilled to try to determine better the location of the geothermal fracture and to get better understanding of the nature of the geothermal field. Figure 2 shows the location of these wells.

Since 1987 about 10 l/s of hot water have been pumped from well SY-4. The temperature has gradually declined and is now 29°C which is really far too low for practical use of the water. No surface activity of the geothermal water was found in September 1994.

2. TEMPERATURE MEASUREMENTS IN THE WELLS

2.1 Analysis of temperature logs and location of aquifers

Well SI-1 was drilled in the western part of the field. It was completed on April 13, 1983 at 100.6 m length. It is an inclined well, deviating about 42° from horizontal with the bottom at 65 m depth below the surface. Six temperature measurements were carried out during and after drilling (Figure 6a). It can be seen from these profiles that there are three aquifers at 48-52 m and the main aquifer is close to the bottom of the well at 100 m (65 m vertical depth). The latest profile shows a down-flow of cold water into the well from shallow depth indicating a cold water aquifer at 20-25 m.

Well SG-2 was completed on October 6, 1983 at 1169 m depth. During drilling nine temperature measurements were performed (Figure 6b) and nine measurements were made after drilling (Figure 6c). The profiles show two main aquifers at 120 and 170-180 m. Three more small aquifers can be seen at 200, 650, and 1030 m, in addition to a cold aquifer at 30-40 m depth. There is a clear temperature inversion at 170 m indicating a horizontal flow.

Well SY-3 was completed on June 13, 1984 at 222 m depth. Several temperature logs were obtained during and after drilling (Figure 6d). All profiles show two relatively cold aquifers at 15 and 55-60 m, with some down-flow from the aquifer at 15 m to that at 55-60 m. Another aquifer can be seen from the measurement which was performed on June 13, 1984 at 150-160 m. The latest profiles show one more aquifer close to the bottom of the well. The profiles show a temperature inversion at 45-50 m indicating horizontal flow there, also there is a slight temperature inversion at 150-160 m depth.

Well SY-4 is close to well SG-2. It was completed on June 29, 1984 at 145.2 m depth. The temperature logs obtained during drilling (Figure 7a) show a cold water aquifer at 10-20 m. It can be seen from most of the profiles that there are two more aquifers at 60-70 m and the main one at 130 m. There is an obvious up-flow from the deepest aquifers to the one at 60-70 m depth.

Well SIS-5 was completed on February 4, 1987 at 330 m depth. Six temperature measurements were made (Figure 7b). It can be seen from these measurements that there are several aquifers at 20-30, 75, 155, 220, and 310 m. There is a down-flow of cold water in the well, clearly seen in the most recent temperature measurement (13.09.1994).

Well SR-6 was drilled in the northern part of the field. It was completed on January 31, 1987 at 60 m depth. The only temperature profile performed (Figure 7c) shows a maximum in temperature (12.3°C) at about 35 m which indicates a horizontal flow in the vicinity of the well. It also shows a small aquifer at 35 m.

Well SR-7 was drilled on February 1, 1987 down to only 20 m depth. The temperature measurement shows no aquifers (Figure 7d).

Well SR-8 was completed on February 1, 1987 at 60 m depth. Two temperature profiles were obtained (Figure 8a). The first is still affected by the drilling (warming by air), while the second one shows more stable conditions. The logs show an aquifer at 55 m.

Well SR-9 is a shallow well, it was drilled on February 2, 1987 to only 20 m depth. No aquifers can be seen from the temperature measurement (Figure 8b).

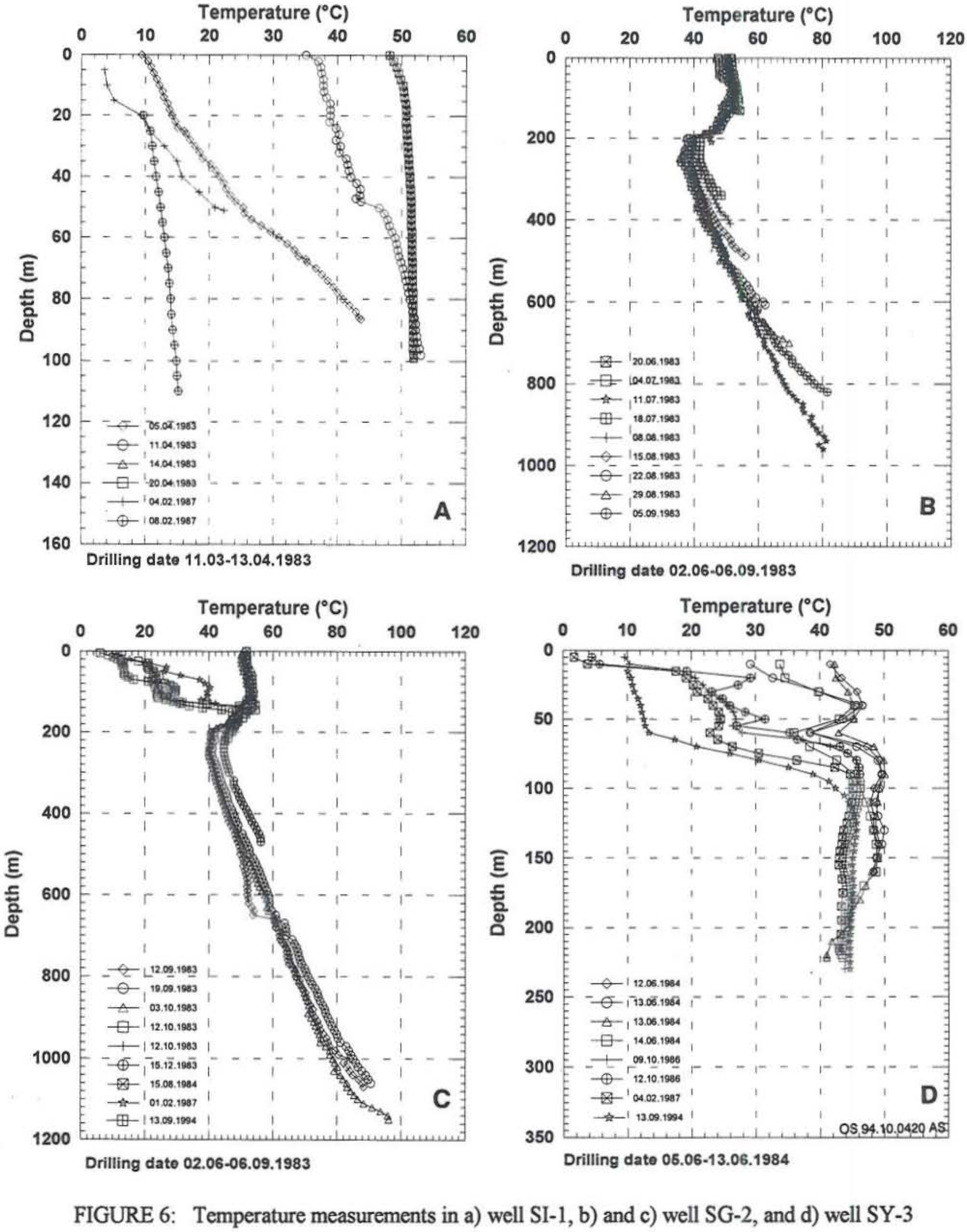

FIGURE 6: Temperature measurements in a) well SI-1, b) and c) well SG-2, and d) well SY-3

Well SR-10 was completed on February 3, 1987 at 60 m depth. The temperature curve (Figure 8c) shows aquifers at 10 and 45 m with a down-flow between them.

Well SR-11 was completed on February 4, 1987 at 60 m depth. Three temperature measurements were performed after the end of the drilling (Figure 8d). These profiles show a main aquifer close to the bottom of the well and a small aquifer at 50 m.

