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ASSESSMENT OF THE OLAFSFJORDUR LOW-TEMPERATURE GEOTHERMAL FIELD, N-ICELAND

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ABSTRACT

In this report, an assessment is made of the Olafsfjordur (Laugarengi) low-temperature geothermal field in central northern Iceland using available data from geological surveying, temperature logging, well tests and lumped parameter modelling. It is one of the geothermal fields that supplies the town of Olafsfjordur with hot water for space heating and tapwater. Main feed zones in wells were found from circulation losses during drilling and temperature logs. In a lumped parameter model used in this study, calibration was based on data accumulated over a 5 year period of observations of the reservoir response to production. The obtained data were used for predicting the reservoir response to various constant production rates over the next 5 years. The present trend of drawdown can be maintained at an average production rate no larger than 20 l/s. Interpretation of well tests and lumped modelling indicate low transmissivity and permeability but fractures and dykes play a major role in the hydrogeological systems and control the hydrogeothermal activity of this area.

1. INTRODUCTION

The Laugarengi geothermal system at Olafsfjordur has been studied by various specialists through the years and several reports have been written (e.g., Karlsdottir and Helgason, 1978; Axelsson, 1991; Tomasson et al., 1992; Torfason, 1994). The geothermal activity in Olafsfjordur was especially studied during the summer of 1977, by taking temperature logs and measuring flow of the wells, along with geological and geophysical surface exploration. Studies on geothermal activity have now begun again due to ideas on extended utilization for new farms and heating of summer houses. Production monitoring has been limited, but began on a regular basis in 1991, as well as water-level and water temperature monitoring.

2. THE OLAFSFJORDUR - LAUGARENGI GEOTHERMAL FIELD

The Laugarengi low-temperature geothermal field at Olafsfjordur is one of two geothermal fields utilized for space heating by the town of Olafsfjordur (population 1200) in central northern Iceland (Figures 1 and 2). The Olafsfjordur Municipal Heating Service started operation for space heating in 1944. It has utilized two production areas, Skeggjabrekka since 1944 and Laugarengi since 1975. Studies on the geothermal field at Laugarengi began in 1973 and two wells OB-1 and OB-2 were drilled in 1972 and 1973. Well OB-3 was drilled two years later (in 1975) and produced 13.5 l/s in free-flow, which was increased to 24 l/s by pumping. Well OB-4 was drilled in 1982 and proved to be far more productive than well OB-3, and has since replaced it as the main production well.

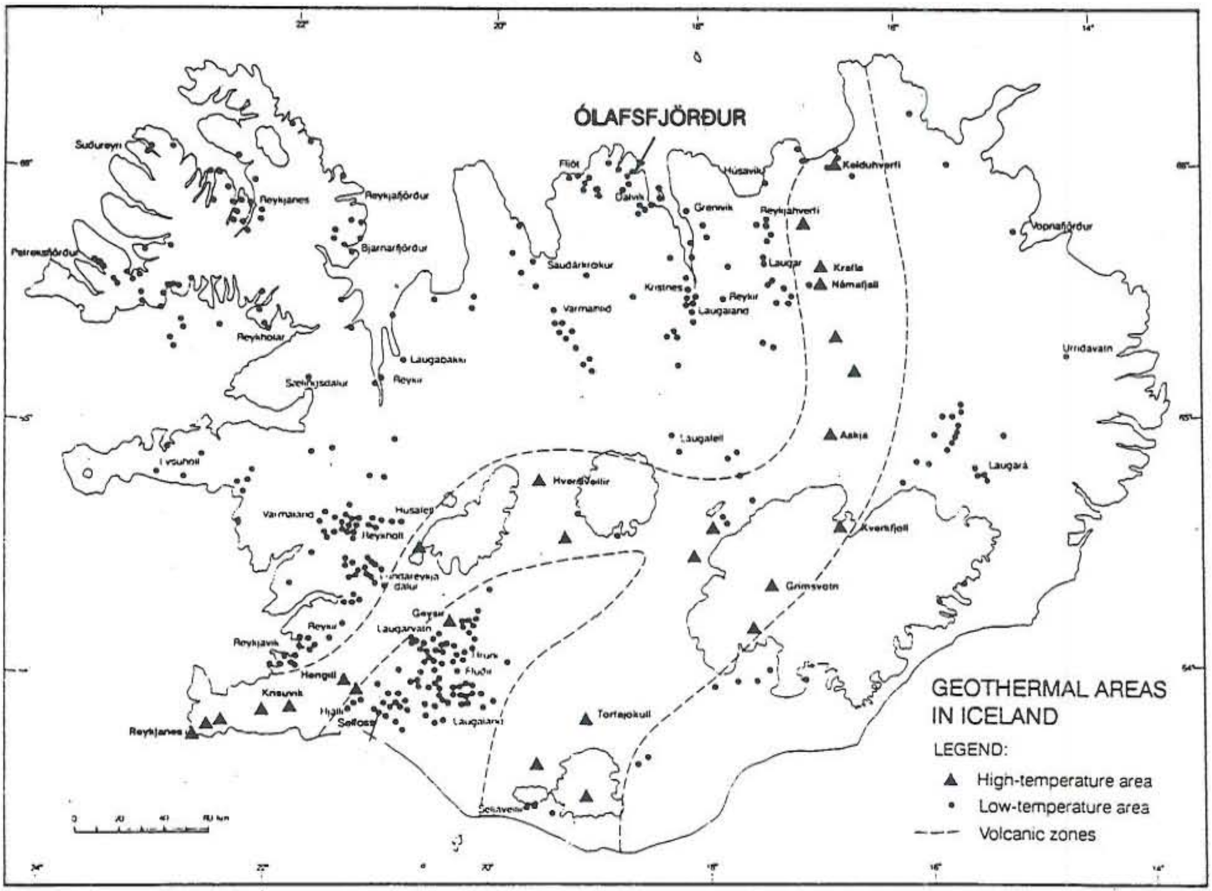

FIGURE 1: Geothermal areas in Iceland and the location of Olafsfjordur

2.1 Geology

Various methods are used, when studying geothermal activity, to identify likely positions of the up-flow channels of the hot water. These channels usually lie parallel to the dykes and are most often associated with faults and fractures in the rock basement. It is not always sufficient to study the surface in order to locate wells. The most common direction and slope of faults and dykes in the vicinity have to be checked, and the status of the wells that have already been drilled. In Olafsfjordur, magnetic measurements were carried out at Laugarengi to map dykes and faults close to the surface. Several geological studies have been carried out in Olafsfjordur. Tertiary basaltic layers extend deep into the formation. Between the lava layers there are sedimentary layers and scoria beds, varying in thickness, (the ruffled part of the layers), and horizontal intrusions. The deep geological formation is regular and usually slopes about 10° to the west. Faults and dykes have only been partly mapped. The general picture is rather simple, west-sloping basaltic layers with faults and dykes cutting them perpendicularly. The fractures and the dykes are thought to control the geothermal activity in this area (Karlsdottir and Helgason, 1978).

According to drill cuttings the lithology is classified into the following formations (Figure 3):

1) Fine grained basalt;
2) Fresh medium to coarse grained basalt;
3) Altered medium grained basalt;
4) Fresh glassy basalt;
5) Altered glassy basalt;
6) Coarse sediments (intermediate-layers).

