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ANALYSIS OF TEMPERATURE MEASUREMENTS, WELL TEST DATA AND PRODUCTION HISTORY OF THE BOTN LOW-TEMPERATURE GEOTHERMAL FIELD, N-ICELAND

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ABSTRACT

The Botn field is one of five low-temperature geothermal fields in Central North Iceland utilized for space heating in the town of Akureyri. Since 1981 six wells have been drilled in the field, BN-1 and HN-10 as production wells, and BY-4, BY-3, BY-2, and HY-12 as exploration wells. About 29 temperature logs are available from these wells, and the production and water level changes have been recorded since 1981. A pressure transient test was performed in the field in June 1990. On the basis of these data, the thermal characteristics of the reservoir were analysed, and the main feedzones identified. The hot water upflow appears to be from the western part of the reservoir at depth towards the centre of the reservoir at shallow levels (BY-3). Analysis of well test data from the reservoir was done using semi-log, and computerized methods. Comparable results were obtained using both methods. The reservoir has a transmissivity of about 5.3×10^{-9} m^3/Pa-s. The water level history of the reservoir was simulated using a lumped parameter model. The model has a great storage coefficient indicating free-surface storage. Future water level changes were calculated for various production rates showing a very slow future decline. A simple cold water down-flow model was used to simulate water temperature and chemistry changes in well HN-10. According to this model the water temperature of the well will decline from about 80 to 73°C in the next 15 years.

1. INTRODUCTION

The Botn low-temperature geothermal system is located in Tertiary rock formations in the Central part of North Iceland. Production from the field started in 1981 and since then the average yearly production has been about 30 l/s. The response of the system is characterized by a great pressure draw-down and considerable cooling, which limits how much hot water can be produced from the field. In addition the upflow zone of the geothermal system does not appear to have been intersected yet by a borehole.

This report presents a reservoir evaluation of the Botn field. It describes work which was carried out as a part of the author´s training at the UNU Geothermal Training Programme in Reykjavík in 1995. Its purpose was to define the temperature distribution and locate the hot water upflow in the field. This may help in locating a new well in the area. The purpose was also to estimate the hydrological parameters of the reservoir and the long term behaviour and size of the geothermal system. Finally the purpose was to predict the future water level and temperature changes.

The report starts by an outline of the geology, geophysics and production history of the Botn field. Following this the temperature distribution and locations of feed-zones are determined on the basis of all available temperature logs. Then pressure transient test data from June 1990 are analysed, followed by a simulation of the field's production and water level history, and predictions of the future water level changes. Finally a simulation of changes in chemistry and temperature and predictions of the future temperature changes is carried out.

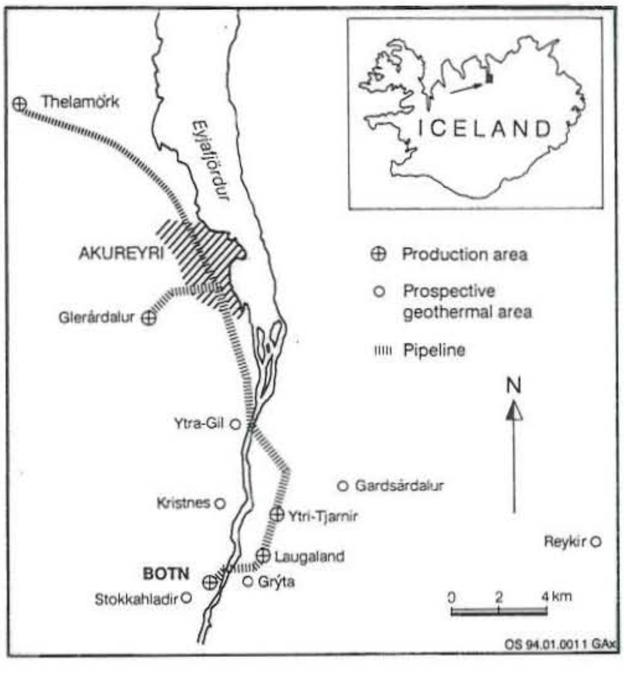

FIGURE 1: Location of the Botn geothermal field

2. THE BOTN GEOTHERMAL FIELD

The Botn geothermal field is located 15 km south of the town of Akureyri with a population of 15,000 (Figure 1). It is one of five small geothermal fields utilized for space heating by "Hita- og Vatnsveita Akureyrar" (Akureyri District Heating Service and Municipal Water Works). The other fields are Thelamörk, Glerárdalur, Ytri-Tjarnir, and Laugaland (Flóvenz et al., 1995). Botn is a low-temperature field with a maximum measured temperature of 97°C. Two production wells have been drilled in the Botn field in addition to four exploration wells. The elevation of the field varies from about 66 m a.s.l. at well BY-4 in the west to about 5 m a.s.l. at well BY-2 in the east. Table 1 lists information on the wells.

TABLE 1: Wells in the Botn geothermal field

Well No.	Year of drilling	Altitude (m a.s.l.)	Casing		Total depth (m)	Type of well
			Diam. (")	Length (m)		
BN-1	1981	23.2			1830	Production
BY-2	1989	5.6	7 5/8	103.8	446	Exploration
BY-3	1989	6.6	5 7/8	40.7	300	Exploration
BY-4	1989	66.1	8 5/8	7.8	403	Exploration
HN-10	1980	22.4	11 3/4	456	1050	Production
HY-12	1989	28.6	8 5/8	5.2	318	Exploration

The rock formations in the Botn area consist mainly of Tertiary (6-10 m. y. old) sub-aerial flood basalts interbedded with thin layers of sediments. The lava pile tilts a few degrees towards the active rift zone (The Mid-Atlantic Ridge). In addition the lava pile is intersected by numerous vertical dykes and normal faults. It has suffered low grade alteration which together with precipitation of alteration minerals has greatly reduced the primary permeability. Recent crustal movements have, however, opened up existing fractures and created new ones providing the flow paths for geothermal water. Most of the low-temperature fields of North Iceland are characterized by secondary permeability in young fractures surrounded by low-permeability rock.

Because of the nature of the low-temperature systems in North Iceland prospecting for vertical fractures is of utmost importance. The methodology used involves ground magnetic surveys, head-on resistivity profiling, temperature measurements in shallow boreholes and geological investigations (Flóvenz and Georgsson, 1982). The five geothermal systems utilized by Hita- og Vatnsveita Akureyrar all have low average permeability. On the basis of interference test data, the permeability-thickness has been estimated between 1 and 12 Dm (10^{-12} m^3).

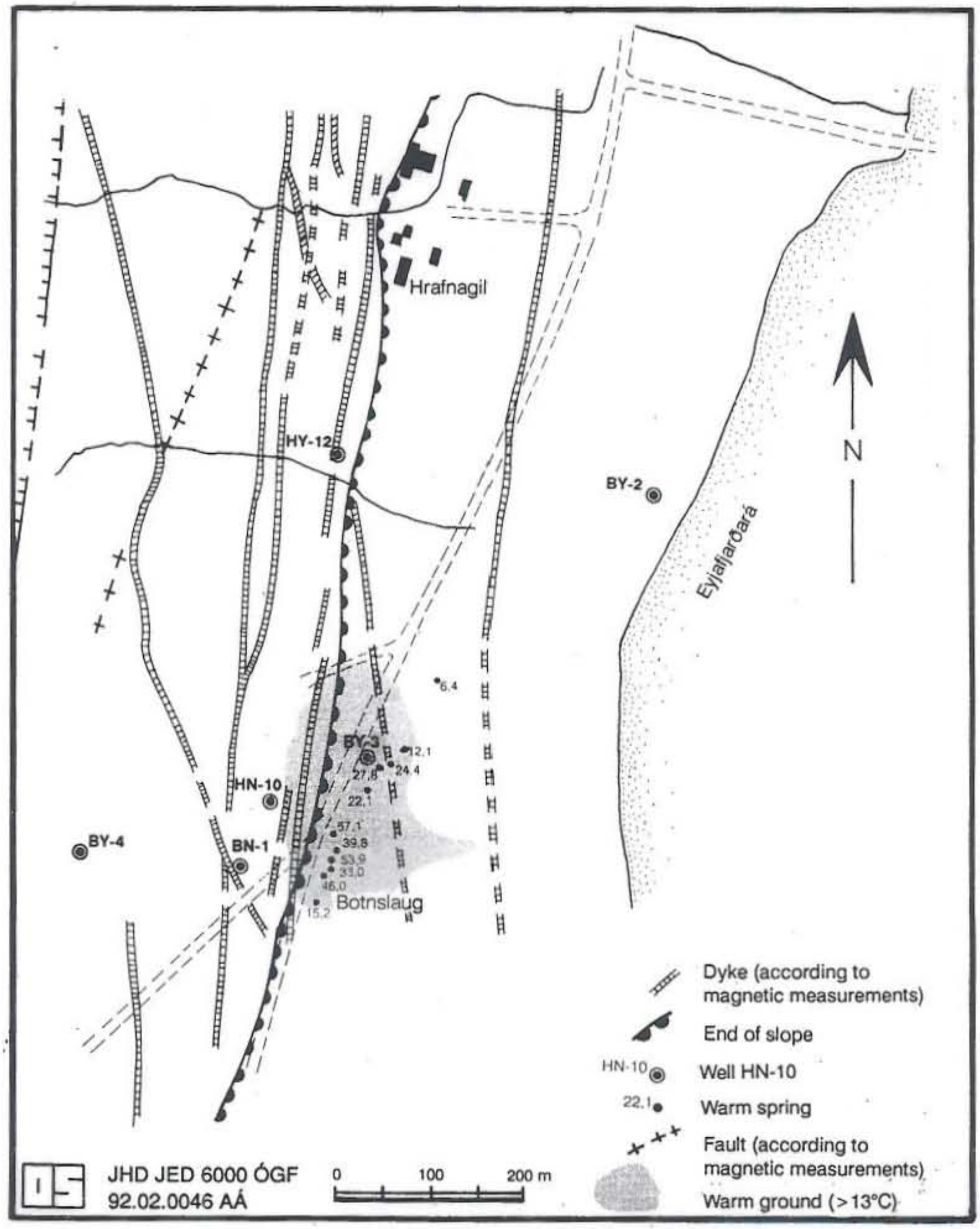

FIGURE 2: Location of wells in the Botn geothermal field and geological structures

The Botn geothermal system has been studied extensively during the last two decades (Flóvenz et al., 1989 and 1991; Axelsson et al., 1988). Detailed subsurface resistivity and magnetic mapping has been carried out to identify dykes and faults. These are recognizable as narrow linear anomalies, especially when the overburden is thin. In the Botn low-temperature field an area of 40 ohmm resistivity was delineated. Some hot springs existed in the centre of the field (Figure 2) before exploitation started, but they have disappeared since production began in 1981. Four exploration wells were drilled, the production response has been monitored carefully and lumped modelling of the Botn system performed. The main objective of this previous work was to locate permeable zones in the deep recharge system. However, the results have not been conclusive with regards to locating sites for new production wells. As a final stage of geothermal research in the area, a detailed 3-dimensional numerical model was developed for the Botn geothermal system (Axelsson and Björnsson, 1993).