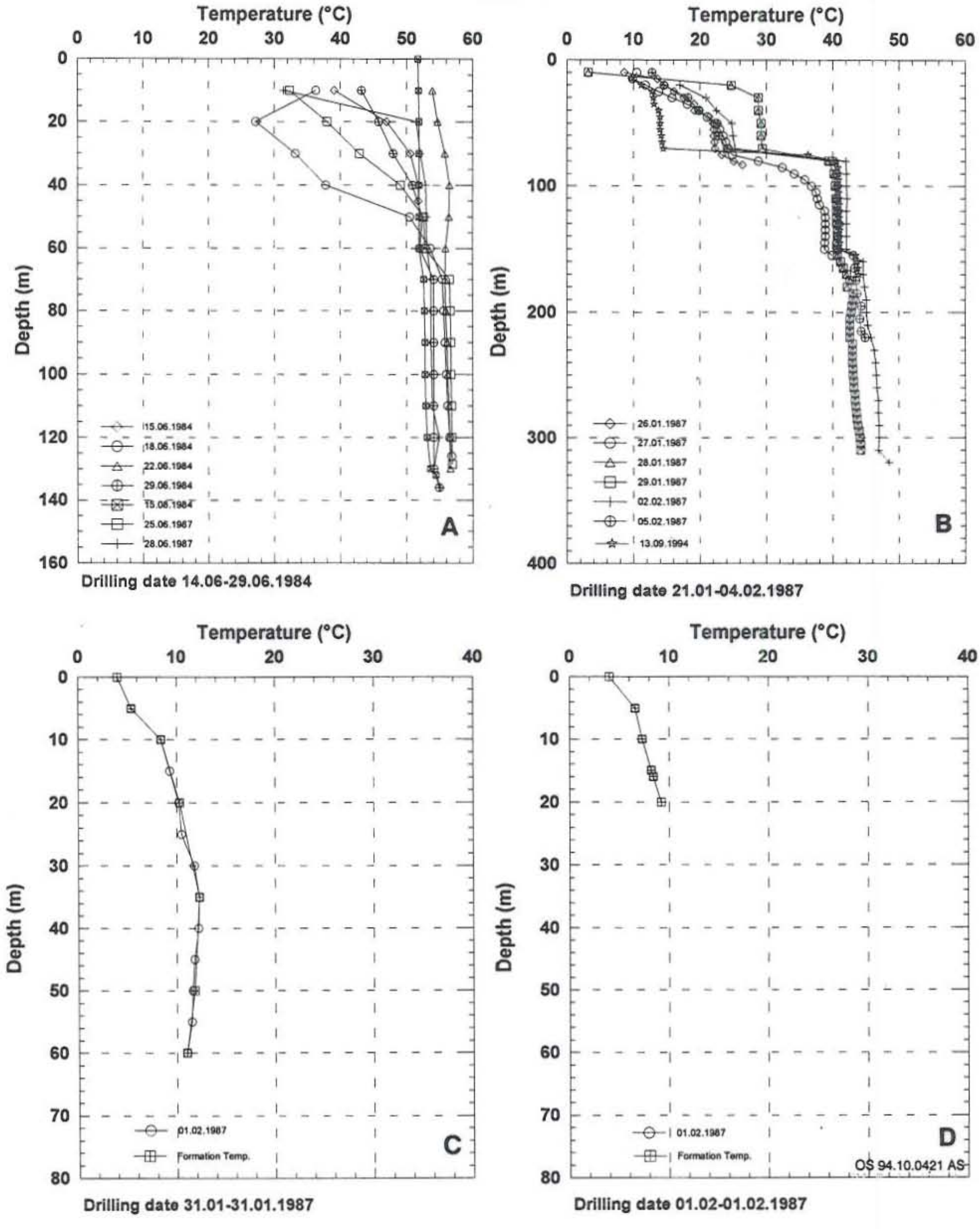

FIGURE 7: Temperature measurements in a) well SY-4, and b) well SIS-5; temperature measurements and formation temperature in c) well SR-6, and d) well SR-7

Well SR-12 was drilled in the southern part of the field. It was completed on February 4, 1987 at 60 m. Two temperature logs were obtained (Figure 9a), that show an aquifer at 60 m. The second log shows almost stable conditions and it can represent the formation temperature.

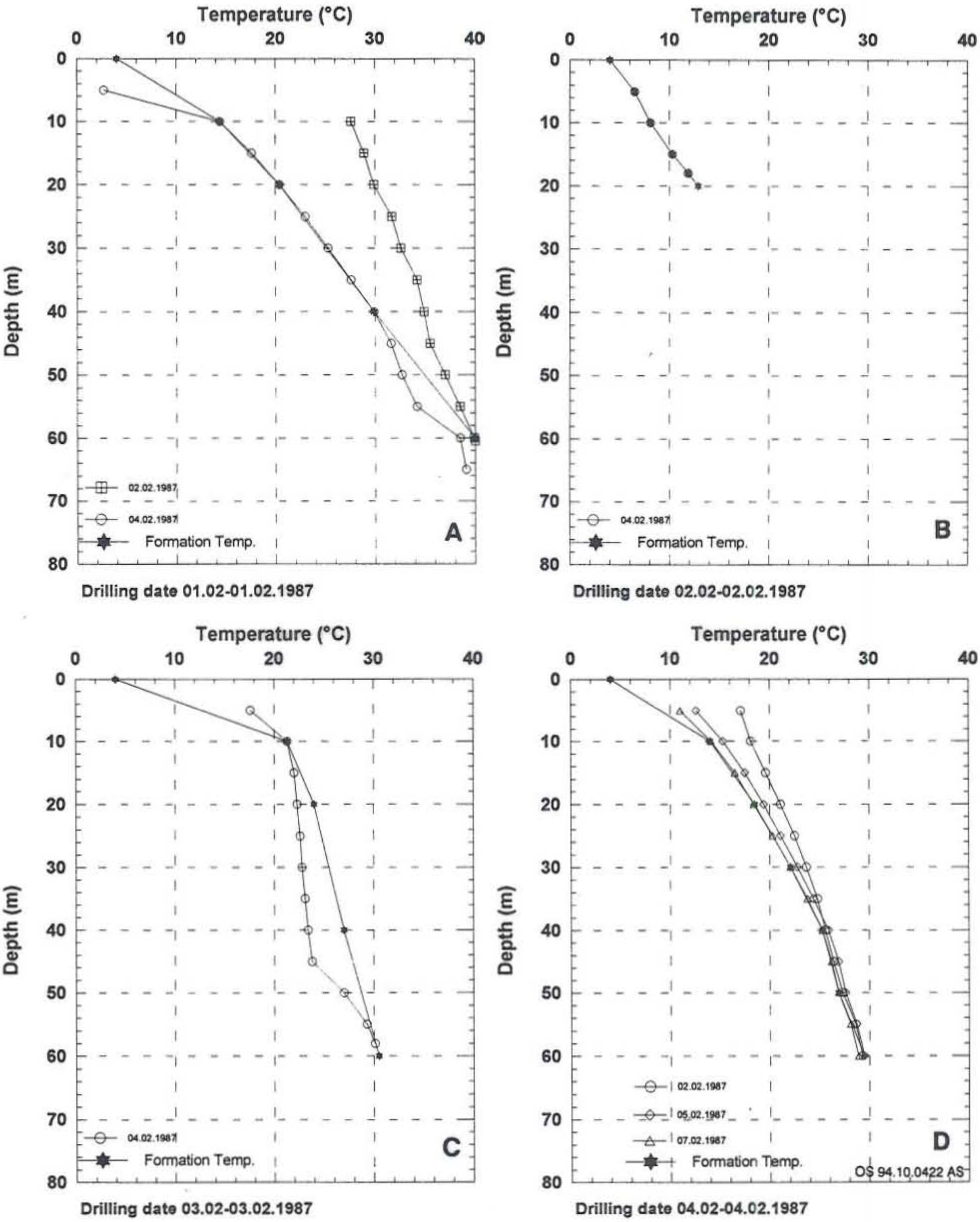

FIGURE 8: Temperature measurements and formation temperature in a) well SR-8, b) well SR-9, c) well SR-10, and d) well SR-11

Well SR-13 is close to well SR-11. It was completed on February 5, 1987 at 60 m depth. Two temperature measurements performed after drilling (Figure 9b) show an aquifer close to the bottom of the well. A small down flow of cold water in the well can be seen in the second curve, from 10 m down to the bottom of the well causing some cooling.