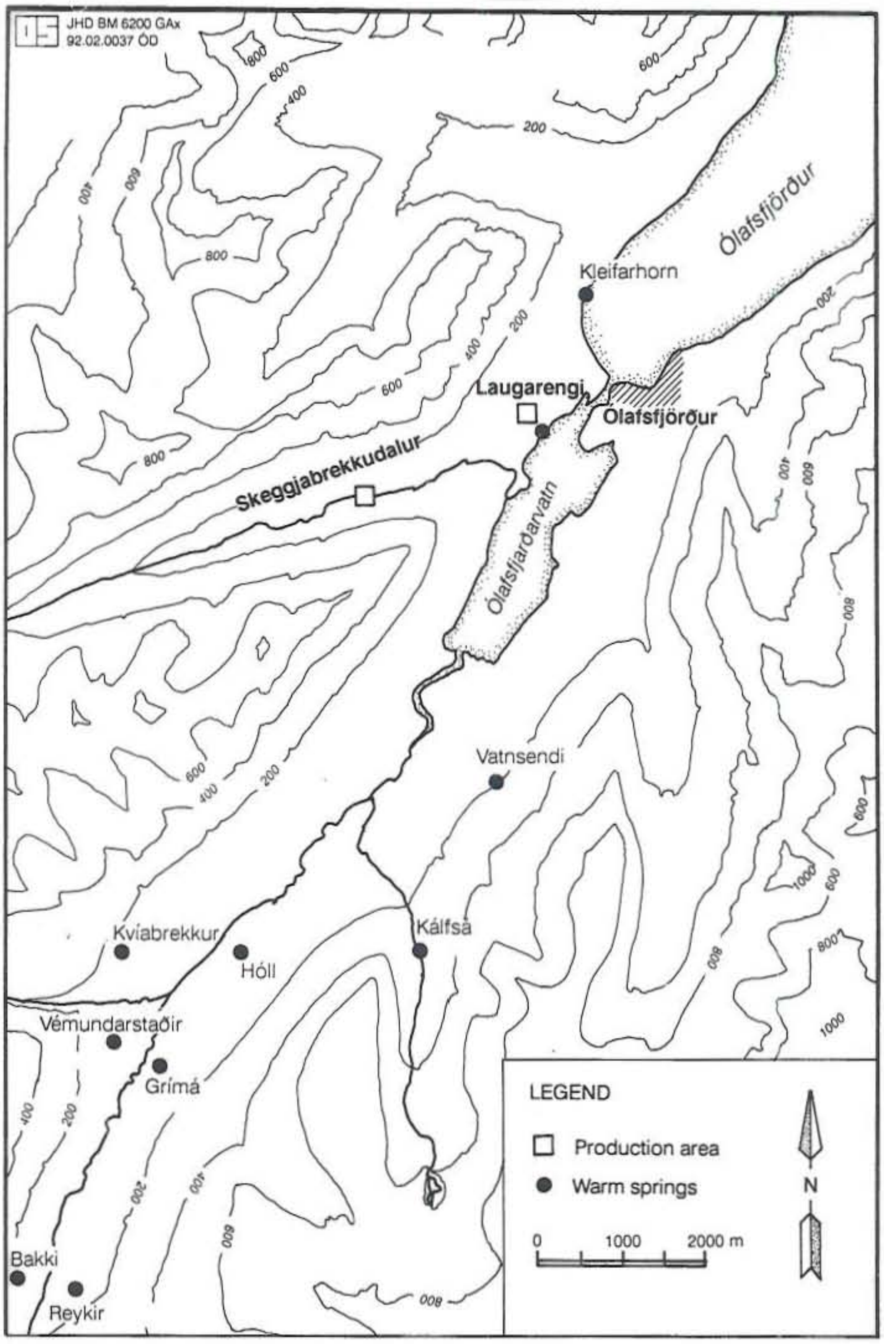

FIGURE 2: Geothermal activity in the Olafsfjordur area (modif. after Karlsdottir and Helgason, 1978)

2.2 History of drilling and utilization

Table 1 shows various data on the four deep wells that have been drilled in the Olafsfjordur (Laugarengi) geothermal field, their location is shown in Figure 4. The wells were meant to cut the up-flow channel of the warm springs, which was expected to be connected to a N-S trending dyke going through the area (Karlsdottir and Helgason, 1978). Well OB-1 was drilled in late 1972 and almost a year later deepened to 467 m. The free-flow was about 1 l/s. Well OB-2 was drilled late in 1973 and was about 299 m deep. The free-flow was also about 1 l/s. The flow from the wells was not sufficient, in order to utilize them for space heating.

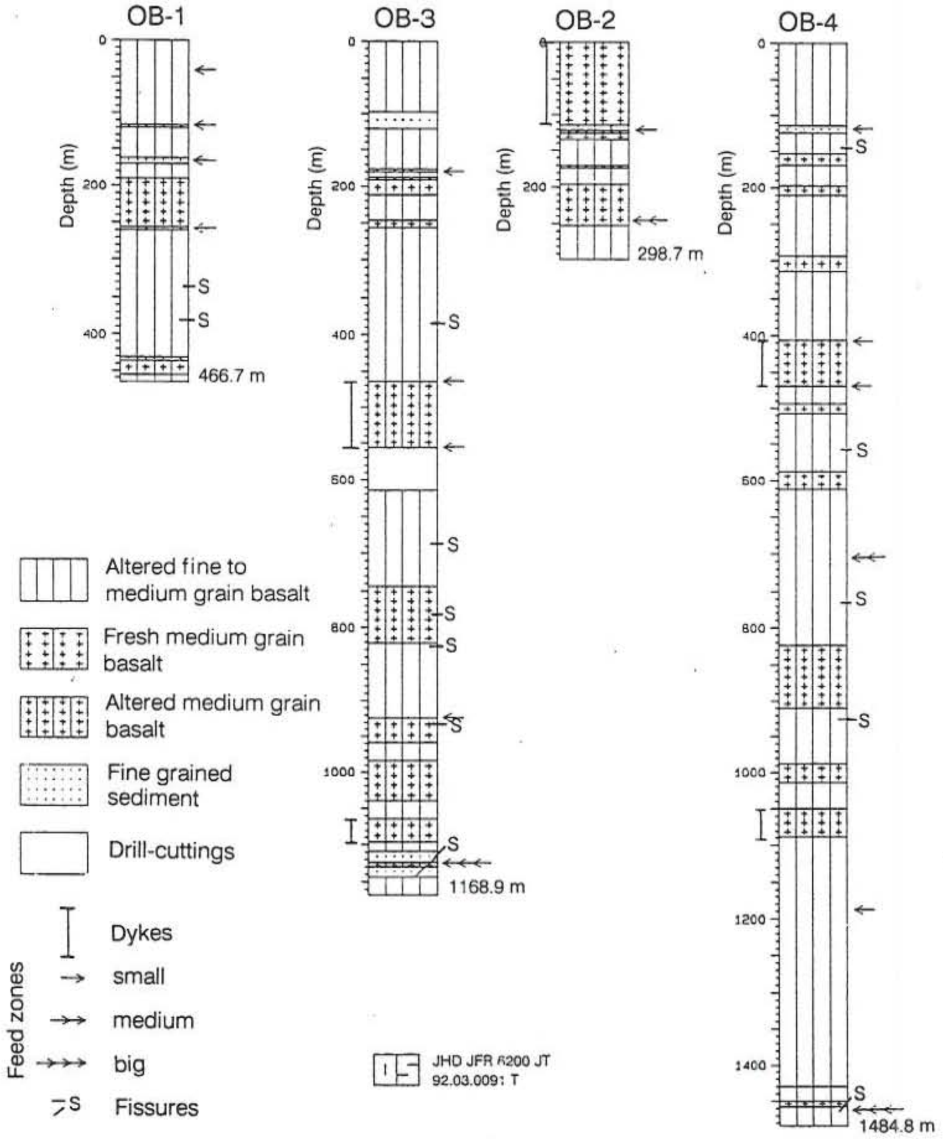

FIGURE 3: Simplified geological profiles, location of dykes, fractures and feed zones of wells OB-1, OB-2, OB-3 and OB-4 in Laugarengi, Olafsfjordur (modified from Tomasson et al., 1992)

TABLE 1: Information on wells in the Laugarengi field, Olafsfjordur

Well no.	**Drilling time**	**Depth (m)**	**Casing**		**Well diameter (")**
			Diameter (")	**Depth (m)**	
OB-1	03.10.72-05.12.72 23.08.73-08.11.73	301.4 466.7	10	10	4 3/4 4 3/4
OB-2	26.09.73-13.11.73	298.7	10 3/4	6	5 5/8
OB-3	15.10.74-25.01.75 12.05.75-30.07.75	613.8 1168.9	10 8 5/8	5.7 110	6 3/4 6 3/4
OB-4	25.06.81-28.08.81 06.07.82- -14.01.83	29 1091 1484.8	16 11 3/4	11 217	19 1/2 8 1/2 7 5/8

Drilling of well OB-3 began in October 1974. It was drilled to 614 m depth with disappointing results. The well was deepened to 1169 m during the summer of 1975 and the flow increased to 13.5 and later to 24 l/s with pumping. Well OB-4 was drilled late in 1982 and early January 1983. It was 1485 m deep and proved to be quite more productive than well OB-3. Well OB-4 has been the production well of Olafsfjordur Municipal Heating Service since 1983.

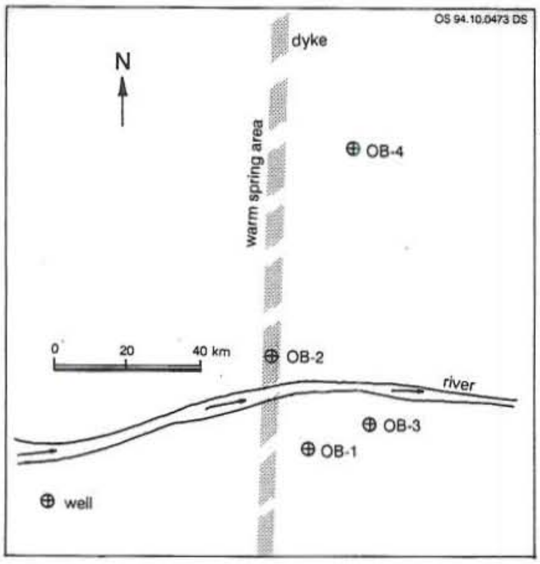

FIGURE 4: Location of Laugarengi wells (modified from Axelsson, 1991)

3. ANALYSIS OF THE TEMPERATURE MEASUREMENTS

Twenty-three temperature logs from 6 boreholes drilled in Olafsfjordur were studied to understand better the temperature distribution in the field (Table 2). The temperature in these wells was measured during and after drilling and pumping. These data have been collected for the past 21 years.