The total production from the field, from 1981 through 1994, was about 12 million tons. Well HN-10 has produced an average of 25 l/s of 84°C water and well BN-1 5 l/s of 95°C water, during this period. Prior to production a 18-22 bar well-head pressure was observed in the production wells. The mass withdrawal has induced a 40 bar draw-down in well HN-10. Most of this draw-down took place in the first months of production. Since then, the draw-down in production wells has remained almost stable due to recharge, which is believed to come from the overlaying ground-water system and from a powerful recharge system of an unknown location (Axelsson and Björnsson, 1993)

3. TEMPERATURE CONDITIONS IN THE BOTN GEOTHERMAL SYSTEM

3.1 Analysis of temperature logs and location of feed-zones

A temperature log is a set of temperature values recorded at different depths down a borehole. These provide important information on temperature conditions, flow paths and feed-zones in geothermal systems. Temperature logs are, however, seriously affected by cooling during drilling, and internal flow in wells. In the Botn geothermal field, many temperature logs have been recorded, during drilling, after drilling and during production. Information about the various temperature logs from the six wells in the Botn field is presented in Table 2.

WELL HN-10 was drilled as a production well in the central part of the field. It was completed in November 1980 at 1050 m depth. Four temperature logs were recorded during and after drilling, these are shown in Figure 3. These profiles indicate that the main feed zones are at depths of 489, 530, 876, and 1050 m (see Table 3).

Based on the temperature profiles from well HN-10, a curve was constructed representing the estimated formation temperature. The main points used are the bottom hole temperature of 88.6°C at 1030 m depth and the surface temperature of 4°C at zero level. The formation temperature is also believed to be less than 80°C at 460 m depth. The estimated formation temperature for HN-10 is presented in Table 4 and in Figure 4.

WELL BN-1 was drilled as a production well in the central part of the field south of well HN-10. It was completed in December 1981 at 1830 m depth. Five temperature logs were recorded during and after drilling, shown in Figure 3. These profiles indicate feed zones at depths of 150, 670, 890-900, 1020, and 1150 m. The main feed zone is believed to be at a depth of 1756 m (Flóvenz et al., 1991).

Based on the temperature profiles of well BN-1, during and after drilling, the formation temperature around the well was estimated. Since the well was producing during all the measurements only a few fixed points are known. The highest measured temperature in the well is 96.8°C at a depth of 892 m which suggests a somewhat higher temperature of the deepest aquifer. Based on the temperature logs the formation temperature is less than 96.8°C at 892 m depth, more than 85°C at 670 m, less than 56.7°C at 140 m and more than 90°C at 1300 m depth (see Table 4 and Figure 4).

TABLE 2: Temperature logs in wells in the Botn field

Well No.	Measurem. date	Meas. depth (m)	Condition of well	B.h.t. (°C)
HN-10	1980-11-11	610	In drill string	86
(54411)	1980-11-26	1040	End of drilling, Q=20 l/s	88
	1980-12-02	1040	Q=15 l/s	88.7
	1990-06-14	1030	Water level 25 m.	88.6
BN-1	1980-08-04	300	In drill string, Q=3 l/s	73.3
(54401)	1980-08-18	1160	After weekend stop, Q=1.6 l/s	83.1
	1980-09-01	1310	After weekend stop, Q=1.6 l/s	88.4
	1980-09-09	1384	End of drilling	86.8
	1980-12-03	892	Q=7 l/s	96.8
BY-2	1989-12-02	235	In drill string	57.5
(54402)	1989-12-03	370	In drill string	62.3
	1989-12-04	432	In drill string	67.6
	1989-12-05	446	Water level 72.2 m	69.3
	1989-12-11	425	Water level 65.7 m	66.2
	1990-01-09	445	Water level 67.4 m	70.3
BY-3	1989-10-27	165	In drill string	62.9
(54403)	1989-10-28	285	In drill string	70.8
	1989-10-30	285	In drill string	75.9
	1989-11-13	290	Water level 2.8 m	77.5
	1990-01-10	300	Water level 137.9 m	77.7
	1990-06-15	300	Pump in HN-10 stopped on 11.06.90, water level 137.5 m	78.3
BY-4	1989-12-14	170	In drill string	33.6
(54404)	1989-12-15	310	In drill string	48.2
	1990-01-08	403	Water level 214.5 m	62.3
	1990-06-16	403	Pump in HN-10 stopped on 11.06.90, water level 85.0 m	63.1
HY-12	1989-12-06	165	In drill string	36.2
(54413)	1989-12-07	310	In drill string	49.4
	1989-12-11	318	5 days after end of drilling	57.3
	1990-01-09	317	Pump in well HN-10 stopped on 11.06.90, water level 78.3 m	57.6

Q: Flow / production from well; B.h.t.: Bottom hole temperature

WELL BY-2 was drilled as an observation and exploration well in the northeastern part of the field. It was completed in December 1989 at 446 m depth. Six temperature logs were recorded during and after drilling, shown in Figure 3. According to these profiles the main feed zones are at depths of 125, and 160-170 m (Table 3).

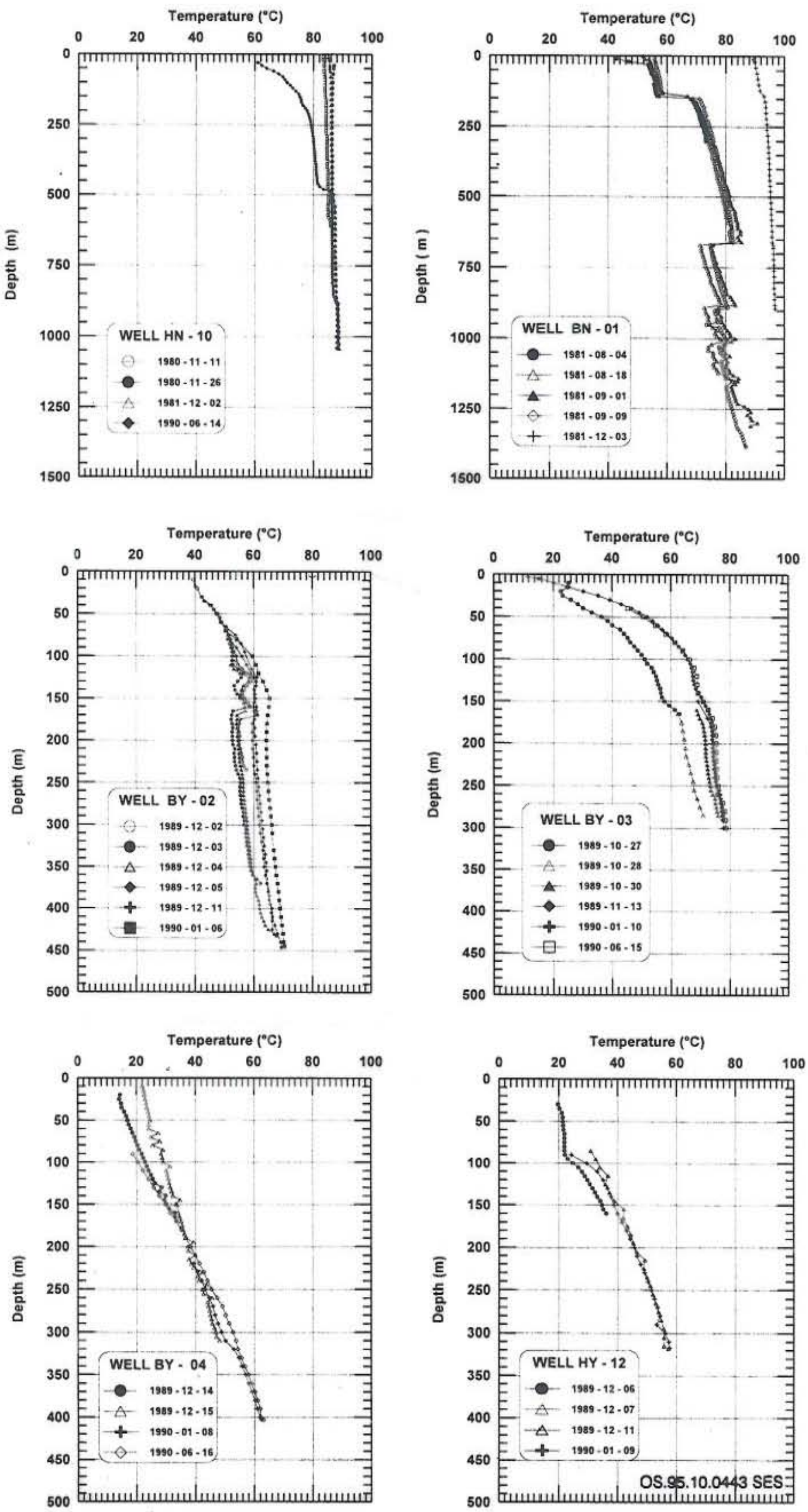

FIGURE 3: Temperature logs in wells in the Botn field

Based on the temperature profiles of well BY-2 a curve was constructed representing the formation temperature. The temperature log recorded on January 9, 1990 is considered to be close to the formation temperature profile of well BY-2 (Table 4 and Figure 4). It was measured only 29 days after drilling, therefore the actual formation temperature could be slightly higher (1-2°C).