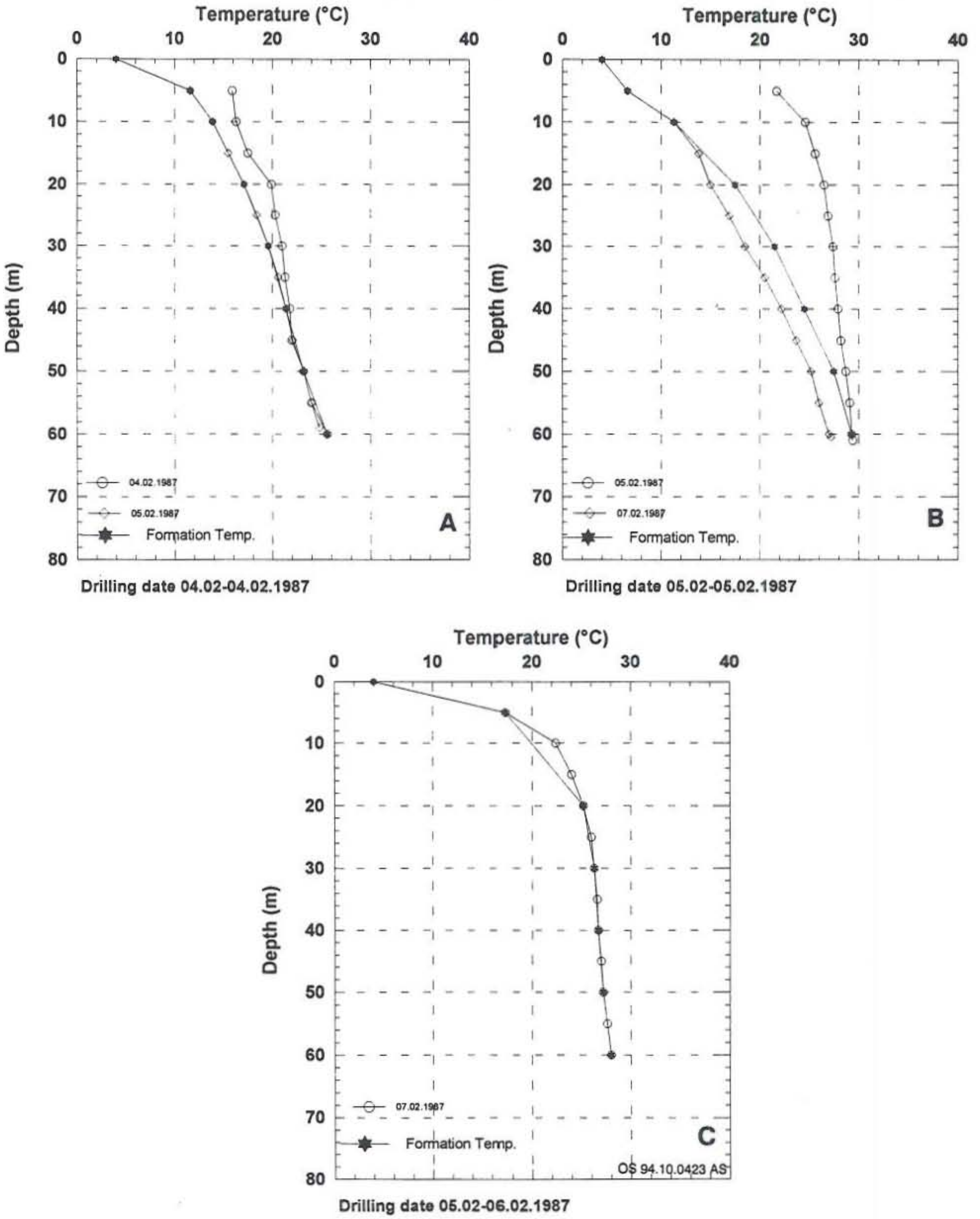

FIGURE 9: Temperature measurements and formation temperature in a) well SR-12, b) well SR-13, and c) well SR-14

Well SR-14 is the last well drilled in the field, it was completed on February 6, 1987 at 60 m depth. The temperature profile in the well (Figure 9c) shows no aquifers.

Table 1 shows a summary of the temperature logging at the Sumarlidabaer field. The locations and the temperatures of the aquifers are shown in Table 2.

TABLE 1: Temperature measurements of wells at Sumarlidabaer

Well No	Drilling dates (from-to)	Total depth (m)	Temperature logging dates	Water level (m)	Comments
SI-1	11.03.1983	100,6	05.04.1983		5 days after stop drilling, Q=0.1 l/s
	13.04.1983		11.04.1983		5 days after stop drilling ,Q=0.1 l/s
			14.04.1983		Q=1 l/s
			20.04.1983		
			04.02.1987	15,5	
			08.04.1987		
SG-2	02.06.1983	1169	20.06.1983		
	06.09.1983		04.07.1983		
			11.07.1983		
			18.07.1983		
			08.08.1983		
			15.05.1983		Q=4.8 l/s
			22.08.1983		Q= 5.4 l/s
			29.08.1983		Q= 6.2 l/s
			05.09.1983		Error in depth scale, Q= 5.0 l/s
			12.09.1983		1 week after end of drilling
			19.09.1983		Error in depth scale
			03.10.1983		Error in depth scale , Q=5.0lL/s
			12.10.1983		
			12.10.1983		
			15.12.1983		
			15.08.1984		
			01.02.1987	10	8 weeks after casing off first 200m
			13.09.1994	12,3	
SY-3	05.06.1984	222	12.06.1984	0,5	1 hour after stop pumping
	13.06.1984		13.06.1984	0,1	1 hour after air lifting
			13.06.1984		1 hour after air lifting
			14.06.1984		12 hours after air lifting
			09.10.1986		
			12.10.1986		
			04.02.1987	12	7 w, after casing first 200m of SG-2
			13.09.1994	13,8	
SY-4	14.06.1984	145,2	15.06.1984		2.5 hours after stop drilling
	29.06.1984		18.06.1984		
			22.06.1984		1 hour after air lifting
			25.06.1984	1,3	
			28.06.1984	9	
			29.06.1984	1,3	
			15.08.1984		After air lifting
SIS-5	21.01.1987	330	26.01.1987	12	After weekend
	04.02.1987		27.01.1987		After one night
			28.01.1987		After one night
			29.01.1987	14	After one night
			02.02.1987		4 days after stop of drilling
			05.02.1987	10,5	1 day after end of drilling
			13.09.1994	13,9	
SR-6	31.01.1987	60	01.02.1987		1 day after end of drilling
	31.01.1987				
SR-7	01.02.1987	20	01.02.1987		12 hours after end of drilling
	01.02.1987				
SR-8	01.02.1987	60	02.02.1987		1 hour after end of drilling
	01.02.1987		04.02.1987	7	
SR-9	02.02.1987	20	04.02.1987		
	02.02.1987				
SR-10	03.02.1987	60	04.02.1987	2	
	03.02.1987				
SR-11	04.02.1987	60	04.02.1987		
	04.02.1987		05.02.1987	4	
			07.02.1987	4	
SR-12	04.02.1987	60	04.02.1987		
	04.02.1987		05.02.1987	2,7	
SR-13	05.02.1987	60	05.02.1987	3,7	
	05.02.1987		07.02.1987	4	
SR-14	05.02.1987	60	07.02.1987	4	
	06.05.1987				

TABLE 2: Location and temperature of aquifers in the wells at the Sumarlidabaer geothermal field

Well no.	Aquifer depth (m)	Aquifer temperature (°C)
SI-1	20-25*	Cold water
	48-52*	26
	100*	52 (main aquifer)
SG-2	30-40	27
	120	53 (main aquifer)
	170-180	49 (horizontal flow)
	200	47
	650	54 (very small)
	1030	79 (very small)
SY-3	15	25
	55-60	27 (horizontal flow)
	150-160	49 (hottest & horizontal flow)
	220	44 (main aquifer)
SY-4	10-20	Cold water
	60-70	53
	130-135	55
SIS-5	20-30	Cold water
	75	25.5
	155	42
	210-220	45
	310-320	46.5 (main aquifer)
SR-6	20-25	Cold water
	35	Cold water & horizontal flow
SR-7	No aquifers	
SR-8	55	34
SR-9	No aquifers	
SR-10	45	23.7
SR-11	50	27
	60	29 (main aquifer)
SR-12	45	22
SR-13	60	29.5
SR-14	No aquifers	

* inclined well deviating 42° from horizontal, depth along the well

2.2 Estimation of formation temperatures

An attempt to reconstruct the temperature profiles has been made for most of the wells in the field, in order to estimate the formation temperature.

Based on the temperature profiles of well SI-1 during and after drilling, a suggested formation temperature curve is constructed (Figure 10). The main points used are the bottom hole temperature, the surface temperature 4°C at zero depth and the segment (50-80 m) in the log performed on April 5,1983.

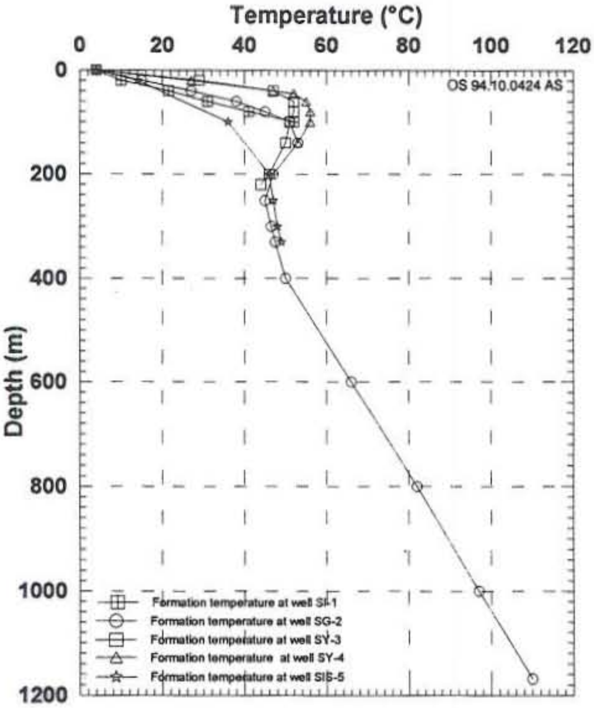

FIGURE 10: Formation temperature in wells SI-1, SG-2, SY-3, SY-4 and SIS-5

A suggested formation temperature profile in well SG-2 (Figure 10) is based on the temperature profile segment (120-460 m) in the temperature profile made on August 15, 1984 and it is extended down to the bottom of the well, through the last point of the log performed on August 29, 1983. Above 120 m the suggested formation temperature curve is connected to the surface temperature point.