TABLE 2: Temperature measurements in the Laugarengi wells

Well no.	Date	Depth (m)	Temperature (°C)	Production (l/s)	Water table (m)	Comments
OB-1	26.07.73	0-296				self flowing, during drilling
	25.09.73	0-471	46.5	2		self flowing, during drilling
	25.09.73	0-280				self flowing, during drilling
	13.10.75	0-435				self flowing, during drilling
	20.06.90	20-50				self flowing, after drilling
OB-2	11.09.74	0-300		1.5		self flowing, after drilling
	13.10.75	0-298		1		self flowing, after drilling
	20.06.90	18-298				self flowing, after drilling
OB-3	01.11.74	0-72				no flow, after drilling
	21.01.75	0-616				self flowing, week af. drilling
	02.04.75	0-616		1		self flowing, after drilling
	18.07.75	0-1024				self flowing, after drilling
	13.10.75	0-1148		18		self flowing, after drilling
	13.09.79	0-1120				after pumping
	20.06.90	30-1124			30	after pumping
OB-4	27.07.82	0-470				during drilling
	27.07.82	0-460				during drilling
	30.08.82	0-1189				during drilling
	21.09.82	0-1340	34	1.1		during drilling
	11.06.91	0-1467				6 hours after pumping
	12.06.91	0-1467			22	33 hours after pumping

3.1 Feed zones

For locating the feed zones, the temperature logs and losses of circulation during drilling were used. The temperature curves show disturbances due to cooling and heating processes.

Well OB-1 was a self flowing well. There are 5 temperature logs (Figure 5 and Table 2). The first feed zone (Table 3) is seen in the temperature logs during drilling at 157-162 m depth and is also confirmed by a small loss of circulation in the same depth during drilling. The second one is seen in three temperature logs during drilling and at 260 m depth.

Well OB-2 was also a self flowing well with two feed zones. The first is seen in all three temperature logs at 125-150 m depth and the second is at about 250 m depth (Figure 6 and Table 3).

Well OB-3 is a self flowing well showing five feed zones. The first is seen at 110 m depth in four temperature profiles after drilling, but it is not confirmed by drilling (Figure 7 and Table 3). The second is seen at 170 m and is confirmed by loss of circulation during drilling at the same depth. The third is seen only in one temperature log after drilling and at the same depth at 920 m during drilling. The fourth zone is at 950 m according to the temperature logs. The fifth is seen in one temperature profile after drilling at 1100 m and by a loss of circulation at this depth during drilling.

TABLE 3: Feed zones in the Laugarengi wells

Well no.	**Feed zones**			
	Depth acc. temp. logs (m)	**Comments**	**Depth of circulation losses (m)**	**Comments**
OB-1	152-162	seen in 5 temp. logs during drilling	165	small feed zone
	260-262	seen in 3 temp. logs during drilling	260	small feed zone
OB-2	125-150	seen in 2 temp. logs after drilling	120	small feed zone
	230-250	seen in 2 temp. logs after drilling	245	medium feed zone
OB-3	110	seen in 4 temp. logs after drilling		
	170	seen in 4 temp. logs after drilling	175	small feed zone
	925	seen in 1 temp. logs after drilling	920	small feed zone
	950	seen in 2 temp. logs after drilling	925	fracture
	1100	seen in 1 temp. logs after drilling	1125	big feed zone
OB-4	155-160	seen in 4 temp. logs during drilling	145	fracture
	400	seen in 2 temp. logs after pumping	405	small feed zone
	465	seen in 2 temp. logs after pumping	470	small feed zone
	530	seen in 2 temp. logs after pumping	560	fracture
	695-700	seen in all temp.logs	700	medium feed zone
	770	seen in 2 temp. logs after drilling	765	fracture
	870-880	seen in 2 temp. logs after drilling		
	900	seen in 2 temp. logs after drilling	925	fracture
	1170	seen in 1 temp. logs after drilling	1185	small feed zone
	1210	seen in 2 temp. logs after drilling and after pumping		
			1460	big feed zone

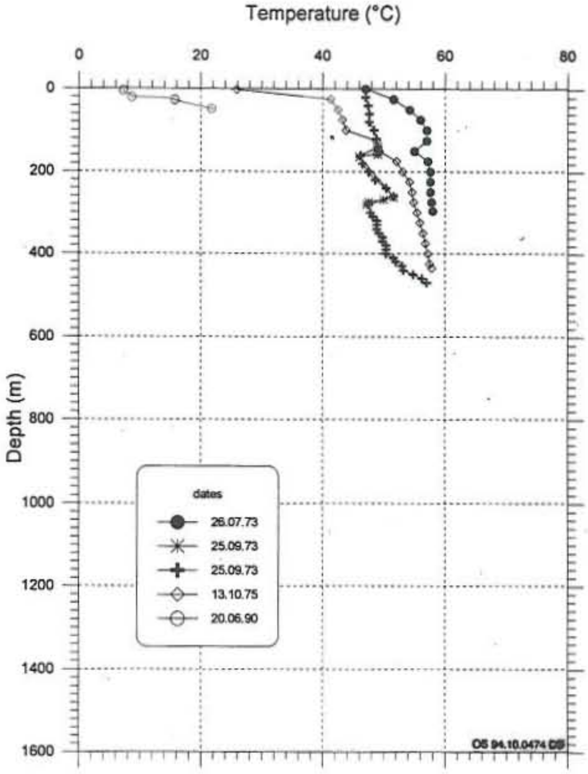

FIGURE 5: Temperature logs form well OB-1

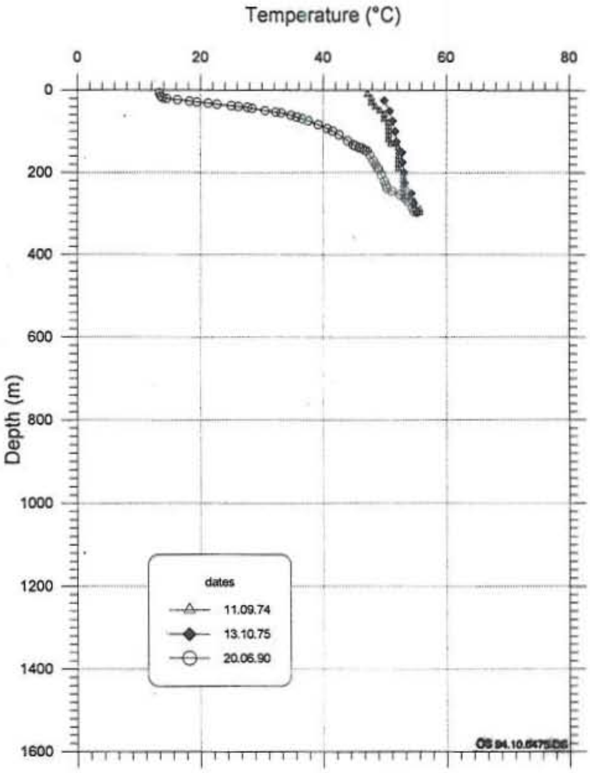

FIGURE 6: Temperature logs from well OB-2

Well OB-4 is the main production well in the field. Eleven feed zones have been recognized (Figure 8 and Table 3). The first one is seen in four temperature profiles during drilling between 155-160 m and also confirmed by a fracture at 145 m depth in the lithology. The second feed zone is seen in two temperature logs after pumping, at 400 m depth and by a small loss of circulation at 405 m. The third one is seen in two temperature profiles after pumping at 465 m and also confirmed by a small loss of circulation at 470 m depth. The fourth is seen in two profiles after pumping at 530 m and is probably confirmed by a fracture at 560 m depth. The fifth is seen in all temperature profiles and clearly confirmed by one medium loss of circulation at 700 m depth. The sixth one is seen in temperature loss after drilling, but unconfirmed by drilling. The next four feed zones are seen in temperature logs after drilling and are at 870-880, 900, 1170 and 1210 m. But the deepest and main feed zone of the well at 1460 m can not be seen in the temperature logs.

All the wells at Olafsfjordur (Laugarengi), except well OB-2, are east of the proposed dyke, which they were meant to cut (see Figure 4). Well OB-2 was drilled directly on top of the dyke. It is possible to trace individual layers between the wells in the top 300 m of the geological formation. A sedimentary layer at 100 m depth is found in all the wells except well OB-2. Also, an olivine-tholeiite basalt layer around 200 m is found in all the wells, and a layer of tholeiite basalt with scattered plagioclase porphyritic basalt is at around 300 m depth in the wells, except well OB-4. There is therefore no reason to suspect any great faults between the wells in the upper 300 m and no evidence indicates faults at greater depths.