WELL BY-3 was drilled as an observation and exploration well in the eastern part of the field northeast of well HN-10. It was completed in October 1989 at 300 m depth. Six temperature logs were recorded during and after drilling, shown in Figure 3. It appears from these profiles that the main feed zones are at depths of 150 and 260 m (Table 3).

The temperature log from June 15, 1990 is considered to be close to the formation temperature profile for well BY-3 (Table 4 and Figure 4). It was measured 145 days after drilling of the well was completed.

WELL BY-4 was drilled as an observation and exploration well in the western part of the field. It was completed in December 1989 at 403 m depth. Four temperature logs were recorded during and after drilling, shown in Figure 3. According to these profiles the main feed zone is at 318 m depth. The temperature log from June 16, 1990 is considered to be close to the formation temperature profile for well BY-4 (Table 4 and Figure 4). It was measured 145 days after drilling.

WELL HY-12 was drilled as an exploration and observation well in the northern part of the field. It was completed in December 1989 at 318 m depth. Four temperature logs were recorded during and after drilling, shown in Figure 3. It appears from these profiles that the main feed zone is at 95 m depth. The temperature log from January 9, 1990 is considered to be close to the formation temperature profile of well HY-12. It was measured 29 days after drilling of the well, but is similar to the curve measured on December 11th 1989, so the well had probably reached equilibrium.

It should be pointed out, that the feed zones in wells BY-2, BY-3, BY-4, and HY-12 are all very small, so that none of these wells can be used as production wells.

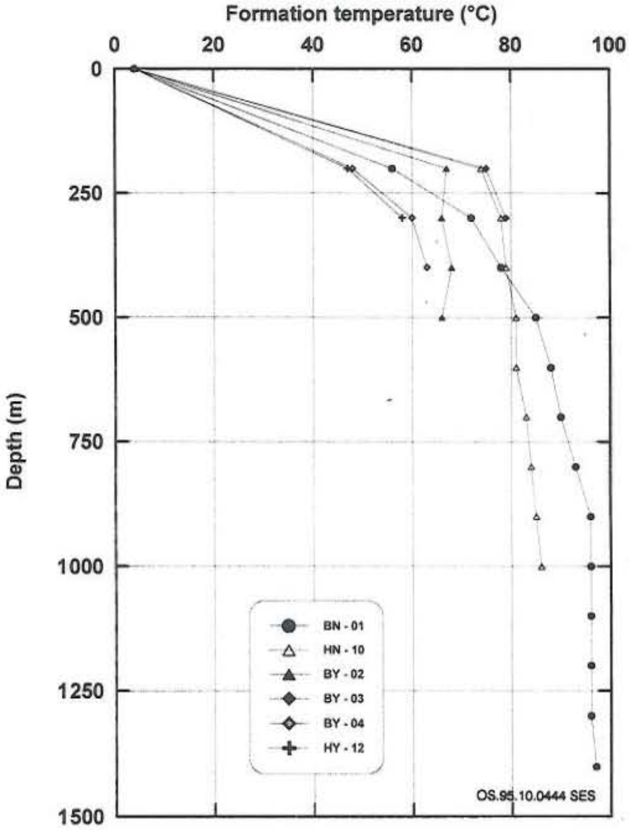

FIGURE 4: Formation temperature profiles from in the Botn field

TABLE 3: Location and temperature of feed-zones in wells in the Botn field

Well No.	Feed zone depth (m)	$T_{Formation}$ (°C)
HN-10	489	<85
	530	<85
	876	<88
	1050	>88
BN-1	150	<55
	670	>85
	890-900	84-96
	1020	>85
	1150	>85
	1756	>97
BY-2	125	60
	160-170	65
BY-3	150	70
	260	78
BY-4	318	55
HY-12	95	25

TABLE 4: Estimated formation temperature in the Botn system

Well No.	Depth (m)	$T_{Formation}$ (°C)
HN-10	100	46
	200	74
	300	78
	400	79
	500	81
	600	81
	700	83
	800	84
	900	85
	1000	86
BN-1	100	46
	200	56
	300	72
	400	78
	500	85
	600	88
	700	90
	800	93
	900	96
	1000	96
	1100	96
	1200	96
	1300	96
	1400	97
BY-2	100	60
	200	64
	300	66
	400	68
	450	70
BY-3	100	67
	200	75
	300	79
BY-4	100	35
	200	48
	300	60
	350	63
HY-12	100	35
	200	47
	300	58

3.2 The temperature distribution

In order to enable visualization of the temperature distribution in the Botn geothermal system, two horizontal maps and two vertical cross-sections were drawn. They are based on the formation temperature profiles for all the wells (Table 4) and drawn with the aid of the SURFER computer software. Figure 5 shows the maps at depths of 200 and 300 m b.s.l. and Figure 6 the N-S and E-W vertical cross-sections. Figure 5 shows a high-temperature anomaly near wells HN-10 and BY-3, and Figure 6 indicates that the hot water upflow is near vertical from depth below well BY-4 in the west, up towards wells HN-10 and BY-3 at shallow levels.

Based on these results, on the apparent location of the hot water upflow, a drilling of a new well is recommended. It should be located in the western part of the field between wells BY-4 and HN-10, and drilled to a depth of 1000-1500 m.

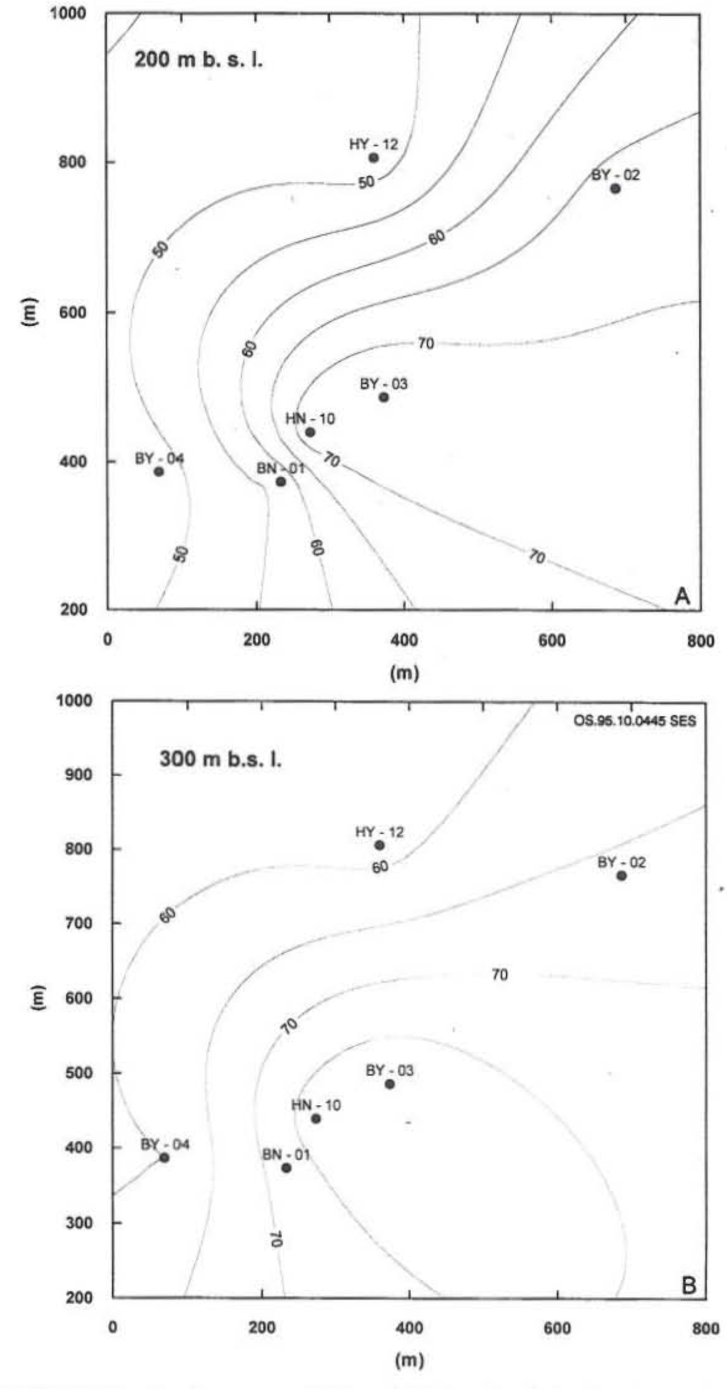

FIGURE 5: Isotherms at 200 and 300 m b.s.l. in the Botn field

4. ANALYSIS OF PRESSURE TRANSIENT TEST DATA

4.1 Description of the June 1990 test

In June 1990 production from well HN-10 was discontinued for about one month. During this period, water level changes were monitored very carefully in all available wells in the Botn area. The data from