In well SY-3 at 65 m the temperature is 52°C according to the bottom hole temperature of the inclined well SI-1. Therefore, the suggested formation temperature (Figure 10) is extended from this point down to the bottom of the well and up to the surface point (4°C at zero depth).

The formation temperature profile in well SY-4 (Figure 10) is based on the first two measurements performed on June 15 and 18, 1984 (Figure 7a). The other measurements are showing a flow in the well.

In well SIS-5 the formation temperature profile is suggested to follow the temperature measurements obtained on February 2, 1987 below 160 m down to the bottom of the well. A smooth line from 160 m is drawn up to the surface temperature at zero depth showing a slight cooling at 75 m. It does not follow the hotter measurements due to the warm-up effect by the drilling air (Figure 10).

The temperature measurement which was performed in well SR-6 is considered as the formation temperature profile, although it was measured only one day after the end of the drilling of the well (Figure 7c). Well SR-7 is a shallow well and the temperature log performed in the well is considered to be the formation temperature profile (Figure 7d). Two temperature measurements were carried out in well SR-8. The second one (04.02.1987) can be smoothed to represent the formation temperature (Figure 8a). Well SR-9 is a shallow well and the temperature profile can be used as the formation temperature curve (Figure 8b). In well SR-10 the suggested formation temperature curve is constructed based on two points; the bottom hole temperature and the point at 10 m. These two points, in addition to the surface temperature were connected by a smooth line (Figure 8c). In well SR-11 the last two temperature measurements show relatively stable conditions and they can be considered as the formation temperature profile (Figure 8d). In well SR-12 two temperature logs were obtained, the second of which shows more stable condition and it can represent the formation temperature (Figure 9a). The formation temperature in well SR-13 is suggested to be a smooth curve, starting at the bottom of the well and then following the temperature profile performed two days after the end of drilling above 10 m (Figure 9b). In well SR-14 the temperature profile obtained two days after drilling is considered to be the formation temperature curve (Figure 9c).

2.3 Temperature distribution

Based on the reconstructed formation temperature curves from the wells in the field, the temperature distribution is presented in three cross-sections and two maps at different depths (Figures: 11, 12, 13, 14, and 15). Figure 11 shows the temperature cross-section AB (for location, see Figure 2) from well SI-1 to well SIS-5 (only the top 400 m of well SG-2 were considered in the cross-section). It shows a temperature anomaly, over 50°C, underneath wells SG-2, SY-3 and mainly SY-4. This is caused by a horizontal flow of hot water perpendicular to the cross-section or at least not along it and it also shows a cold water flow from well SIS-5 towards the production well.

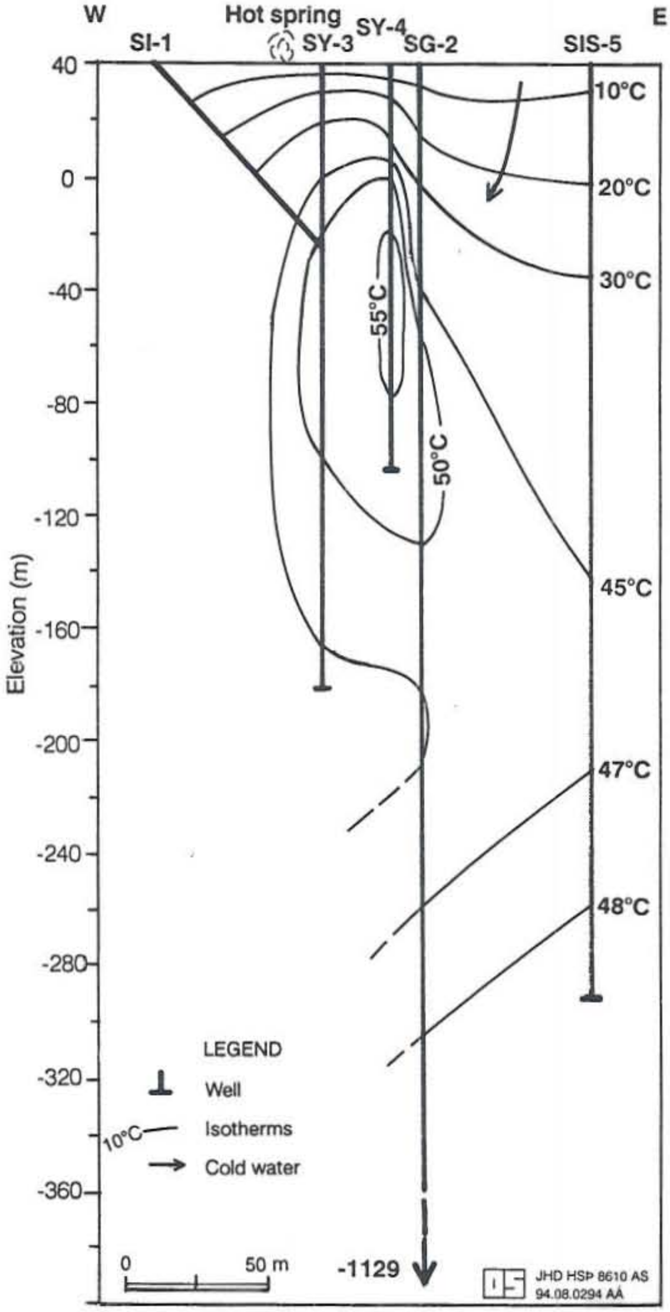

FIGURE 11: Temperature cross-section AB, between wells SI-1 and SIS-5

Figure 12 shows the temperature cross-section AC from well SI-1 to well SR-12. It can be seen from this figure that the flow direction of the warm water is from well SI-1 to well SR-12, i.e. from north to south.

The temperature cross-section CD is shown in Figure 13. It includes wells SR-6, SR-9, SY-4, SR-8, SR-11 and SR-12. It shows a temperature high beneath well SY-4.

The temperature distributions at 20 and 60 m depth are shown in Figures 14 and 15, respectively. It can be seen from Figure 14 that there is a relatively high temperature anomaly, including wells SY-3, SY-4 and is extended to the south to include wells SR-8, SR-10 and SR-14. It has the same direction as the warm spring area (NE-SW). The temperature map at 60 m (Figure 15) shows a temperature anomaly around wells SY-3 and SY-4, but the main trend has shifted and has the direction N-S. The map indicates strongly that the flow direction of the warm water is from north to south.

A general conclusion is that the flow direction of the warm water is from north to south as it appears on the temperature maps and the cross-section AC. Both temperature maps and the two cross-sections AB and CD show cold water flow from the north-eastern corner to the centre of the field.

The cooling in the production well SY-4 is due to ground water flow from the north-eastern part towards the centre of the field. The temperature logs in wells SG-2, SY-3 and SIS-5 show a considerable cooling, mainly in wells SY-3 and SIS-5, compared with the situation before production from SY-4 (Figure 6c, 6d and 7b).