3.2 Formation temperature

In order to study the distribution of cooling or heating in the reservoir, the formation temperature distribution must be known. All temperature measurements during and after drilling and pumping have been studied to gain original information about the initial temperatures in the Laugarengi low-temperature field in Olafsfjordur. Based on that, one profile has been constructed using the temperature log in all 4 wells (Figure 9) showing the expected formation temperature.

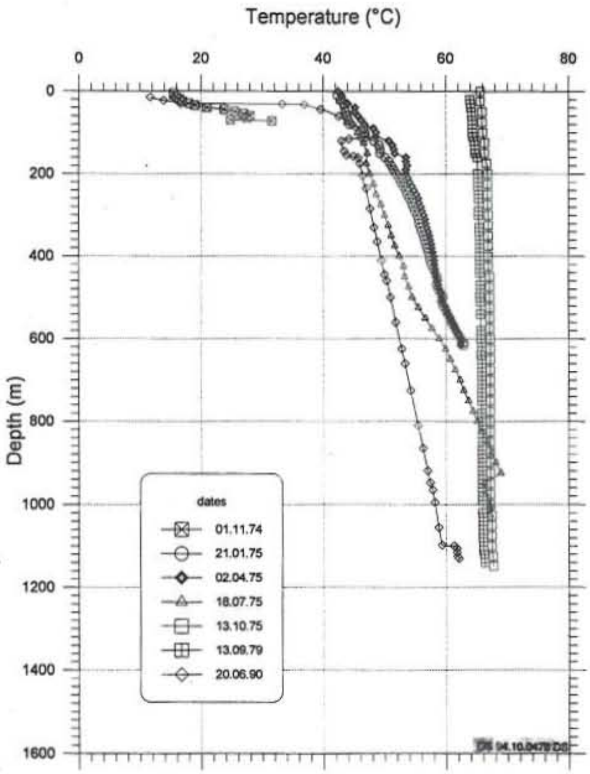

FIGURE 7: Temperature logs form well OB-3

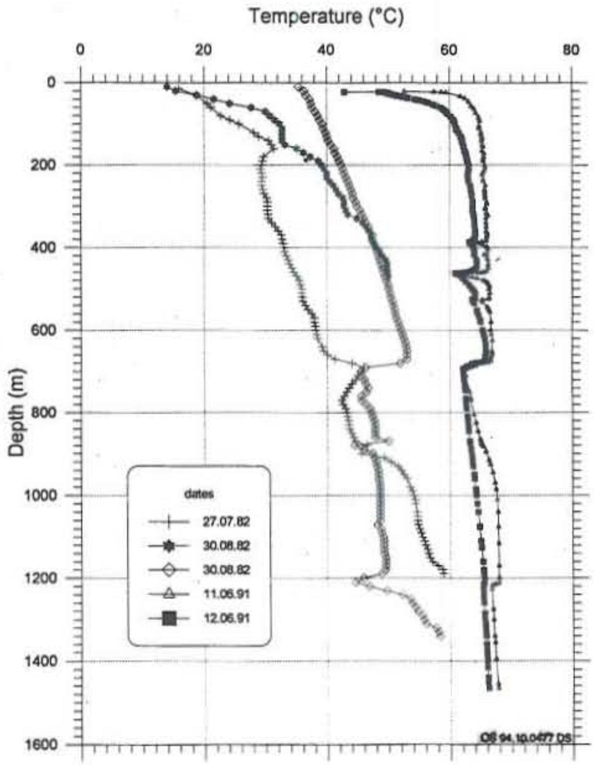

FIGURE 8: Temperature logs from well OB-4

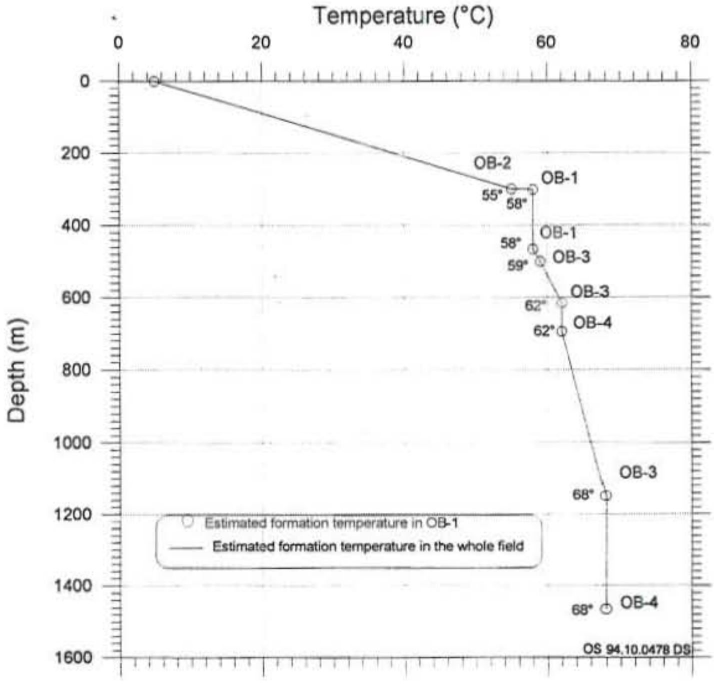

FIGURE 9: Formation temperature for the Laugarengi field

Well OB-1 was completed on Nov. 18, 1973 to a depth of 467 m. For estimation of the formation temperature we can use the temperature logs from Jul. 26, 1973 and Oct. 13, 1975 during drilling. In the first at 301 m depth the temperature is 58°C and in the second the temperature at 467 m is 58°C (Figure 5, Table 4).

Well OB-2 was completed on Nov. 13, 1973 at 299 m depth. The temperature profiles indicate that the formation temperature at the bottom should be 55°C (Figure 6, Table 4).

Well OB-3 was completed on Jul. 30, 1975 at 1169 m depth. The formation temperature in this well can be seen in the temperature measurements obtained on Jan. 21, 1975 and Apr. 2, 1975 and also on Oct. 13, 1975 where measured temperatures are 59, 62, 68°C at 500, 616, and 1148 m depth (Figure 7, and Table 4).

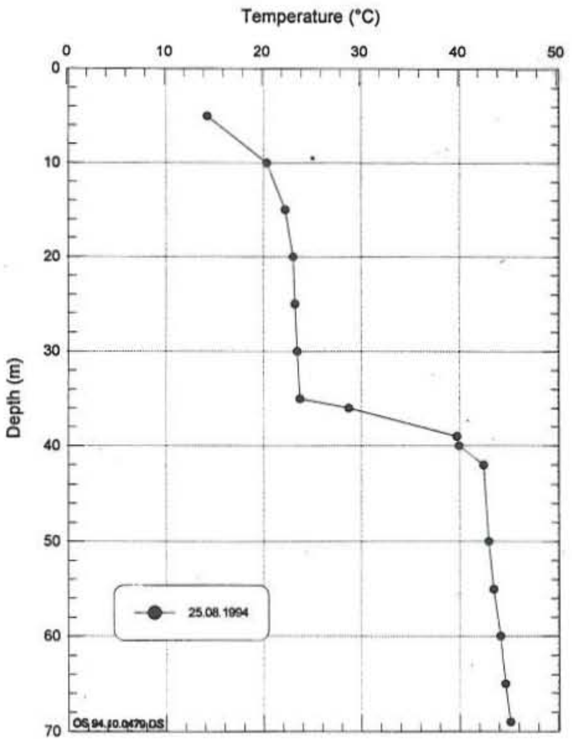

FIGURE 10: Temperature logs form well OB-5

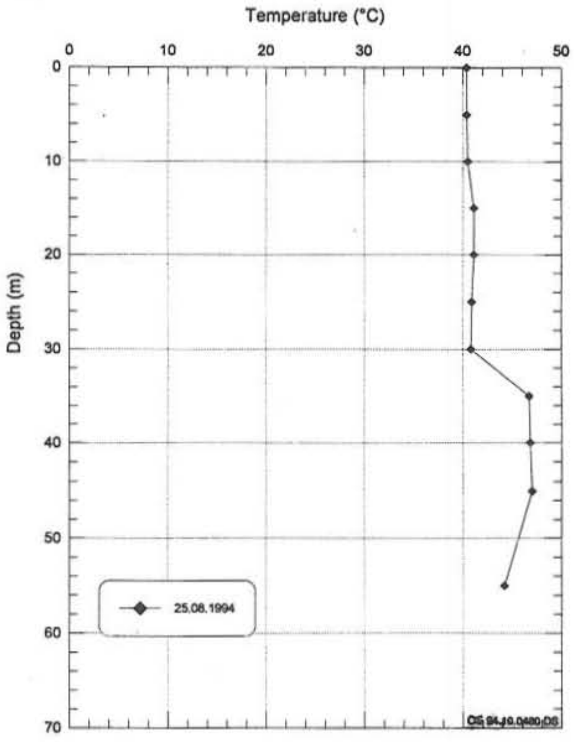

FIGURE 11: Temperature logs from well OB-6

Well OB-4: Completed on Jan.14, 1983, well OB-4 has 6 temperature profiles after drilling and after pumping. Here we can get two points for the formation temperature which are 62°C at the 695 m and 68°C at 1465 m depth (Figure 8, and Table 4).