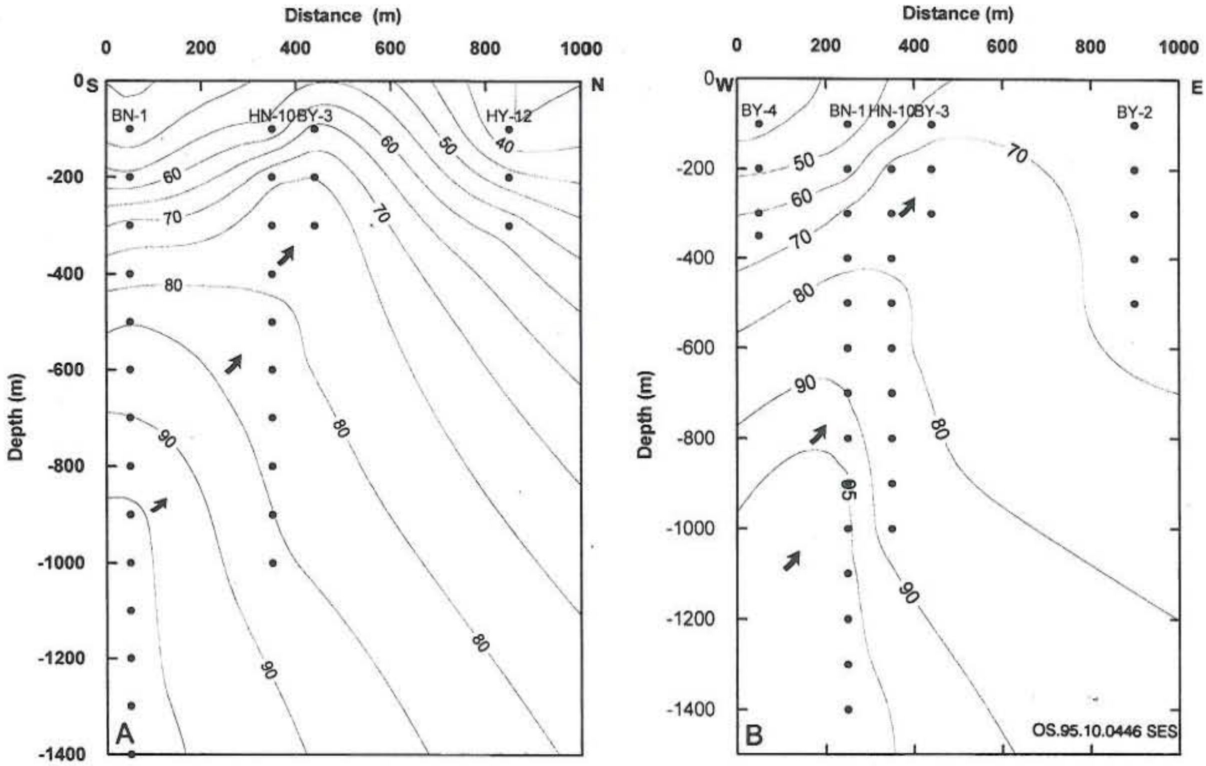

FIGURE 6: Temperature cross-sections through the Botn field;
a) from south to north; b) from west to east

this extensive build-up and interference test were used to estimate the hydrological properties, permeability and storativity of the Botn geothermal reservoir. The data collected are presented in Figure 7. Two methods were used to analyse the data. Firstly, the semi-log method was used to interpret the build-up part of the data. Secondly, computerized analysis was used to interpret the whole data-sets, including the period of variable flow-rate from HN-10 following the build-up period. The VARFLOW computer programme was used for this purpose.

4.2 Pressure transient analysis

The basic reservoir model most commonly used for pressure transient analysis is the so-called Theis-model. It is the basis for the semi-log method as well as the VARFLOW computer code. In the Theis model a production well fully penetrates an aquifer of uniform thickness and homogeneous permeability. The reservoir is impermeable at the top and the bottom and flow to the well is horizontal and radial. Pressure at mid-depth of the aquifer represents the depth-averaged behaviour. The fluid is uniform and of constant compressibility, the reservoir rock has significant compressibility and the fluid compressibility is assumed constant. The reservoir compressibility (wet rock) is then given by (nomenclature, see end of the report):

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

The reservoir is initially at rest. At time = 0 the production well begins discharge at a constant rate Q (m^3/s). The pressure in the reservoir, as a function of time and radial distance, r, from the production well is then given by (Grant et al., 1982)

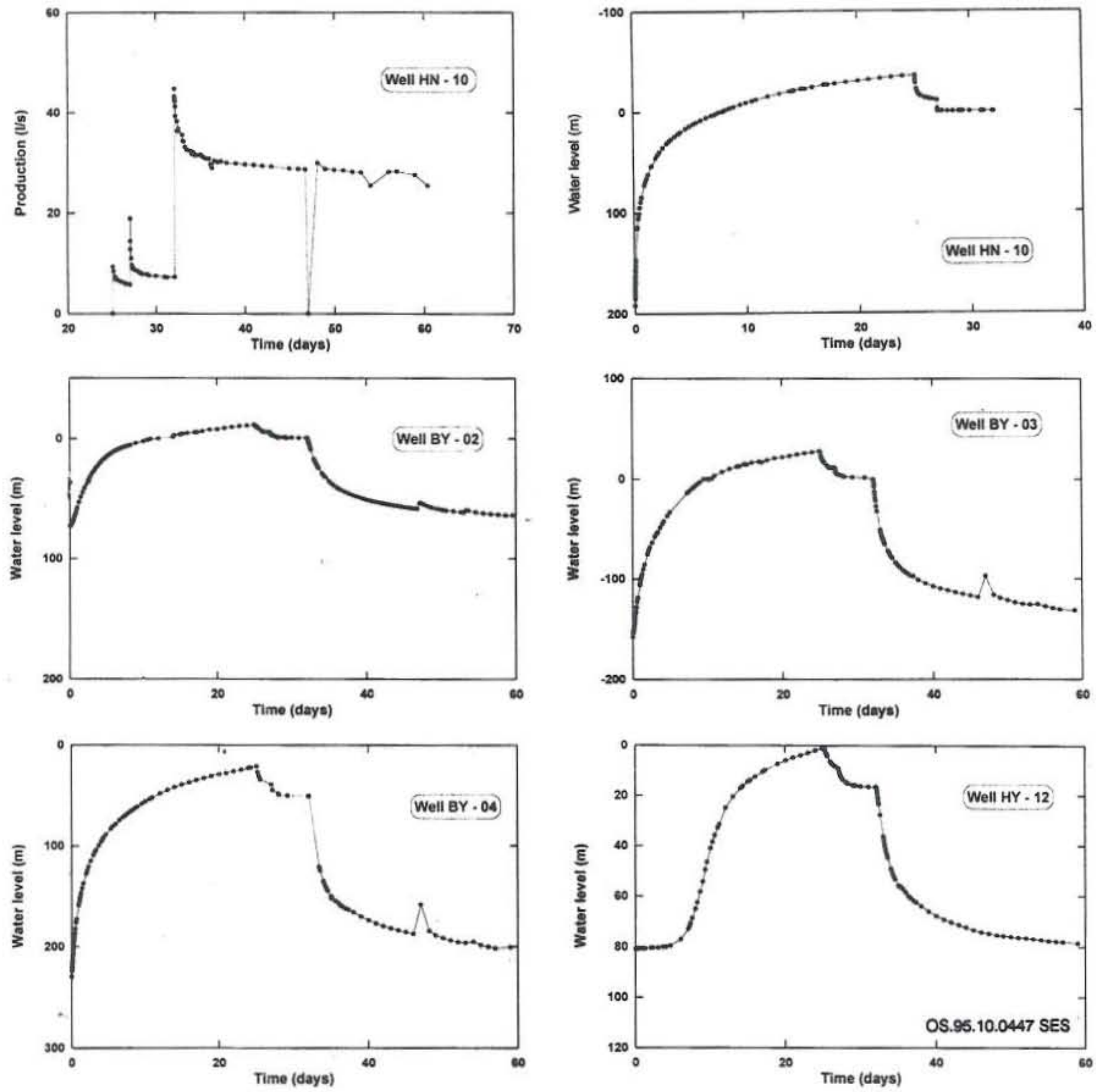

FIGURE 7: Data from the 1990 build-up / interference test in the Botn field

$$\Delta p = p - p_o = -\frac{Q\mu}{4\pi kh} Ei\left(\frac{\mu c_t r^2}{4kt}\right) \tag{2}$$

where $Ei(x)$ is the so-called exponential integral,

$$Ei(x) = \int_x^\infty \frac{1}{s} e^{-s} ds \tag{3}$$

4.2.1 Semi-log analysis

For small values of *x*, the argument of the exponential integral, Equation 2 can be approximated by

$$-\Delta p = \frac{Q\mu}{4\pi kh}(2.303 \log\frac{4kt}{\mu c_t r^2} - 0.5722) \tag{4}$$

Thus if the pressure change is plotted against log (t), i.e. on a semi-logarithmic scale, an asymptotic straight line should be obtained. The line has a slope m, given by

$$m = \frac{2.303\, Q\mu}{4\pi kh} = 0.183\, Q\frac{\mu}{kh} \tag{5}$$

When the slope has been estimated the transmissivity (kh/μ) can be obtained from Equation 5. By using the value of the drawdown Δp on the semi-log straight line, at some selected time (t) the storage coefficient $c_t h$ may be estimated. Based on Equation 4

$$c_t h = 2.25\frac{kh}{\mu}\frac{t}{r^2}10^{-\frac{\Delta p}{m}} \tag{6}$$

In the case where the pressure is observed in the production well itself, a skin factor is sometimes introduced, describing an additional pressure drop at the well face. The pressure drop in the production well is then given by

$$-\Delta p = \frac{Q\mu}{4\pi kh}[2.303 \log\frac{4kt}{\mu c_t r_w^2} - 0.5722 - 2s] \tag{7}$$

And if the storage coefficient of the reservoir is known,the skin factor may be calculated by

$$s = 1.151\,[\frac{\Delta p}{m} - \log\frac{4kt}{c_t \mu r_w^2} + 0.251] \tag{8}$$

where Δp is the pressure change at time t, on the semi-log straight line.