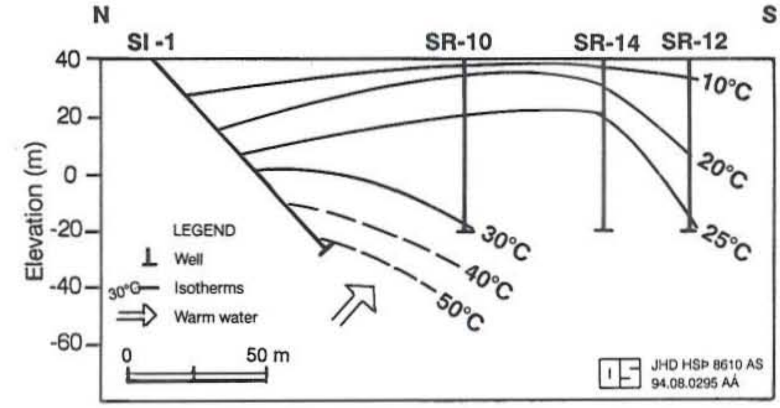

FIGURE 12: Temperature cross-section AC, between wells SI-1 and SR-12

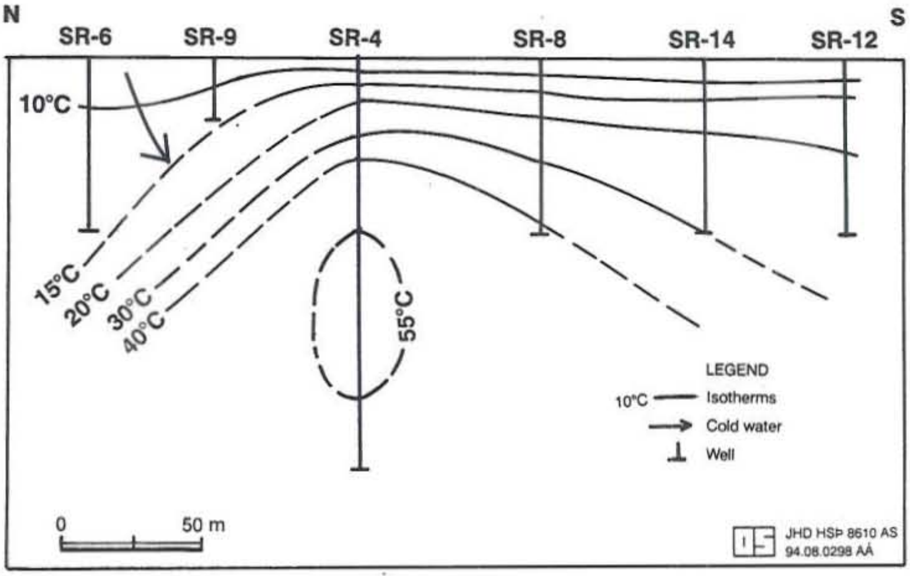

FIGURE 13: Temperature cross-section CD, between wells SR-6 and SR-12

Therefore, the cold water reaches the production well as a result of down-flow in wells SY-3 and SIS-5 and has an easy access between these wells. This result was confirmed by the resent temperature measurements which were performed in wells SY-3 and SIS-5 on September 13th, 1994. Furthermore, the ground water can also infiltrate as a natural down-flow through fractures following the water level lowering. The chemical analysis of the water sample from the production well taken in 1985, shows the effect of the ground water flow into the system, for example the chloride contents of the warm water had been reduced at least 40% and the total dissolved solids at least 30%. So, it was estimated that 25-30% of the water which was taken from the production well SY-4 was originally ground water (Georgsson, 1986). Recent chemical analysis of water sample taken in 1994 confirms that there is ground water flow into the system. Therefore, it is urgent to case or cement wells SY-3 and SIS-5 to reduce the continuing cooling in the production well (SY-4) and hopefully to reverse it.

Looking at the drilling results of well SIS-5 and the temperature cross-sections, one can make the conclusion that the geothermal fracture (the up-flow conduit of the warm water to the springs), which well SIS-5 was supposed to cut, is a shallow fracture and it is permeable to a depth of not more than 200 m.

A computer interpretation of the head-on resistivity profiling is highly recommended to re-evaluate the results of it, especially in order to locate active seismic fractures trending N-S, in the north-western part of the field which may form the up-flow conduit of the warm water in the field. Also, a new exploration well is needed 30-50 m north to northwest of the production well.

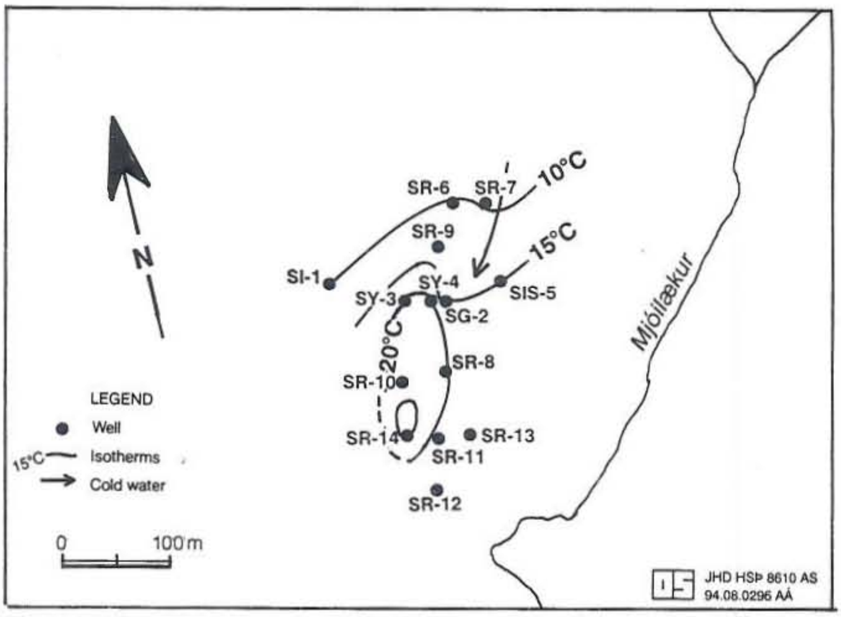

FIGURE 14: The temperature distribution at Sumarlidabaer at 20 m depth

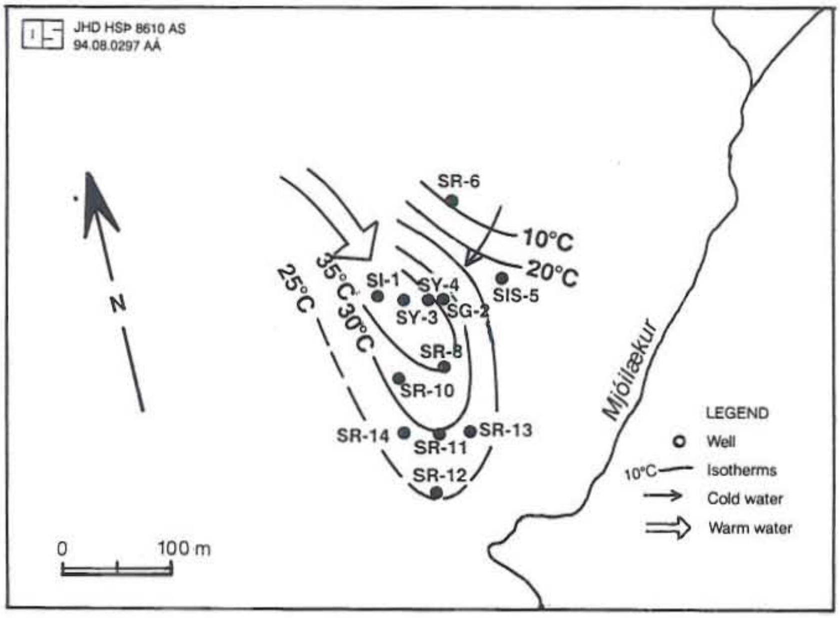

FIGURE 15: The temperature distribution at Sumarlidabaer at 60 m depth

3. WELL TEST ANALYSIS

3.1 Introduction

Well testing methods have been used for decades to evaluate ground water and petroleum reservoirs. These methods have also been successfully applied on geothermal reservoirs, especially for single-phase reservoirs (Grant et al., 1982; Kjaran and Eliasson, 1983). The tests give information on the hydrogeological condition of the well/reservoir system and form a basis for future prediction on well yield and pressure draw-down in the reservoir. During a well test, the flow rate or injection rate is changed. This will create a time-dependent pressure change in the reservoir, which is either monitored in the production well itself (single well test) or in an observation well (interference test).

The main assumptions in the derivation of the isothermal flow equation are: The reservoir is to be horizontal and uniform in thickness with constant porosity and permeability and have an infinite areal extent. It should also be homogenous, isothermal and isotropic. Furthermore, the reservoir fluid is to be in a single-phase condition and occupy the entire pore volume. The pressure gradients should be small, gravity forces can be neglected and a well penetrates the reservoir completely.

The diffusivity equation describes horizontal flow of a single-phase, slightly compressible fluid through a homogeneous and isotropic porous media. The equation can be written as (the variables are defined in the nomenclature at the end of the report)

$$\frac{\partial P}{\partial t} = D\left[\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r}\right] \tag{1}$$

where D is the reservoir diffusivity, defined as

$$D = \frac{kh}{\mu}\frac{1}{\phi ch} = \frac{T}{S} \tag{2}$$

Here we make the assumption that k, μ, ϕ, ρ and c are independent of pressure. The initial and boundary conditions can then be stated as follows:

$$P(r,0) = P_o \qquad \text{for } 0 \le r \le \infty$$

$$\lim_{r \to \infty} P(r,t) = P_o$$

$$Q = -\frac{2\pi khr}{\mu}\frac{\partial P}{\partial r} \qquad at\ r = r_w \tag{3}$$

A solution to Equation 1 is given as follows:

$$P(r,t) - P_o = \frac{Q\mu}{4\pi kh}\int_x^{\infty}\frac{e^{-u}}{u}du = \frac{Q}{4\pi T}\int_x^{\infty}\frac{e^{-u}}{u}du \tag{4}$$

where

$$x = \frac{S}{4T}\frac{r^2}{t}$$

Equation 4 is called the Theis solution to the diffusivity equation.

3.2 Well test analysis methods

The well known methods of analyzing test data are based on the Theis solution to the diffusivity equation. From these methods the semi-log plot (Cooper- Jacob) and Horner plot will be introduced in the following.