TABLE 4: Formation temperatures

Well no.	Depth (m)	Formation temperature (°C)
OB-1	301 467	58 58
OB-2	299	55
OB-3	500 616 1148	59 62 68
OB-4	695 1465	62 68

3.3 Field measurements in the Laugarengi geothermal field

On August 25, 1994 the author took part in measuring temperatures in two new wells at the Laugarengi geothermal field. Two shallow exploration wells (OB-5 and OB-6) that were drilled just a few days before, were observed. Temperature logs of the wells (Figures 10 and 11) show a down-flow from about 10 m to about 45 m in well OB-5, but an up-flow from similar depth in OB-6. The wellhead of OB-5 is a few meters higher than for OB-6 with water-level at around 2 m, which explains why OB-5 is not self-flowing like OB-6.

3.4 Conceptual model

Figure 3 shows a simplified lithological section for the four deep wells in Laugarengi, and also dykes and fractures that have been found. The main aquifers are also shown, but their location is based on changes in flow during drilling and temperature logs, which were already discussed. Figure 12 shows a schematic cross-section through the Laugarengi field, based on geological, geophysical and hydrological information.

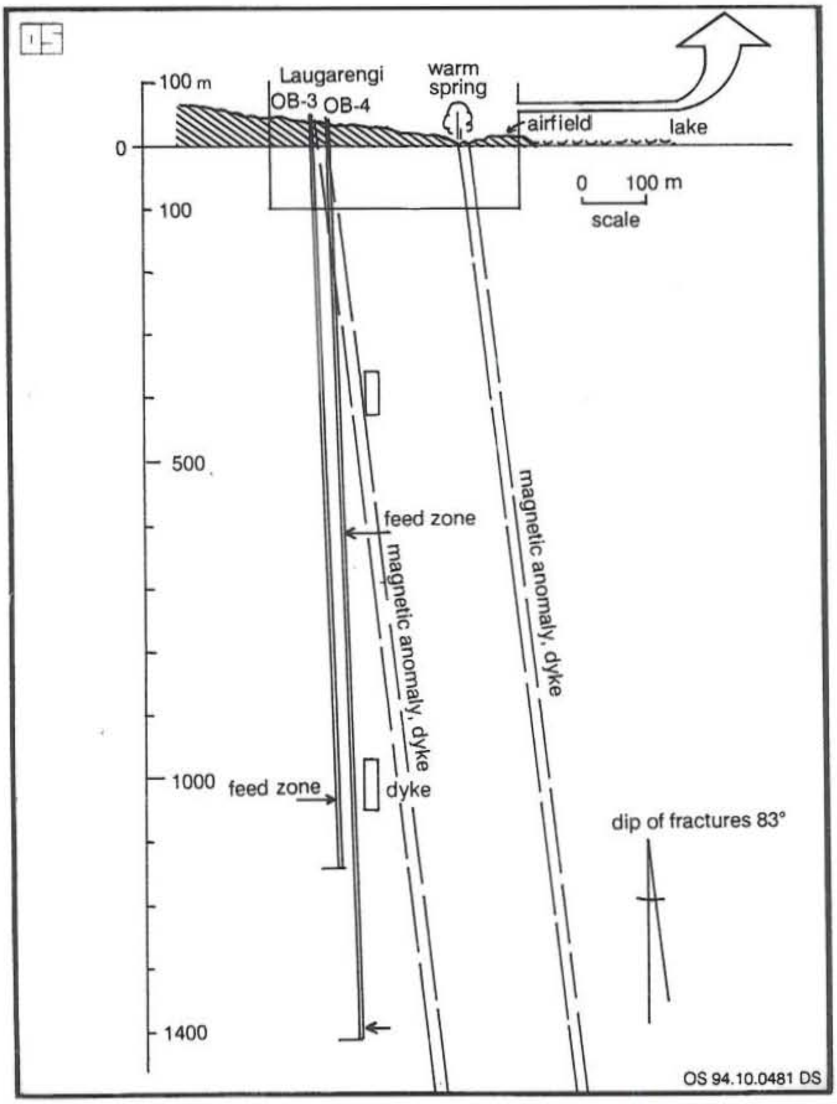

FIGURE 12: Schematic cross-section through the Laugarengi field (Torfason, 1994)

Well OB-1 does not intersect the dyke, which was the suspected up-flow channel of the warm springs. Wells OB-3 and OB-4 appear to cut a dyke between 400 and 500 m, and another dyke at 1050-1100 m depth. There is some evidence of small aquifers near the upper dyke in both wells, at the upper edge in well OB-3 but on either side of the dyke in well OB-4. There are no aquifers near the lower dyke. It is assumed that these two dykes are parallel. In the middle part of well OB-4, there is a good aquifer at 700 m. There a permeable fracture might be close to well OB-4. No aquifer is found at this depth in well OB-3.

The best aquifers in wells OB-3 and OB-4 are below the two dykes. In well OB-3, at 1110 m, an aquifer is positively connected with a fracture. It is in a sedimentary layer with medium to coarse grained basalt in the centre. In well OB-4 the main aquifer is at 1465 m depth, probably connected to a fracture, as high circulation losses occurred at this depth during drilling.

4. WELL TEST ANALYSIS

If a well is pumped at a constant flow rate, we can use the draw-down (water level) at every moment after the initiation of pumping to estimate some reservoir parameters. This task was first solved by Theis in 1935. These simple theories of well tests are described by Grant et al. (1982) and Kjaran and Eliasson (1983).

The solution includes the exponential integral E_1 which, for small x (long time) has the following asymptotic form, where $\gamma = 0.5772$ is the Euler's constant

$$E_1(x) \approx -\ln x - \gamma = -2.303\log_{10}x - \gamma \tag{1}$$

The solution to Theis problem is

$$-\Delta p = p_0 - p = \frac{q\mu}{4\pi kh}(2.303\log_{10}\frac{4kt}{\mu c_t r^2} - 0.5772)$$

$$= m[\log_{10}t + \log_{10}\frac{4k}{\mu c_t r^2} - \frac{0.5772}{2.303}] \tag{2}$$

where

$$m = \frac{2.303q\mu}{4\pi kh} \tag{3}$$

For convenience we define $m^* = m/\rho g$ and $Q = 1000\,q$, Equation 3 can then be written

$$m^* = \frac{2.303Q\mu}{4\pi kh\rho g1000} \tag{4}$$

By plotting the water level changes versus time on a semi-logarithmic scale, the transmissivity T^* from the slope m^* can be found from

$$T^* = \rho g\frac{kh}{\mu} = \frac{2.303Q}{4\pi 1000m^*} \tag{5}$$

The total formation compressibility can be calculated from the porosity ϕ, the compressibility of water c_w and the compressibility of the rock c_r

$$c_t = c_w\phi + c_r(1-\phi) \tag{6}$$

Equation 2 can be written as

$$\frac{\Delta p}{m} = -\log_{10}(\frac{4kh}{\mu}\frac{1}{c_t h}\frac{t}{r^2}) + 0.251 \tag{7}$$

Therefore, the storativity is

$$s = c_t h = 2.25\frac{kh}{\mu}\frac{t}{r^2}10^{\frac{-\Delta p}{m}} \tag{8}$$

It is difficult to choose an appropriate value for the distance between the wells, because the main feed zones in OB-3 and OB-4 are at different depths, 1125 and 1460 m, respectively. Here r =360 m is used. The following properties of water were assumed: a temperature of 68°C; pressure 50 bar; porosity 10%; rock compressibility, $c_r = 0.15\text{x}10^{-10}$ Pa^{-1}; density of water, $\rho_w = 981.0$ kg/m^3; compressibility of water, $c_w = 4.50\text{x}10^{-10}$ Pa^{-1}; total compressibility, $c_t = 0.585\text{x}10^{-10}$ Pa^{-1}; and dynamic viscosity, $\mu = 0.417\text{x}10^{-3}$ Pa-s.

4.1 Pumping test and semilog analysis of observation well OB-3 (the first hours)

Well OB-3 was used as an observation well in a pumping test in well OB-4, in July 1990. Figure 13 shows the results of the well test. Figure 14 shows the semilog analysis to estimate transmissivity and storativity of the reservoir. The slope m^* of the curve in Figure 14 was estimated to be 6.48 m/cycle, and the flow rate Q = 23.4 l/s. Therefore, from Equation 4, the transmissivity $T^* = 6.6\text{x}10^{-4}$ m^2/s, and the permeability thickness $kh = 29\text{x}10^{-12}$ m^3.