4.2.2 Computerized analysis

The semi-log method can only be used when the well discharge is approximately constant. In cases were the production is variable, such as the case of well HN-10 (see Figure 7), the pressure change in the Theis model may be calculated by the following equation

$$\Delta p(t) = \frac{\mu}{4\pi kh}\int_0^t \frac{q(\tau)}{t-\tau}\exp[\frac{-\mu c_t r^2}{4k(t-\tau)}]\,d\tau \tag{9}$$

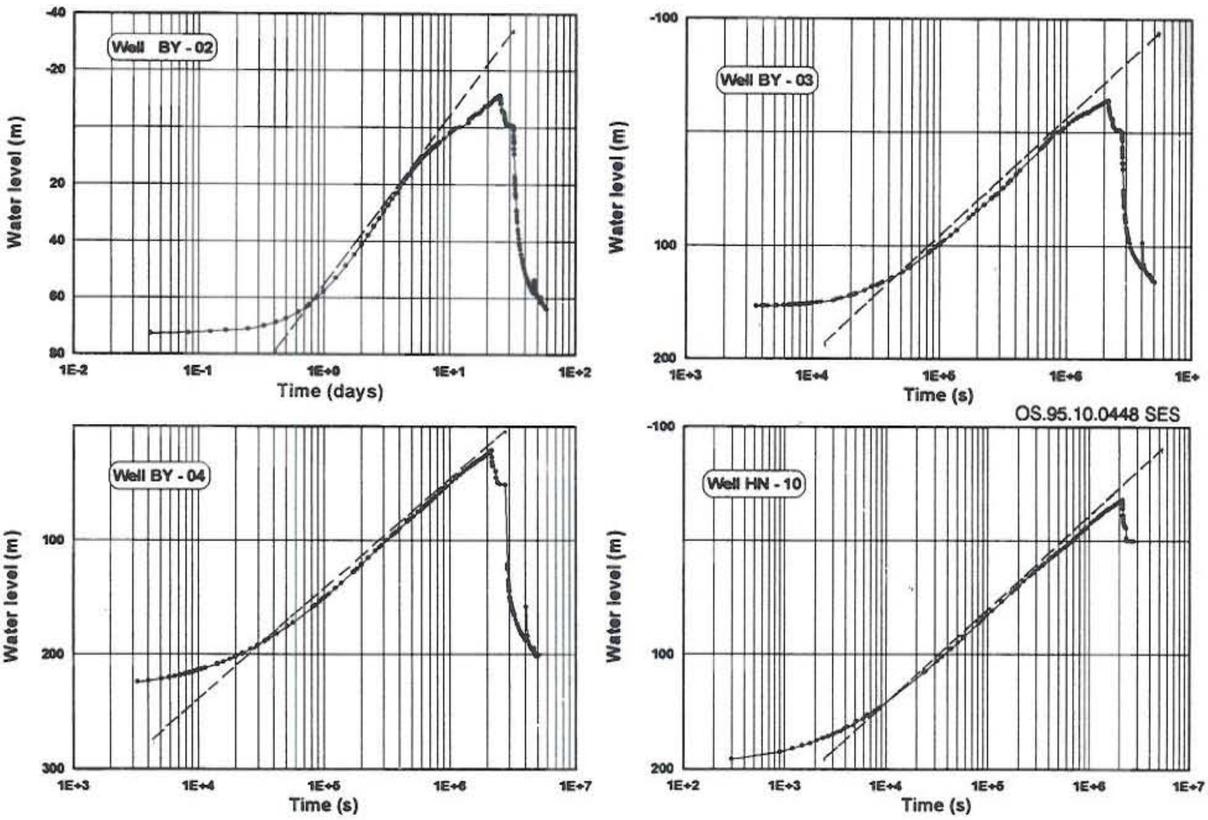

FIGURE 8: Semi-log analysis of the 1990 interference data from the Botn field

The VARFLOW computer code, which is based on this equation, can be used to analyse pressure transient data by varying the parameters until a satisfactory fit is obtained (EG&G and Lawrence Berkeley Laboratory, 1982). In addition VARFLOW can be used to calculate pressure changes caused by several production/injection wells, all with variable flow rates. VARFLOW can also incorporate a no-flow or constant pressure boundary as well as permeability anisotropy.

4.3 Results

The semi-log plots of the 1990 test data with the semi-log straight lines are presented in Figure 8 and Table 5 shows the results of the semi-log analysis. The results indicate a low permeability. By assuming the reservoir thickness estimated for BY-3 a skin factor for HN-10 of -4.8 is estimated. A negative value of the skin factor indicates a higher well-face permeability, maybe due to the drilling operation itself.

TABLE 5: Results of semi-log analysis of 1990 pressure transient test (skin factor of HN-10 is -4.8)

Well No.	Distance to product. well (m)	Semi-log slope (m)	Transmissivity kh/μ (10^{-9} m³/Pa-s)	Permeability thickness-kh (10^{-12} m³)	Storage coefficient $c_t h$ (10^{-9} m/Pa)	Reservoir thickness for ϕ=5% (m)
HN-10	0.11	75	7	2.35		825
BY-2	433.3	64	8.2	2.73	4.55	110
BY-3	93.3	100	5.28	1.76	36.3	825
BY-4	173.3	100	5.28	1.76	6.34	150

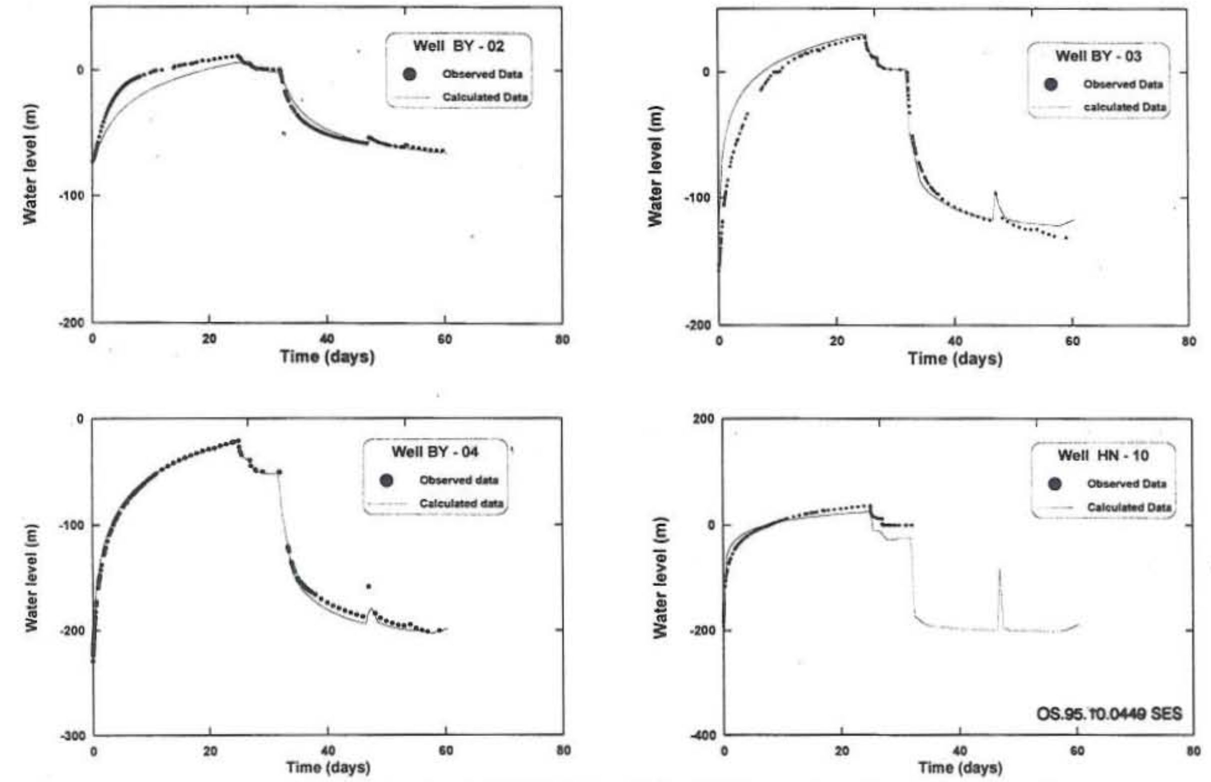

FIGURE 9: Simulation by VARFLOW of the 1990 test data from the Botn field

The VARFLOW computer code was also used to analyse the data from the test. This was done by varying the reservoir parameters; transmissivity, storativity and initial water level until a good fit was obtained for the five wells. The results are shown in Figure 9 and Table 6. Results comparable to the semi-log results are obtained, in particular regarding the permeability.

TABLE 6: Results of computerized analysis by VARFLOW of the 1990 pressure transient test data from the Botn field (skin factor of HN-10 is -4.8)

Well No.	Initial pressure (m)	Transmissivity (10^{-9} m^3/Pa-s)	Storativity (10^{-9} m/Pa)
HN-10	65	10	6.3
BY-2	55	8	7.9
BY-3	80	8	1.05
BY-4	50	5.5	5.2
HY-12	55	9	5.2

5. SIMPLE MODELLING OF WATER LEVEL CHANGES IN THE BOTN SYSTEM

The primary objective of mathematical modelling of geothermal reservoirs is to obtain data that will assist in the decision making process during reservoir management. Modelling is also important as a tool for resource assessment. As mentioned earlier in this report, production from the Botn field started in 1981. The detailed production histories of wells HN-10 and BN-1 as well as the water level history of HN-10 for the period from 1981 through 1994 are available and suitable for simple modelling. In this study modelling by VARFLOW and lumped modelling was attempted. Simple models, such as lumped parameter models, are characterized by one or more parameters representing a combination of primary parameters in different regions of the reservoir. Lumped parameter models have been developed for many geothermal reservoirs (Bödvarsson et al., 1986; Axelsson, 1989).