3.2.1 Semi-log plot

Equation 4 can be expanded as a convergent series

$$P(r,t) = \frac{Q}{4\pi T}[-0.5772 - \ln x + x - \frac{x^2}{2\,2!} + \frac{x^3}{3\,3!} \; ... \;] \tag{5}$$

If r is small and t is large, the value of x becomes negligible. In that case Equation 5 can be written as

$$P(r,t) = \frac{Q}{4\pi T}[-0.5772 - \ln\frac{r^2S}{4Tt}] \tag{6}$$

or if we use the $\log_{10}$ basis for the logarithm

$$P(r,t) = \frac{2.30Q}{4\pi T}\log\frac{2.25Tt}{r^2S} = m\log\frac{2.25Tt}{r^2S} \tag{7}$$

If we plot the pressure changes, P, as a function of the logarithm of time, we find a straight line of slope m. This line can be used to determine transmissivity and storativity of the reservoir.

The change in pressure from the graph during one log-cycle (ΔP_{10}) gives the slope as

$$\Delta P_{10} = \frac{2.30Q}{4\pi T} = m \tag{8}$$

This equation can be solved for the transmissivity. Furthermore, if we read the time t_o where $P = 0$, Equation 7 can be rearranged to calculate the storativity

$$S = \frac{2.25Tt_o}{r^2} \tag{9}$$

3.2.2 The Horner plot method

When a well is shut down after a steady production Q, at time Δt, the water level recovers to the initial water level prior to pumping. This recovery can be imagined as another hypothetical well at pumping rate $-Q$, which is superimposed on the other at $t = \Delta t$. Before $t = t_o$, Equation 7 is valid. After the well is shut off, we can use the methods of superposition and get

$$P(r,t) = \frac{2.30Q}{4\pi T}\log\frac{t+\Delta t}{\Delta t} \tag{10}$$

When we plot the pressure recovery as a function of log $((t + \Delta t)/\Delta t)$, we get a straight line. By measuring the pressure change ΔP_{10} over one log-cycle, we obtain transmissivity by using Equation 8.

3.3 Interpretation of a well test at Sumarlidabaer

In 1986, well SY-4 at the Sumarlidabaer geothermal field was tested. First the well was tested by pumping in two steps observing pressure changes in the same well and in close-by wells (SG-2 and SY-3). The first step lasted for 130 minutes with a pumping rate of 8.3 l/s, whereas the second step lasted another 170 minutes and the pumping rate was increased to 16.5 l/s. The water level recovery (pressure build up) was observed in well SY-3 after shut-off for about 20 minutes. Then a long-term test was conducted and 16.5 l/s pumped from the well SY-4 for seven days (10,000 minutes). The water level was observed in the same well and the pumping caused a drop in water level of about 8 m.

A standard procedure was followed in the interpretation of the pressure changes; data for the long-term test was plotted on a semi-log graph (Figure 16a) and the transmissivity was computed by Equation 8. Data for the build up test from well SY-3 was plotted by the Horner plot method (Figure 16 b), then the transmissivity and the storativity were computed from Equations 8 and 10. For the short-term test, the second step data was plotted on a semi-log plot (Figure 16 c,d), so that the initial time and pressure could be taken at the time when the flow was increased. This assumes that the well had established quasi-steady-state condition at the end of the first flow step. The storativity and transmissivity were computed by Equations 8 and 9.

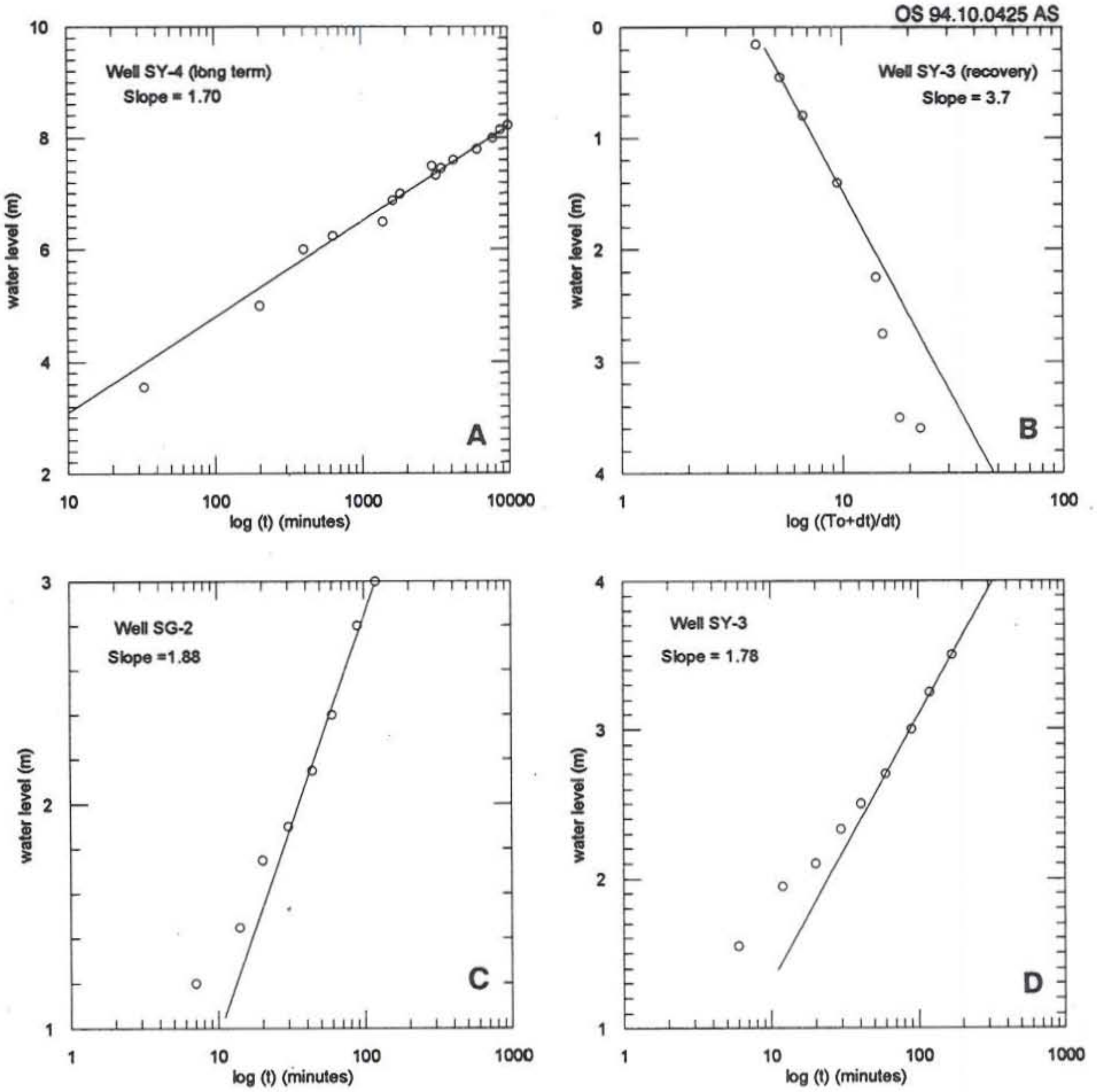

FIGURE 16: Well test results at Sumarlidabaer, a) Theis plot of water level changes in well SY-4, b) Horner plot of water level recovery in well SY-3, c) Theis plot of water level changes in well SG-2, d) Theis plot of water level changes in well SY-3

The skin factor was calculated from the following equation (Kjaran and Eliasson, 1983):

$$s = \frac{\Delta P}{m} - \log\left(\frac{4kt}{\mu c_t (r_w)^2}\right) + 0.251 \tag{11}$$

It was found to be 0.67 by assuming 400 m thickness of the reservoir, the positive value of the skin factor indicates a lower well-face permeability than in the reservoir. The skin effect may result from drilling operation.

Table 3 shows the main parameters of the well tests in the reservoir. Calculated results of some of the hydrological properties of the reservoir are shown in Table 4.

TABLE 3: The main parameters of the well tests at Sumarlidabaer reservoir

Well no.	Initial water level (m)		Average production (l/s)		Slope - m (Pa/cycle)		$\mu \times 10^{-3}$ (Pa-s)	$C_t \times 10^{-10}$ (1/Pa)	r (m)
	Pumping	Build-up	Pumping	Build-up	Theis	Horner			
SG-2	0.2		8.2		1.88		0.55	0.58	40*
SY-3	0.7	3.5	8.2	16.5	1.78	3.7	0.55	0.58	50*
SY-4	0.5		16.5		1.7		0.55	0.58	0.1

* The distance between the main feed-zones in the wells. Density of water at 50°C is 988 kg/m³.