From Figure 13, the initial water level was estimated to be close to 10 m, so $\Delta p = 0$ at $t = 3$ min = 180 s (see Figure 14). By using Equation 8 we get storativity $s = 2.1\ 10^{-10}$ m/Pa and thickness h = 3.7 m.

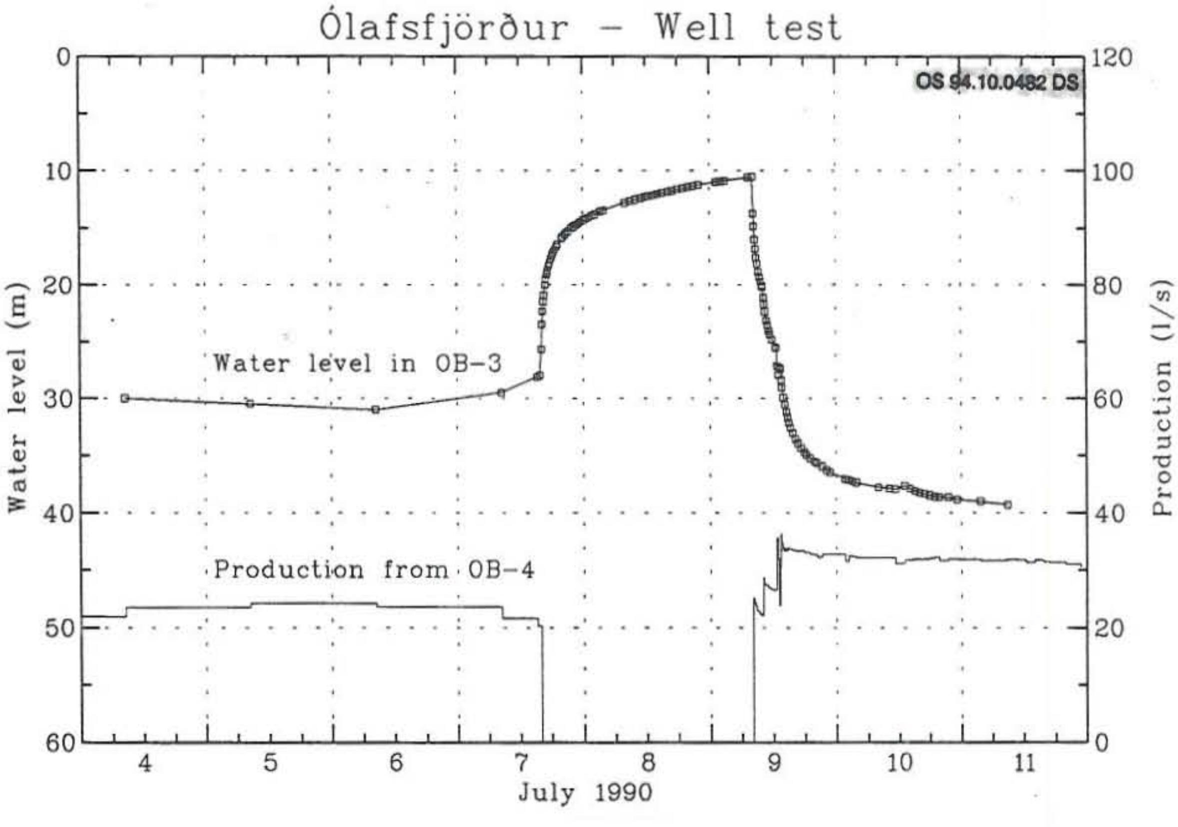

FIGURE 13: Results of a pumping test in well OB-4, with well OB-3 as a observation well

4.2 Pumping test and semilog analysis of observation well OB-3 (last days)

Figure 15 shows a semilog graph of the water level in well OB-3. The slope m^* of this curve is 5.21 m/cycle and the flow rate is not very well defined, Q = 10-30 l/s (Figure 13), leading to T^* = 4-11x10^{-4} m^2/s, and kh = 15-46x10^{-12}m^3. Selecting initial water level to be 25-35 m (t = 200-2000 s) leads to the storativity, s = 1-38x10^{-10} m/Pa and h = 2-65 m.

4.3 Recovery test

This test is based on the measurements of water level recovery data after pumping stopped. This method is also based on the Theis equation where a constant flow rate is needed. Using the same semilog graph analysis we can estimate transmissivity and storativity of the reservoir. As we can see in Figure 16 the curve of the pumping well OB-4 is not a straight line. This is probably due to changes in the density of the hot water due to temperature changes. For further estimations, available data and results from observation well OB-3, can be used.

It is estimated that m^* is 5.74 m/ cycle, Q is 24 l/s (see Figure 13). This leads to $T^* = 7.7\ \mathrm{m^2/s}$, $kh = 33\times10^{-12}\ \mathrm{m^3}$ and selecting the initial water level of 30 m leads to $s = 0.8\times10^{-10}$ m/Pa and $h = 1.4$ m.

4.4 Discussion

Results from the well tests give properties of the reservoir, like transmissivity, storativity and permeability thickness. Available data show low transmissivity and permeability thickness but these properties probably do not play the main role in geothermal activity of this field (see Table 5). Obtained results of thickness do not describe

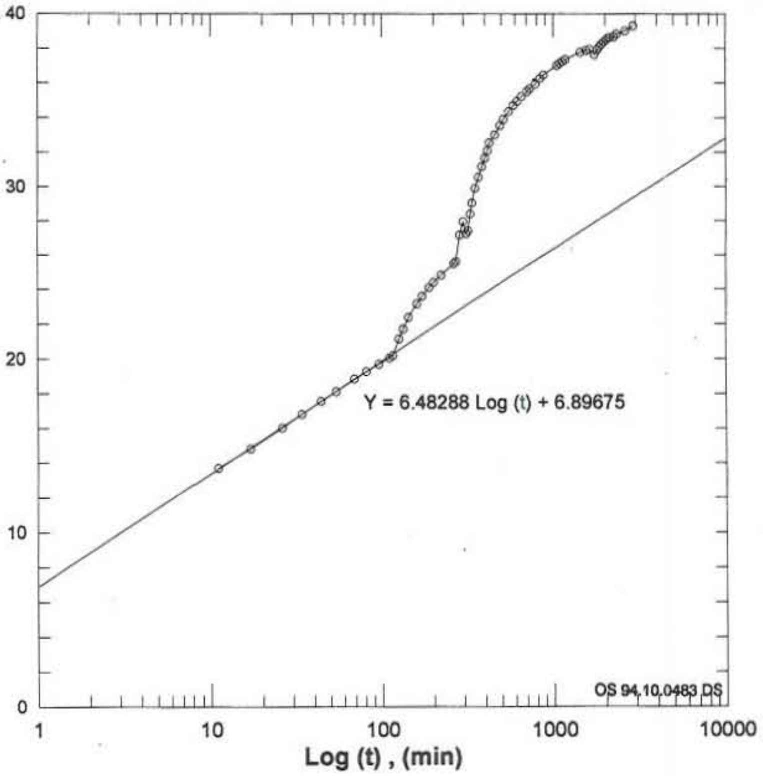

FIGURE 14: The semilog analysis on the first hours of the pumping test in well OB-3

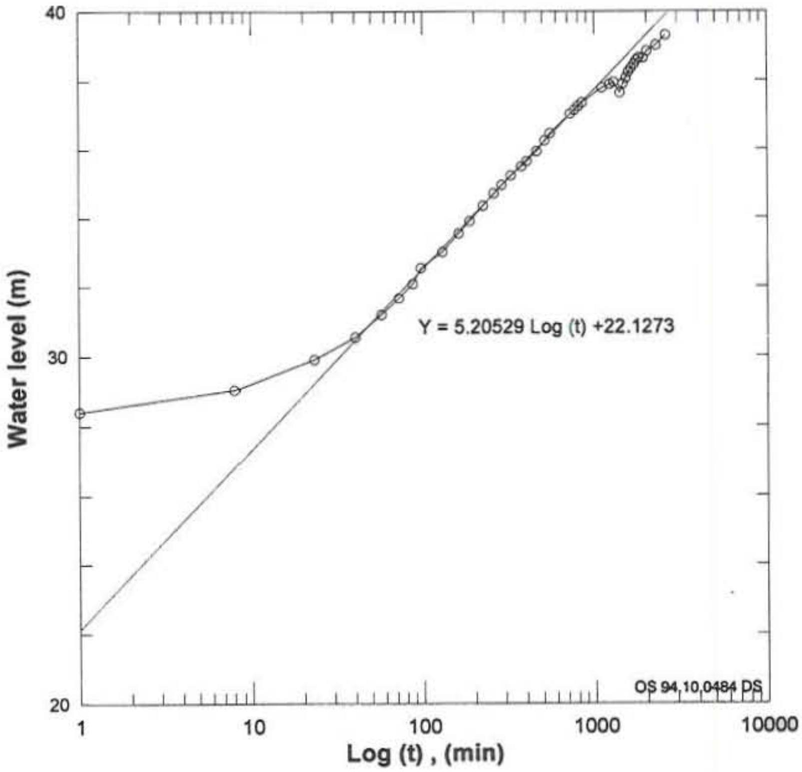

FIGURE 15: The semilog analysis on the last days of the pumping test in well OB-3

the real situation because the well test cannot embrace the whole reservoir but only a little part of it (the area of influence vs. pumping time probably had not been so large). These results may also indicate that the simplified model is inadequate for this field.