5.1 Modelling by VARFLOW

VARFLOW was used to simulate the water level history of well HN-10 with the production histories of wells HN-10 and BN-1 as an input. The hydrological parameters were varied until a satisfactory match was obtained. The results are presented in Figure 10, obtained by using:

$kh/\mu = 9\text{x}10^{-9}\ \text{m}^3/\text{Pa-s}$ $\qquad c_t h = 5.3\text{x}10^{-9}\ \text{m/Pa}$

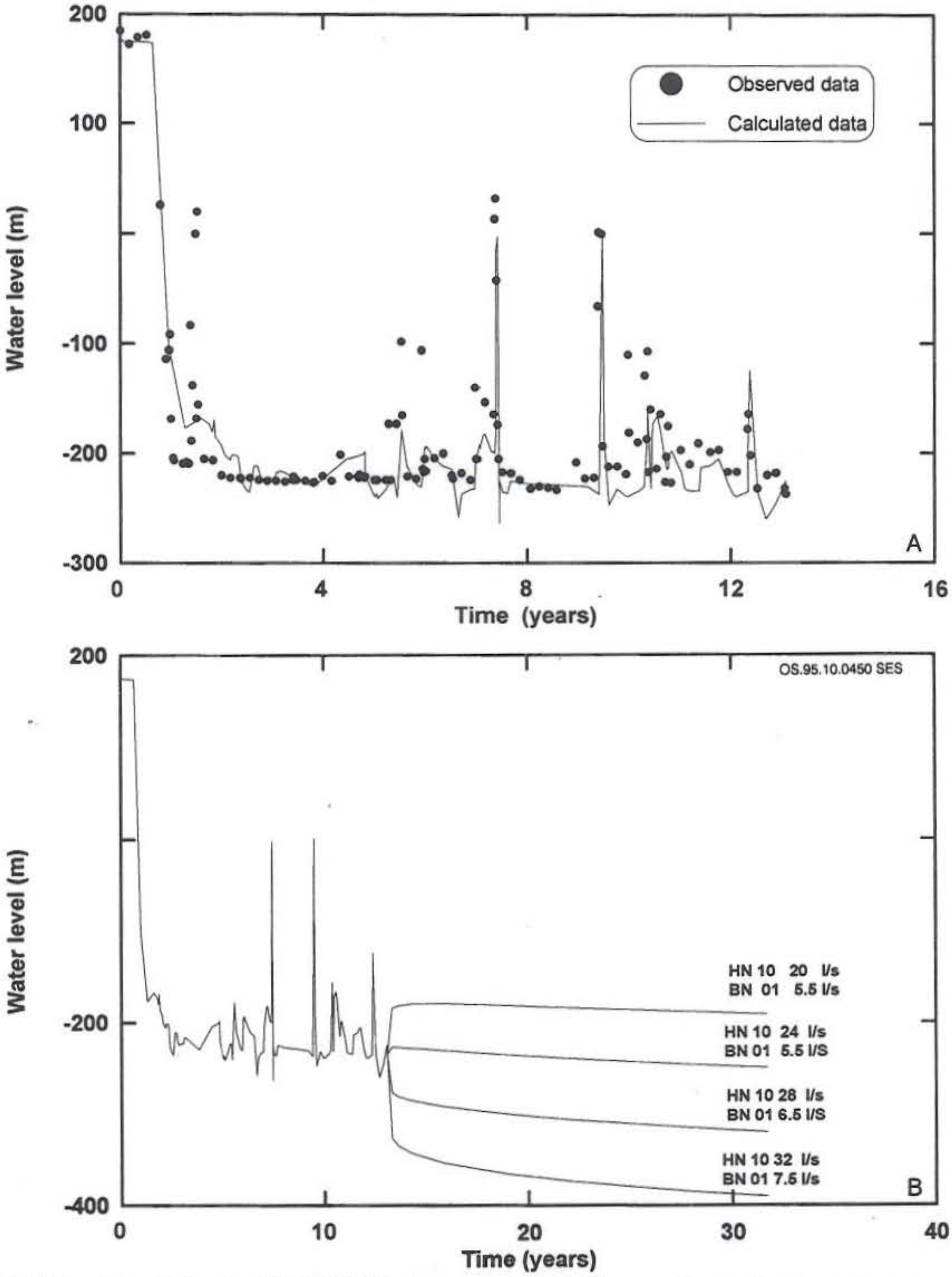

FIGURE 10: Simulation by VARFLOW of the water level history of well HN-10 in the Botn field, a) comparison between observed and calculated water level, b) future predictions for a few cases of constant production

These parameters are comparable to the results presented in Tables 5 and 6. VARFLOW was finally used to calculate future predictions for a few cases of constant production, and the results are also presented in Figure 10.

5.2 Lumped modelling

5.2. 1 Theory and method of simulation

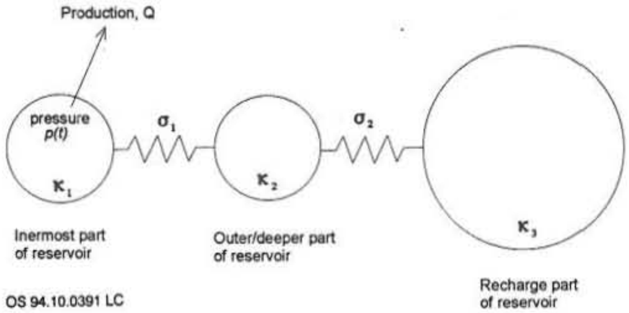

FIGURE 11: A schematic figure of a lumped model (Axelsson, 1989)

Figure 11 shows the principal idea behind lumped models. Most such models use two or three tanks to represent the entire system. One of the tanks represents the well field, and the others act as recharge parts either at depth or outside the main reservoir. Each tank ignores the reservoir geometry. A lumped network of tanks is considered to be either open or closed. When the network is open, one of the tanks is connected to a system with a constant pressure. When the network of tanks is closed, the tanks are not connected to an outside recharge system and the pressure of the system declines continuously as production proceeds. The mathematical equations describing the behaviour of the lumped system with N tanks are the following (see nomenclature at the end of the report):

$$\kappa_i \frac{dp_i}{dt} = \sum_{k=1}^{N} q_{ik} - \sigma_i (p_i - p_o) - Q_i \tag{10}$$

$$q_{ik} = \sigma_{ik}(p_k - p_i) \tag{11}$$

where p_i is the pressure in tank i, q_{ik} the flow from tank k to tank i, and Q the production from tank i. The storage coefficient of a tank is defined by

$$\kappa_i = \frac{\Delta m}{\Delta p} = V_i S \tag{12}$$

where Δp is the increase in pressure resulting from an addition of mass Δm, V_i is the tanks volume and S its storativity. The conductance of the conductor connecting two tanks is defined by

$$\sigma_{ik} = \frac{q_{ik}}{p_k - p_i} \tag{13}$$

A step change in production from 0 to Q at time $t = 0$ results in the pressure change with time in an open N-tank model

$$p(t) = p_o - \sum_{j=1}^{N} q \frac{A_j}{L_j}(1 - e^{L_j t}) \tag{14}$$

For a closed N-tank model system the following formula is used

$$p(t) = p_o - \sum_{j=1}^{N-1} q \frac{A_j}{L_j}(1 - e^{L_j t}) - QBt \tag{15}$$

The coefficients A_j, L_j and B are complex functions of κ_1, κ_2,.....κ_N and σ_{12}, σ_{23},.....σ_N (Axelsson, 1989).

The programme LUMPFIT, used here for the lumped modelling tackles the simulation problem as an inverse problem. It automatically fits the analytical response functions of lumped models to the observed data by using a non-linear iterative least-squares technique for estimating the model parameters (Axelsson, 1989; Axelsson and Arason, 1992). The input of LUMPFIT includes:

1. A series of time points t_o, t_1,.....t_M;
2. The production history q_o, q_1,.....q_M where q_i is the average production rate between the time t_{i-1} and t_i, and q_o is the average production up to time t_o;
3. The observed pressure or water level data, w_j, w_{j+1},.....w_M, at times t_j, t_{j+1},.....t_M, where $t_j \geq t_0$.

The calculated water level or pressure is then

$$w_{calc}(t_o) = w_o \tag{16}$$

$$w_{calc}(t_k) = w_o + \sum_{i=1}^{k} (q_i - q_{i-1})[B(t_k - t_{i-1}) + \sum_{j=1}^{N} \frac{A_j}{L_j}(1 - e^{-L_j(t_k - t_{i-1})})] \tag{17}$$

for k = 1, ...M.

A two tank open model has N=2 and B=0. A three tank closed model has N=2 and B>0. The programme LUMPFIT finds the coefficients A_j, L_j and B that minimize the sum

$$Min\,[\sum_{i=j}^{M} (w_i - w_{calc}(t_i))^2] \tag{18}$$

In order to assess the quality of various fits, the coefficient of determination R^2 is defined

$$R^2 = \frac{\sum_{i=j}^{M} (w_i - w_a)^2 - \sum_{i=j}^{M} (w_i - w_{calc}(t_i))^2}{\sum_{i=j}^{M} (w_i - w_a)^2} \tag{19}$$

where w_a is the mean of the observed water level data. The coefficient of determination takes values between 0 and 1, but is most often written in %. It describes the fraction of the variance in the observed data, about the mean of the observed data, which is explained by the model.

5.2.2 Modelling results

A lumped parameter model was created in order to simulate the production history of the Botn field. The simulation was carried out automatically by the programme LUMPFIT. No assumptions were made in advance on the properties of the reservoir. In the first step a closed one-tank model was used, which represents the simplest model possible. Then the model was modified and more tanks added to the system until a satisfactory fit was achieved. The parameters of two models (open one-tank and closed two-tank) are shown in Table 7. The best fitting model was a closed two-tank model, which resulted in a coefficient of determination of only 62%. Neither a better fit could be achieved nor a more complex model used. This is probably because of the characteristics of the production history. It is dominated by a great initial draw-down, very slow, long-term decline and some irregular, but sudden, water level changes. The coefficient of determination is almost the same for both the open one-tank and closed two-tank models, this indicates that both models represent the reservoir equally well.