TABLE 4: The results of well test analysis at Sumarlidabaer reservoir

Well no.	Transmissivity kh/μ (m^3/Pa-s)		Permeability thickness kh (m-d)		Storativity $C_t h$ (m/Pa)		Aquifer thickness (m)	
	Theis (10^{-8})	Horner (10^{-8})	Theis	Horner	Theis (10^{-8})	Horner (10^{-8})	Theis	Horner
SG-2	9.5		52		3		576	
SY-3	8.8	8.4	48	46	2.1	2.1	368	367
SY-4	18		99					

It can be seen from Table 4 that the transmissivity values calculated from the short-term test data using Theis plot in the two observation wells (SG-2 and SY-3), range from 8.8×10^{-8} to 9.5×10^{-8} m^3/Pa-s. The Horner plot method gives almost the same transmissivity value or 8.4×10^{-8} m^3/Pa-s. On the other hand, transmissivity value calculated from the long-term test data using Theis plot method is twice that calculated from the short-term tests (18×10^{-8} m^3/Pa-s). This indicates that the permeability of the reservoir is increasing as the cone of depression increases, i.e. the permeability is higher in the reservoir away from the well. The table also shows that the storativity of the reservoir ranges from 2.1×10^{-8} to 3.0×10^{-8} m/Pa and the calculated thickness of the reservoir is between 367 and 576 m.

4. SIMULATION OF WATER LEVEL DATA FROM THE LAUGALAND GEOTHERMAL FIELD BY A LUMPED PARAMETER MODEL

4.1 Theory and methodology

Detailed numerical modelling of geothermal reservoirs is time consuming, costly and requires large amounts of field data. Lumped parameter modelling is, in some cases, a cost effective alternative. It uses an automatic non-linear least-squares iterative process which requires very little time compared to more complex numerical modelling. It is ideal in the cases where data on subsurface conditions are scarce but when pressure response of a reservoir has been monitored carefully for some time. The method can also be used as a first stage in a more detailed modelling study of a reservoir as well as to provide independent checks on results of more complex modelling methods. Lumped parameter method has been successfully used in simulating several low-temperature geothermal fields in Iceland. A brief description of this method will be presented, but the details of the theoretical background are given by Axelsson (1985, 1989).

A general lumped network consists of total capacitors or tanks with capacitances (mass storage coefficients, κ). A tank has the mass storage coefficient κ when it responds to the load of liquid mass, M, with the pressure $p = M/\kappa$. The tanks are pair-wise connected by up to $N(N-1)/2$ resistors or conductors of conductivity $\sigma_{ik}(\sigma_{ii}=0)$. The mass conductivity of a resistor is σ when it transfers $q = \sigma\ \Delta p$ units of liquid mass per unit at the impressed pressure differential Δp (Axelsson, 1989). The particular element σ_{ik} connects the i and k tanks and because of linearity $\sigma_{ik} = \sigma_{ki}$. The network is open in the sense that the tank i is connected by a resistor of conductivity σ_i to an external tank which maintains equilibrium pressure. The network is closed when $\sigma_i = 0$ for $i = 1,2,...N$ (Axelsson, 1989). The basic equation describing the model is given as

$$WL(t) = Q[\sum_{i=1}^{N}[\frac{A_i}{L_i}(1-e^{-L_i t})] + Bt] \tag{12}$$

To simulate pressure response (water level) data from a liquid-dominated geothermal reservoir, an appropriate or best fitting lumped model with parameters, κ_i and σ_i, is chosen. Fluids are produced from one of the tanks of the geothermal reservoir. The resulting pressure $p(t)$ is then observed in any given tank of the lumped model (Figure 17).

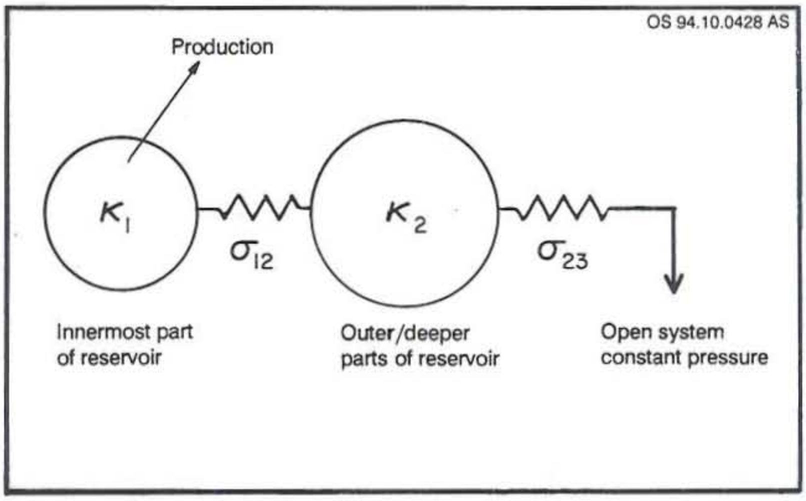

FIGURE 17: General open 2 tank parameter model used in the simulation of the Laugaland field

Tank capacity, κ, in a liquid geothermal system can result from two types of capacity effects of a reservoir, storage or releasing mechanism (Axelsson, 1989). First, the capacity may be controlled by the liquid and formation compressibility, and is then given by

$$\kappa = V \rho c_t \tag{13}$$

The total compressibility is given by

$$c_t = \phi c_w + (1-\phi) c_r \tag{14}$$

Second, the capacity may be controlled by a free surface mobility, where

$$\kappa = \frac{A\phi}{g} \tag{15}$$

The geothermal model can be used to assess the production potential of the reservoir. This is done by using the lumped parameter model to predict the pressure changes in the reservoir for different cases of future production. The maximum acceptable draw-down in the production wells can be used to estimate the maximum potential of the system.

4.2 Simulation results

Lumped parameter modelling was used to simulate the water level data with production from the Laugaland geothermal field, S-Iceland. Laugaland is a small low temperature geothermal field, which has two production wells GN-1 and LN-4. The water temperature is 85-100°C. Fluid extraction and reservoir draw-down have been monitored monthly since the start of the production in 1982. Even more, the production history of well GN-1 has been monitored weekly since 1988. Therefore, excellent production history data were available for this modelling.

An attempt was made to simulate the detailed water level data with production (weekly and monthly) by open two tank and closed three tank models. The open two tank model gives a very good match (Figure 18). On the other hand, the closed three tank model was unstable, and it gave a negative value for the slope of the long-term draw-down (B), which is possible mathematically but physically impossible. However, it gave excellent results for the monthly data (Figure 18). The open two tank model was selected for the future simulation of the reservoir.

Fluids are produced from the first tank κ_1 and the water level is monitored in the same tank. The first tank κ_1 can be considered as the main production reservoir or well area and the other tank κ_2 acts as the surrounding and deeper part of the geothermal system, which is connected to an open system (Figure 17). The open system (recharge area) is most likely the ground water system in the area, which is colder than the other parts of the reservoir.

The simulation process was carried out automatically, by using the LUMPFIT computer program (Axelsson and Arason, 1992). A first guess of the lumped model parameters was made and the parameters were automatically changed by an iterative process until a least-squares fit was obtained. No prior assumptions were made on the properties of the reservoir. The results and the parameters of the simulation are shown in Table 5.

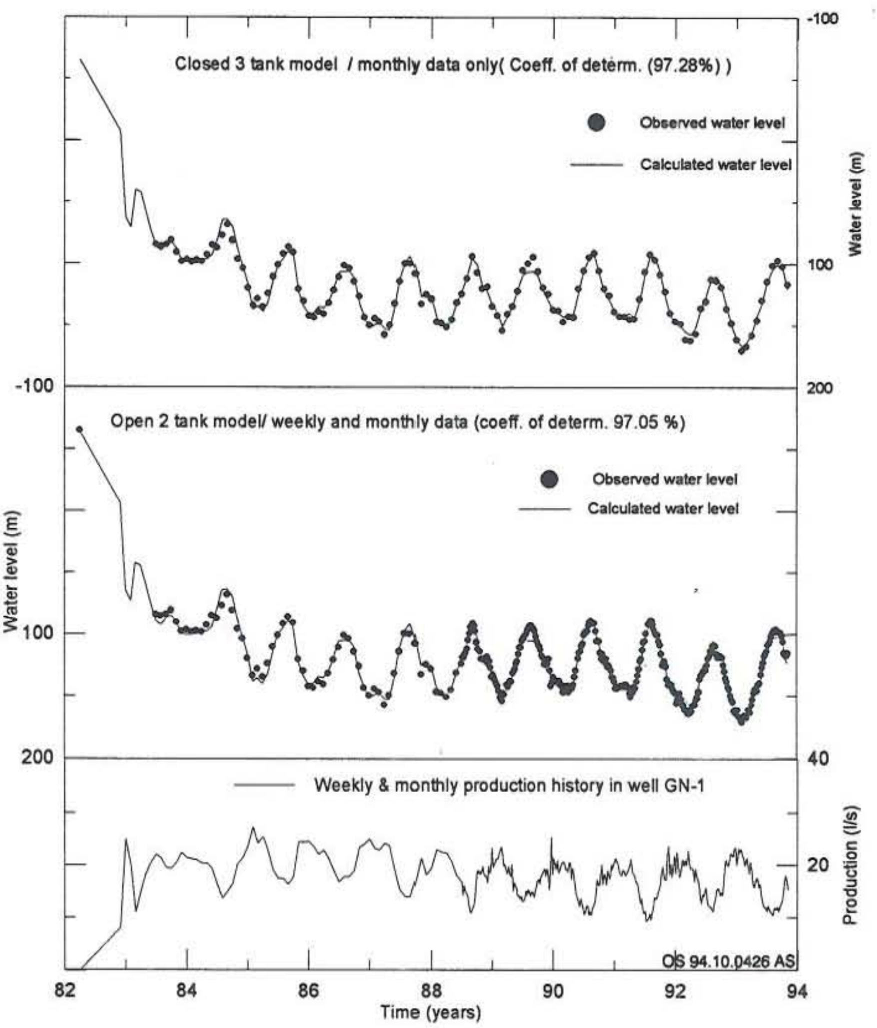

FIGURE 18: Comparison between observed and calculated water level at the Laugaland geothermal field (open 2 tank and closed 3 tank models)