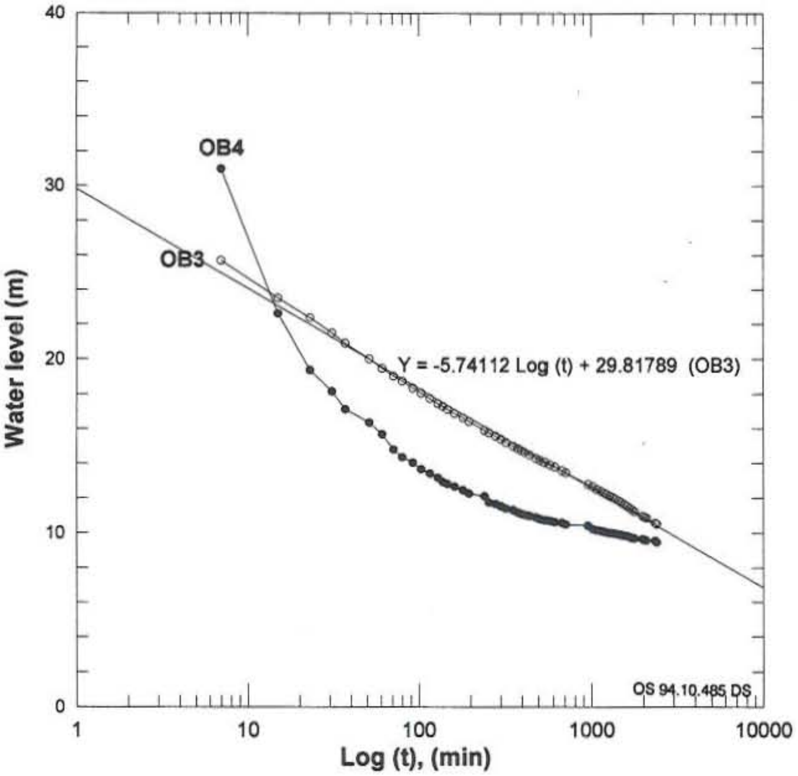

FIGURE 16: Recovery tests of wells OB-3 and OB-4

TABLE 5: Comparison of transmissivity and storativity from well test data

Properties	Pumping test (first hours)	Pumping test (last days)	Recovery test
T^* (m^2/s)	6.6×10^{-4}	$4\text{-}11 \times 10^{-4}$	7.7×10^{-4}
kh (m^3)	29×10^{-12}	$15\text{-}46 \times 10^{-12}$	33×10^{-12}
s (m/Pa)	2.1×10^{-10}	$1\text{-}38 \times 10^{-10}$	0.8×10^{-10}
h (m)	3.7	2-65	1.4

5. SIMPLE LUMPED MODEL

To obtain information on the properties of the Olafsfjordur low-temperature geothermal system as well as to predict the response of the system to future production and estimate production potential of the system a lumped parameter model was used. The optimal production strategy of a geothermal field cannot be obtained without using a good reservoir model. It should give a clear picture of the conditions in the reservoir during future exploitation. All plans for changing the production scheme should be carefully checked by the model.

5.1 The lumped model

A lumped model is a simple model used for simulations of pressure (or water level) response data. It does not consider the internal structure of the system. Lumped models use few parameters to represent the entire

A lumped model is a simple model used for simulations of pressure (or water level) response data. It does not consider the internal structure of the system. Lumped models use few parameters to represent the entire system (Figures 17 and 18). One of the blocks may represent production reservoir and the other the recharge part of the system. Most lumped parameter models use two or three tanks. The programme LUMPFIT tackles the simulation problem as an inverse problem. It fits analytical response functions of lumped models to observed data by using a non-linear iterative least-squares technique for estimating the model parameters (Axelsson and Arason, 1992).

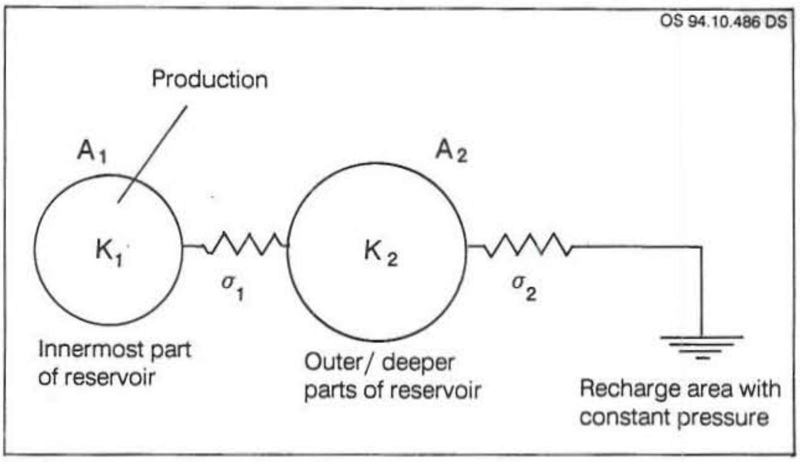

FIGURE 17: The general idea of the lumped parameter model (Axelsson, 1989)

In Figure 17 κ_1 and κ_2 are the mass storage coefficients of the tanks, A_1 and A_2 are the top surface area of the tanks, σ_1 and σ_2 simulate flow resistance between the tanks (permeability). The storage coefficients can possibly be due to compressibility storage or a mobility of a free surface.

In the case of a compressibility storage

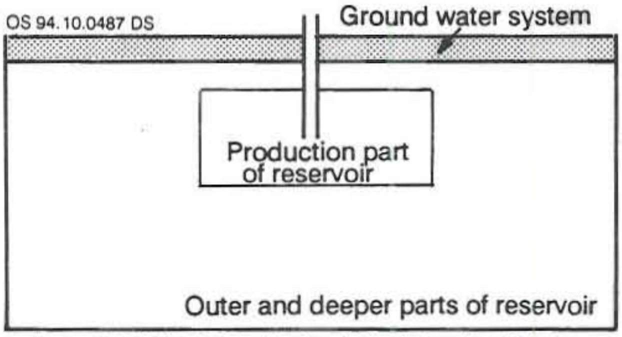

FIGURE 18: A simplified sketch of the lumped parameter model

$$\kappa = \frac{m}{p} = Vs = V\rho c_t \tag{9}$$

where c_t is defined by Equation 6.

In the case of a storage due to a mobility of a free-surface

$$\kappa = Vs \quad with \quad V = Ah \tag{10}$$

and

$$s = \frac{\phi}{gh} \tag{11}$$

Therefore

$$\kappa = Ahs = \frac{A\phi}{g} \tag{12}$$

In the case of a 1-D flow, the conductance of the resistors can be estimated as

$$\sigma = \frac{q}{\Delta p} = \frac{kA}{\nu L} \tag{13}$$

When a lumped model with n tanks is present, the mass flow between tank i and tank k is q_{ik} , the conductance of the resistor between these thanks is σ_{ik} , the production rate from tank i is Q_i . If p_0 is the equilibrium pressure, the basic equations describing mass flow and pressure changes in the tanks are

$$q_{ik} = \sigma_{ik}(p_k - p_i) \tag{14}$$

$$\kappa_i \frac{\partial p_i}{\partial t} = \sum_{k=1}^{n} q_{ik} - \sigma_i (p_i - p_0) - Q_i \tag{15}$$

Pressure changes with time in open n-tank model system is as follows:

$$p(t) = p_0 - \sum_{k=1}^{n} Q \frac{A_k}{L_k} (1 - \exp^{L_k t}) \tag{16}$$

And for a closed system

$$p(t) = p_0 - \sum_{k=1}^{n} Q \frac{A_k}{L_k} (1 - \exp^{L_k t}) - QBt \tag{17}$$

where A_k , L_k and B are coefficients used in lumped modelling.

To estimate the permeability-thickness, kh, of the Olafsfjordur (Laugarengi) reservoir, two dimensional flow is assumed. The two tanks may be envisioned as two concentric cylinders of thickness h. By defining r_1 as the radius of half the inner cylinder, and r_2 as the radius to the center of the outer ring, the conductance of the first resistor is

$$\sigma_1 = \frac{2 \pi h}{\ln \frac{r_2}{r_1}} \frac{k}{\nu} \tag{18}$$

or

$$kh = \frac{\sigma_1 \ln \frac{r_2}{r_1} \nu}{2 \pi} \tag{19}$$

5.2 Modelling results and conclusions

Two lumped models were used in this study, a closed two tank and an open two tank. The simulated field data were production and water level changes from 1989 to 1994 (Figures 19 and 20). The parameters of the models are shown in Tables 6 and 7. It was impossible to reach a coefficient of determination better than 57.2% for the closed two tank and 78.8% for the open two tank model. The turbulence parameter *C* for the pumping well OB-4 is 0.015 m/(kg/s)^2. Initial water level was estimated to be 40 m above earth surface.