TABLE 7: Parameters of the two lumped models used in the study

Parameter	Open one-tank	Closed two-tank
A_1	129	129
L_1	10.6	10.7
B		0.0296
κ_1(kg/Pa)	25	25
σ_1(kg/Pa-s)	0.838×10^{-5}	0.850×10^{-5}
Coeff. of determ. (%)	61.9	62

5.3.2 Reservoir properties

The lumped models may be used to derive some of the properties of the reservoir. If an assumption is made that the storage, or capacitance, is controlled by the liquid and formation compressibility, the volume of the different tanks can be estimated as

$$V = \frac{\kappa}{\rho_w c_t} \tag{20}$$

where ρ_w is the liquid density and c_t is the total compressibility ($c_t = \phi\, c_w + (1-\phi)\, c_r$). Assuming a porosity of 5%, the volume of the first tank (κ= 24.9718 ms^2) is estimated at 0.05 km^3 and the volume of the second tank (κ=108,527 ms^2) at 254 km^3. Clearly the volume of the second tank is very great and not realistic. On the other hand it can be assumed that the storage of the second tank is controlled by the mobility of a free surface. The surface area of the reservoir can then be estimated by

$$A = \frac{\kappa g}{\phi} \tag{21}$$

Thus the area of the second tank is estimated at 2.12 km² which may be considered realistic.

The permeability can be estimated by using the following equation if one assumes one-dimensional (1-D) flow

$$k = \sigma \frac{L \upsilon}{A'} \tag{22}$$

A' is the cross-sectional area of the system perpendicular to the 1-D flow and L is the ½ length of the system. Assuming that $A' = 1$ km², and $L = 1.1$ km, k is estimated to be 2.3×10^{-15} m².

Assuming two-dimensional (2-D) flow the average permeability can be estimated by using the equation

$$k = \frac{\sigma \ln(r_2/r_1)\, \upsilon}{2\pi h} \tag{23}$$

where h is the thickness of the system assumed to be 1 km and r_1 and r_2 are the inner and outer radii of the system, $r_1 = 0.07$ km and $r_2 = 0.49$ km. Thus, the average permeability k for 2-D flow is estimated to equal 1.1×10^{-15} m².

5.2.4 Future predictions

One of the main purposes of simulating a reservoir is to be able to predict water level changes for a given future production scheme. The best fitting lumped model is considered suitable to predict the water level in the actual reservoir. Different production rates were assumed from the two productive wells, HN-10 and BN-1. Figure 12 shows the results, which indicate that if the production is increased the draw-down will increase drastically. Otherwise, the long-term decline will be very slow.

6. CHEMICAL CHANGES AND COOLING OF THE BOTN SYSTEM

During the 14 year production history the chemistry and temperature changes of discharged water, as well as the flow rate, have been recorded in well HN-10. A simple model with cold water down-flow was used to simulate the changes in chemistry and temperature, to estimate the reservoir volume and porosity, and to predict future changes in water temperature (Björnsson et al., 1994). This simple model is shown in Figure 13. It consists of an infinite groundwater aquifer with water temperature T' and solute concentration C'. The production part of the reservoir has a volume V, variable temperature $T(t)$ and chemical concentration $C(t)$, with an initial temperature T_o and concentration C_o. The inflow from the outer and deeper parts of the geothermal system is R (kg/s) with temperature T_R and concentration C_R. A variable production of Q (kg/s) starts at time $t=0$, inducing down-flow of the groundwater. This model can be used to estimate the volume of that part of the system where mixing of geothermal water and cold groundwater takes place (V). In the model the base inflow, R, is assumed constant with a fixed chemical composition and temperature and represents the hot part of the production induced recharge, in addition to the natural recharge. The cold water down-flow is variable and represented by $q(t)$ (see Figure 13).

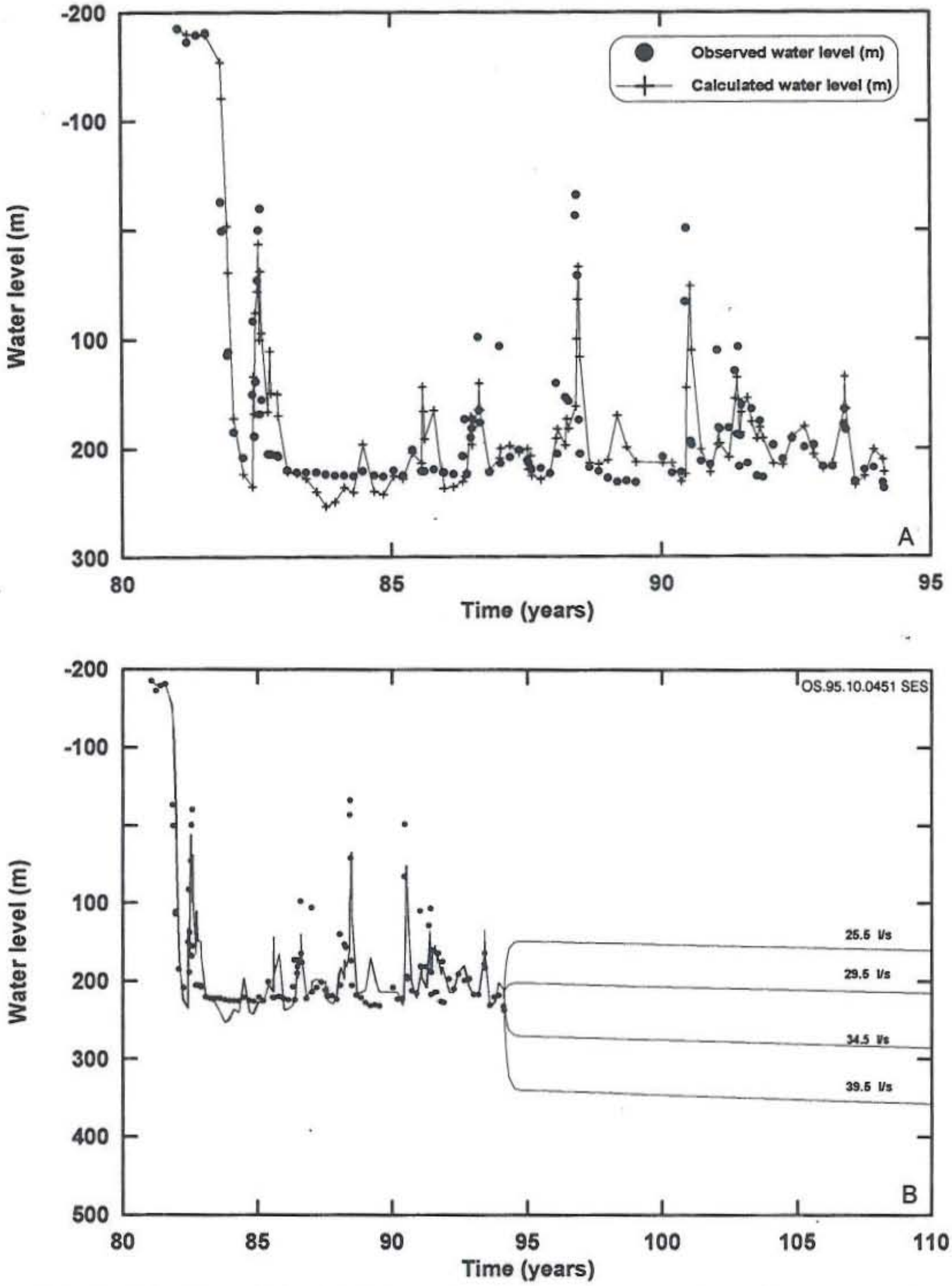

FIGURE 12: Simulation by LUMPFIT of the water level history of well HN-10 in the Botn field; a) comparison between observed and calculated water level with a closed two tank model; b) predicted water level

The equations describing the response of the model are mathematical solutions of differential equations describing the conservation of the mass of a given chemical substance and conservation of energy (Björnsson et al., 1994). These depend on the properties of the water and rock formation, like the density and heat capacity of water, the porosity of the rocks in the production part of the system and the volumetric heat capacity of the reservoir rocks. The production may be approximated by $Q(t) \approx Q_i$ for $t_{i-1} \leq t < t_i$, $I = 1, 2, \ldots$..and we define

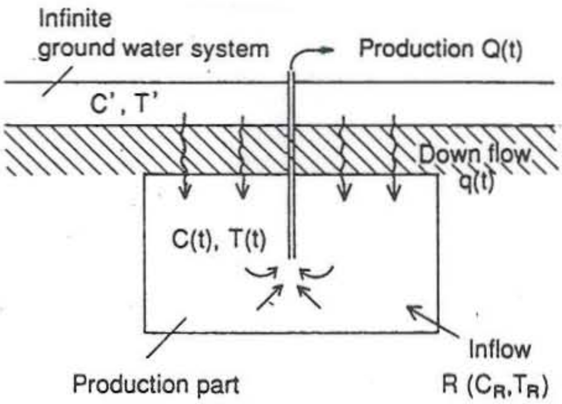

FIGURE 13: A schematic figure of a simple model simulating cold down-flow

$$C_i = C(t_i), \qquad T_i = T(t_i), \qquad \Delta t_i = t_i - t_{i-1}.$$

The governing equation in terms of the chemical concentration for the simple model is

$$C_i \approx C_{i-1} e^{-\alpha Q_i \Delta t_i} + \frac{(Q_i - R)C' + R C_o}{Q_i}(1 - e^{-\alpha Q_i \Delta t_i}) \qquad for\ i = 1, 2, ... \tag{24}$$

where $\alpha = 1/(V\rho_w \phi)$, is a time constant for the chemical changes.

The governing equation for the temperature of the produced water is

$$T \approx T_{i-1} e^{-\alpha Q_i \Delta t_i} + \frac{(Q_i - R)T' + R T_o}{Q_i}(1 - e^{-\beta Q_i \Delta t_i}) \qquad for\ i = 1, 2, ... \tag{25}$$

where $\beta = c_v / V(\rho c)$, and $(\rho c) = \rho_w c_w \phi + \rho_r c_r (1 - \phi)$.