Analysis based on simulation results and by using Equations 13, 14 and 15 indicate that the Laugaland geothermal field is likely to have a connected free surface mobility, since its volume is expected to be small, or about 1 km^3. Otherwise, based on its capacity, its volume would be more than 90 km^3 which is too large to accept. The area of the first tank (well area) is 4.3×10^{-3} km^2 while the area of the second tank (the surrounding and deeper part of the reservoir) is 2.2 km^2 as computed by Equation 15.

4.3 Future predictions

The main objective of modelling a geothermal system is to assess its production potential. The open two tank model gives an optimistic future prediction of the pressure changes (water level draw-down). On the other hand, the closed tank model gives a pessimistic long term prediction, so that the optimum production rates can be selected.

The lumped-fit models (open two tank and a closed three tank for the monthly data only) were used to predict the water level changes in the reservoir for different production rates. Future productions were set at a constant rate of 10, 15, 20, 25, and 30 l/s and water level in the reservoir calculated up to the year 2005. The results of the prediction are shown in Figure 19. It can be seen from the figure that there is little difference

TABLE 5: Results of the simulation at Laugaland geothermal field

Parameter	Model	
	Open 2 tank[1]	Closed 3 tank[2]
*L*1	10.67	11
*A*1	73.2	72.33
*L*2	0.1	0.2
*A*2	0.71	0.78
B		0.13
RMS (m)	3.8	3.79
κ_1 (ms^2)	43.5	43.9
κ_2 (ms^2)	4578	3591
κ_3 (ms^2)		21065
$\sigma_{1\text{-}2}$ (ms)	0.146 x 10^{-4}	0.15 x10^{-4}
$\sigma_{2\text{-}3}$ (ms)	0.148 x 10^{-4}	0.2 x 10^{-4}
Coeff. determ (%)	97.05	97.28

1) Weekly and monthly data; 2) Monthly data only.

between the two models. Only 10 m difference is in the predicted draw-down values between the optimistic prediction (open two tank) and the pessimistic prediction (closed three tank). It also, shows that the optimum production rate for the next 10 years is 15 l/s in order to keep the draw-down close to the present limits.

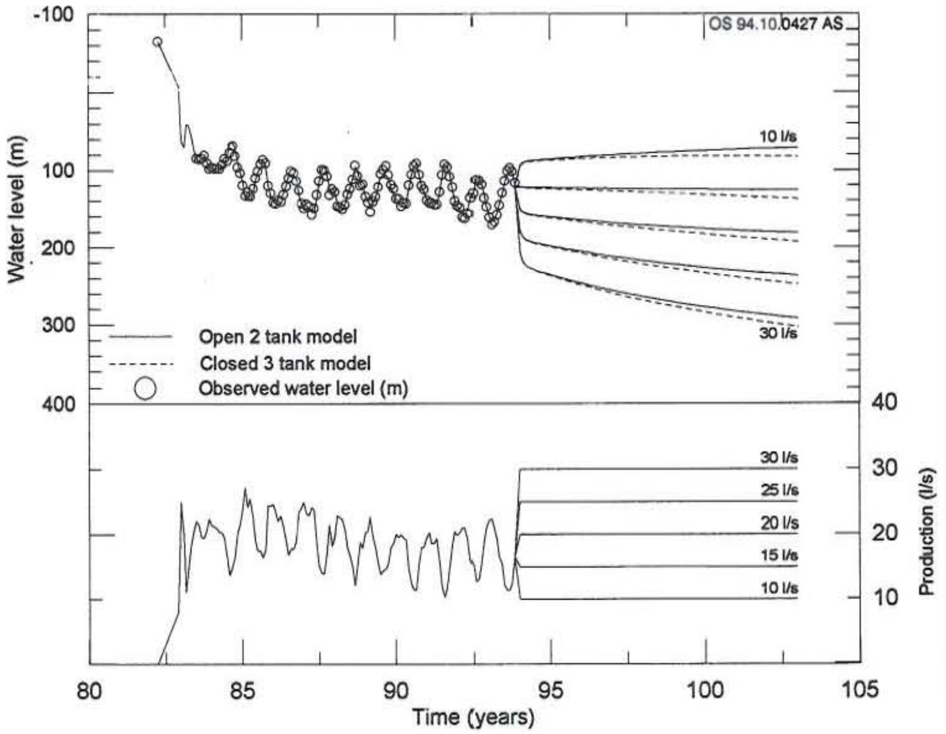

FIGURE 19: The predicted changes in water level at the Laugaland geothermal field for the next 10 years (1995-2005) at different pumping rates using open 2 tank and closed 3 tank models

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Sumarlidabaer geothermal field

5.1.1 Conclusions

1. The flow of warm water towards the Sumarlidabaer geothermal field is from northwest but cold water flows into the system in the northeastern part of the field.

2. The cause of the continued cooling in the production well (SY-4) in the field is thought to be mainly due to down-flow of cold ground water through wells SY-3 and SIS-5.

3. The geothermal fracture which forms the conduit of the warm springs water seems to be shallow, reaching only to a depth of about 200 m.

4. The transmissivity of the Sumarlidabaer reservoir ranges from 8.8 to 10×10^{-8} m^3/Pa-s; the storativity is between 2.1 and 3.0×10^{-8}m/Pa; and the calculated thickness of the reservoir is about 470 m.

5.1.2 Recommendations

1. Immediate cementing of wells SY-3 and SIS-5 is needed to stop the cooling in the production well.

2. New temperature measurements are needed in the other wells (shallow exploration wells) to find out if there is down-flow of cold water through them.

3. A computer interpretation of the head-on resistivity profiling is highly recommended to check further on the fractures, mainly the active seismic fractures trending N-S.

4. Drilling of an exploration well is recommended, 30 to 50 m north to northwest of the production well.

5.2 Laugaland geothermal field

1. The simulation of the Laugaland geothermal field using an open two tank lumped parameter model indicates that the volume of the reservoir is about 1 km^3 and that it is connected to an open system (recharge area) which is most likely the ground water system in the area.

2. Simulation of future response of the Laugaland reservoir indicates that the optimum production rate for the next 10 years is 15 l/s, in order to keep the water level at the present depth.

3. The only recommendation I can suggest is that the present production rate of the Laugaland reservoir should be reduced from 20 to 15 l/s to keep the water level in the reservoir for the next 10 years at the present depth.

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NOMENCLATURE

A = Top surface area of the reservoir that a tank simulates (m^2)
A_i = Lumped parameter ($1/m^2s^2$)
B = Slope of the long term draw-down
c = Compressibility (1/Pa)
c_t = Total compressibility of the water saturated formation (1/Pa)
c_w = Compressibility of water (1/Pa)
c_r = Compressibility of rock matrix (1/Pa)
D = Reservoir diffusivity (m^2/s)
g = Acceleration of gravity (m/s^2)
h = Reservoir thickness (m)
k = Permeability (m^2)
kh = Permeability thickness (darcy-m or m^3)
L_i = Lumped parameter (1/s)
M = Liquid mass (kg)
m = Slope of the semi-log straight line (Pa/log-cycle)
P = Pressure (Pa)
P_0 = Initial pressure (Pa)
Q = Volume flow rate (m^3/s)
r = Radial distance (m)
r_w = Radius of the well (m)
S = Storativity (m/Pa)
s = Skin factor
t = Time (s)
T = Transmissivity (m^3/Pa-s)
V = Volume of the reservoir that the tank simulates (m^3)
$WL(t)$ = Water level at a given time (m)

ϕ = Porosity
μ = Dynamic viscosity (Pa-s)
δ = Symbol for partial derivative
κ = The tank capacity (ms^2)
σ = The conductivity between tanks (ms)
ρ = Water density (kg/m^3)

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