The results of the simulation are presented in Figure 14. They are based on the following:

$\alpha = 2.20 \times 10^{-10}$ kg^{-1}	$T_o = 85.5$°C
$\beta = 0.35 \times 10^{-10}$ kg^{-1}	$T' = 40$°C
$C' = 40$ mg/l	$R = 15$ kg/s
$C_o = 87$ mg/l	

Based on α and β the volume V is estimated to equal 0.056 km^3 with an average porosity of 8.3%.

One application of the cold water down-flow model, is the estimation of cooling in the geothermal reservoir due to inflow of colder fluids. Therefore, the model was used to predict water temperature changes for the next 15 years with three different flow rates 25, 30, and 40 l/s respectively. Figure 14 shows that for well HN-10 the water temperature will decline from about 80 to 73°C in the next 15 years with a production of 30 l/s, due to the cold water down flow. The water temperature decline will increase with increasing production.

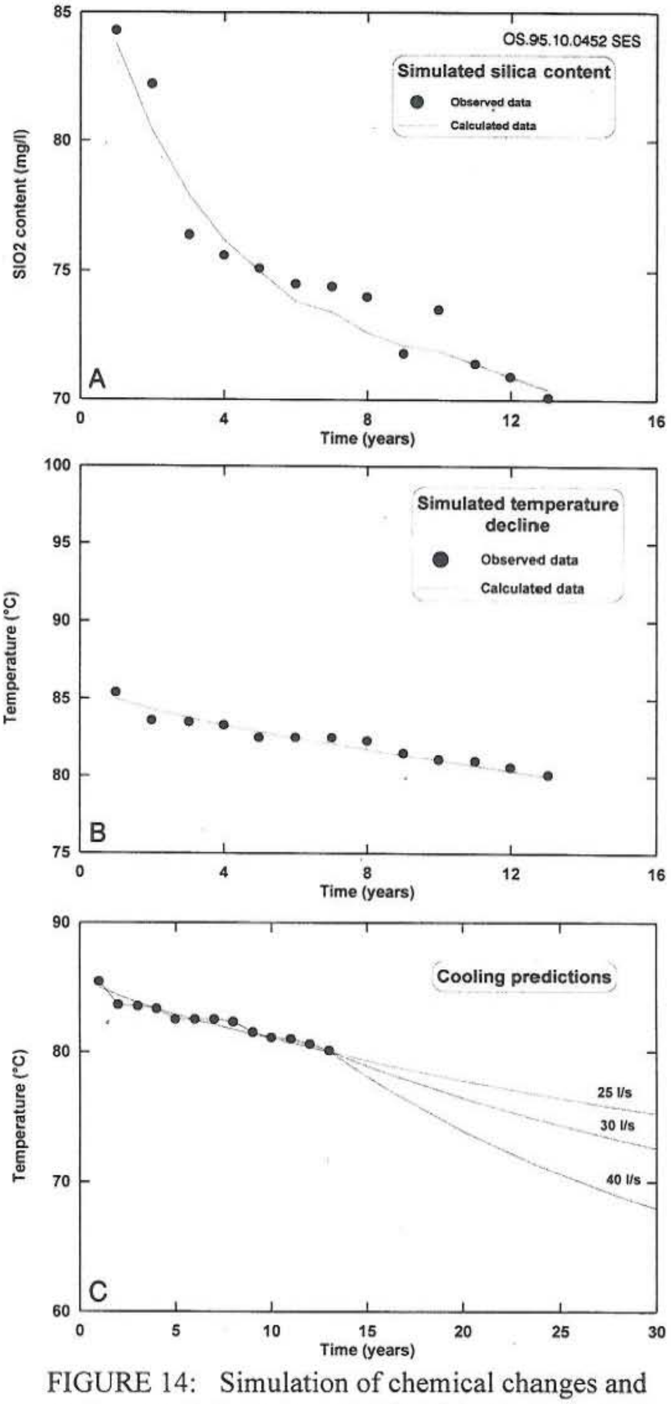

FIGURE 14: Simulation of chemical changes and cooling predictions in well HN-10 in the Botn field

7. CONCLUSIONS

The results of this study may be summarized as follows: The formation temperature of the Botn system was estimated, and the feedzones identified by analysing all available temperature logs. The hot water upflow in the system appears to be near-vertical from depth below well BY-4 in the west, up towards wells HN-10 and BY-3 at shallow levels.

The Botn geothermal field is characterized by a fracture zone, and a few dykes. It is small in volume (1.75 km^3) and has a low permeability thickness (5.28 x 10^{-9} m^3). This leads to a great initial pressure draw-down in well HN-10, during production. The long term water level decline in well HN-10, however, is very slow due to free-surface storage.

The water temperature of well HN-10 initially at 85.5°C, will decline to 73°C in another 15 years due to cold water down flow. The cooling predicted may cause well HN-10 to cease to be economical some time in the future. However, based on the location of the upflow suggested here, a location of a new production well to the west of well HN-10 is suggested that may intersect the geothermal water upflow at greater depth.

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Finally, I dedicate this work to my family Magda and Omar.

NOMENCLATURE

A	= Area of tank (m^2)
A'	= Area of 1-D resistor (m^2)
C'	= Solute concentration in ground water system (mg/l)
$C(t)$	= Reservoir chemical concentration (mg/l)
C_o	= Initial concentration (mg/l)
c_t	= $c_w \phi + c_r (1-\phi)$ or total compressibility of water saturated formation (1/Pa)
c_r	= Compressibility of rock matrix (1/Pa)
c_w	= Compressibility of water (1/Pa)
$c_t h$	= Storage coefficient (m/Pa)
g	= Acceleration of gravity (m/s^2)
h	= Reservoir thickness (m)
k	= Reservoir permeability (m^2)
kh	= Permeability thickness (m^3)
kh/μ	= Coefficient of transmissivity (m^3/Pa-s)
L	= Length of 1-D resistor (m)
m	= Slope of semi-log straight line (m/log-cycle)
p	= Pressure (Pa)
p_0	= Initial pressure (Pa)
Q	= Volumetric flow rate (m^3/s)
q	= Mass flow rate (kg/s)
R	= Inflow from outer and deeper parts of the geothermal system (kg/s)
r_1	= Inner radius of 2-D resistor
r_2	= Outer radius of 2-D resistor
r	= Radial distance (m)
r_w	= Radius of production well (m)
S	= Storativity (m/Pa)
s	= Skin factor
t	= Time (s)
T'	= Temperature of ground water (°C)
$T(t)$	= Reservoir temperature (°C)
T_o	= Initial temperature (°C)
Δt_i	= Time step in the chemical/temperature calculations (s)
V	= Volume (m^3)
$w(t)$	= Water level at given time (m)
α	= Chemical time constant (kg^{-1})
β	= Thermal time constant (kg^{-1})
ϕ	= Porosity
κ	= Mass storage coefficient of tank (kg/Pa)
μ	= Dynamic viscosity (Pa-s)
ν	= Kinematic viscosity of geothermal water (m^2/s)
ρ	= Density (kg/m^3)
$\sigma_{1,2}$	= Flow conductance between tanks (kg/Pa-s)

REFERENCES

Axelsson, G., 1989: Simulation of pressure response data from geothermal reservoirs by lumped parameter models. *Proceedings of the 14th Workshop on Geothermal Reservoir Engineering, Stanford University, Ca.*, 257-263.

Axelsson, G., and Arason, P., 1992: *LUMPFIT, automated simulation of pressure changes in hydrological reservoirs. Version 3.1, user's guide.* Orkustofnun, Reykjavík, 32 pp.

Axelsson, G., and Björnsson, G., 1993: Detailed three-dimensional modelling of the Botn hydrothermal system in N-Iceland. *Proceedings of the 18th Workshop on Geothermal Reservoir Engineering, Stanford University, Ca.*., 159-166.

Axelsson, G., Tulinius, H., Flóvenz, Ó.G., and Thorsteinsson, Th., 1988: *Geothermal resources of Hitaveita Akureyrar. Future prospects in 1988.* Orkustofnun, Reykjavík, report OS-88052/JHD-10 (in Icelandic), 35 pp.

Björnsson, G., Axelsson, G., and Flóvenz, Ó.G., 1994: Feasibility study for the Thelamörk low-temperature system in N-Iceland. *Proceedings of the 19th Workshop on Geothermal Reservoir Engineering, Stanford University, California*, 5-13.

Bödvarsson, G.S., Pruess, K., and Lippmann, M.J., 1986: Modelling of geothermal systems. *J. Pet. Tech., 38*, 1007-1021.

EG&G Idaho, Inc., and Lawrence Berkeley Laboratory, 1982: *Low to moderate temperature hydrothermal reservoir engineering handbook.* Idaho Operations Office, report IDO-10099, appendix E, USA, 40 pp.

Flóvenz, Ó.G., Axelsson, G., and Gudmundsson, A., 1991: *Geothermal exploitation at Botn and Hrafnagil 1989-1990; exploration wells and water level measurements.* Orkustofnun, Reykjavík, report OS-91008/JHD-02 (in Icelandic), 89 pp.

Flóvenz, Ó.G., Árnason, F., Finnsson, M., and Axelsson, G., 1995: Direct utilization of geothermal water for space heating in Akureyri, N-Iceland. *Proceedings of the World Geothermal Congress 1995, Florence, Italy, 3*, 2233-2238.

Flóvenz, Ó.G., and Georgsson, L.S., 1982: Prospecting for near vertical aquifers in low-temperature geothermal areas in Iceland. *Geoth. Res. Council, Transactions, 6*, 19-22.

Flóvenz, Ó.G., Gudmundsson, Á., Thorsteinsson, Th., and Hersir, G.P., 1989: *The Botn geothermal area. Results of geothermal research 1981-1989.* Orkustofnun, Reykjavík, report OS-89018/JHD-03 (in Icelandic), 92 pp.

Grant, M.A., Donaldson, I.G., and Bixley, P.F., 1982: *Geothermal reservoir engineering.* Academic press, New York, 369 pp.