Predictions were calculated for only a short period of time because water level measurements did not start earlier than in 1989. Predicted water level, assuming a flow rate of 20 l/s for the next five years, is 20-25 m below the surface.

TABLE 6: Parameters of the two lumped models

Parameters	κ_1 (ms^2)	κ_2 (ms^2)	σ_1 (10^{-4} ms)	σ_2 (10^{-4} ms)	**Coeff. of determin. (%)**
Closed two tank model	88.93	145179	0.4376	-	57.2
Open two tank model	35.65	1217.4	0.7788	0.7289	78.8

Assuming a thickness of the reservoir of 1000 m, an attempt was then made to calculate permeability thickness of the aquifer and compare this with results obtained from pumping tests. The results are comparable with results from well tests and show also low permeability thickness (See Tables 5 and 7).

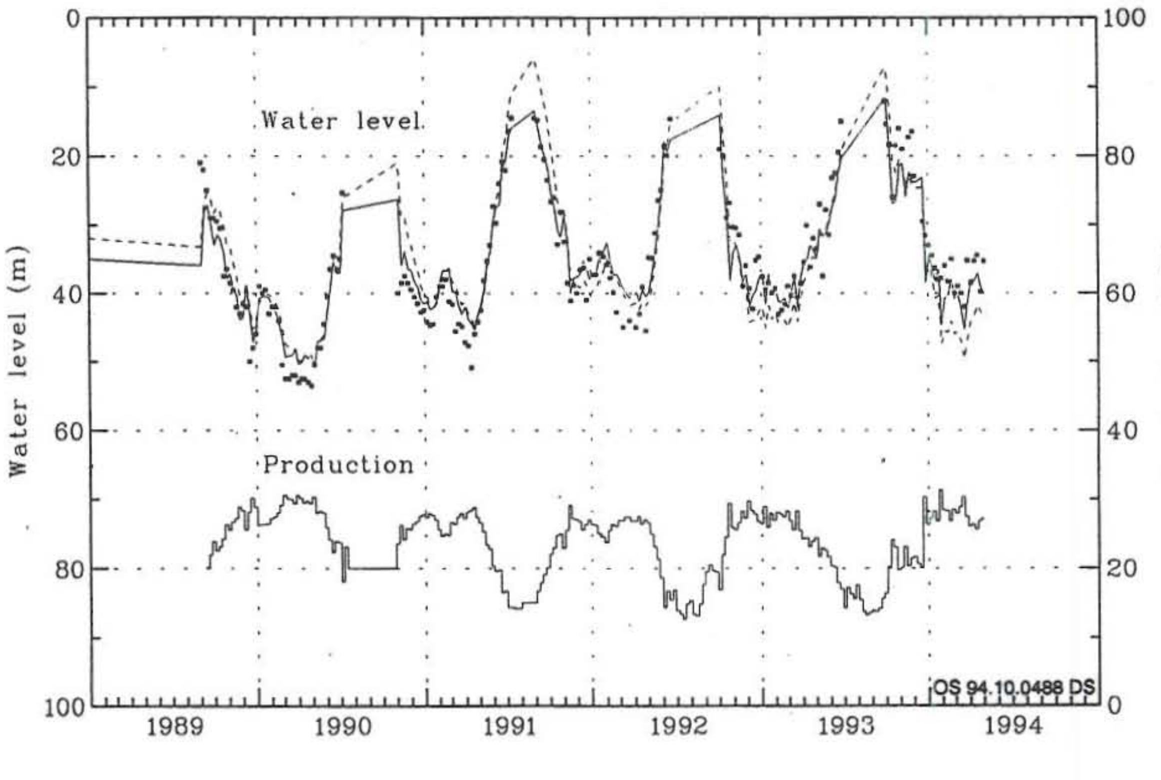

FIGURE 19: Production and water level history of the Laugarengi geothermal field in Olafsfjordur

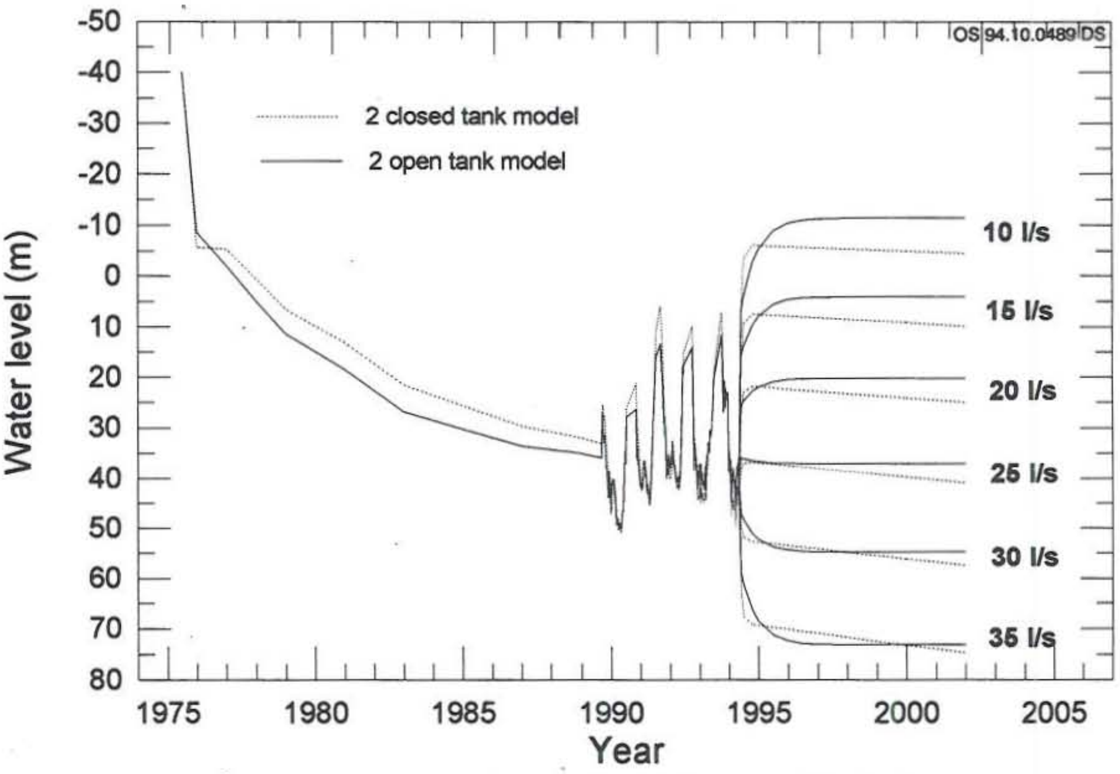

FIGURE 20: Predicted changes in the water level in Laugarengi for the the next 5 years at different flow rates using the two tanks closed and two tanks open models

TABLE 7: Calculated results of the reservoir parameters

Parameters	**Model type**	
	Closed two tank model	**Open two tank model**
A_1 (m^2)	8724	3497
A_2 (m^2)	14.24 10^6	0.2 10^6
V_1 (m^3)	1.55 10^9	0.6 10^9
V_2 (m^3)	2534 10^9	21.24 10^9
kh (m^3)	11 10^{-12}	10 10^{-12}

6. CONCLUSIONS AND RESULTS

The main task of this work was to make an assessment of the Laugarengi low-temperature field in Olafsfjordur. From the analysis and interpretation of temperature measurements, available data of well tests and lumped models, the main conclusions and results of the study can be summarized as follows:

1. Faults and dykes cutting perpendicularly through the lava formations play a main role in the hydrogeological system.

2. Analysis of temperature measurements show up-flow channels lying parallel to dykes and fractures. The main feed zones were located from circulation losses during drilling and temperature logs.

3. Formation temperature at 1200 m depth is 68°C.

4. Well test analysis indicate that the transmissivity, $T^* = 6\text{-}8\text{x}10^{-4}\ \text{m}^2/\text{s} = 60\ \text{m}^2/\text{day}$, and permeability thickness, $kh = 30\text{x}10^{-12}\ \text{m}^3 = 30$ D-m.

5. It was possible to fit the observed water level changes from 1989 to 1994 with closed and open two tank lumped parameter models.

6. Predicted water level, assuming a flow rate of 20 l/s for the next five years, is 20-25 m below surface.

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NOMENCLATURE

$A_{1,2}$ = Area of resistors (tanks)
A = Area of the resistor (m^2)
c_w = Compressibility of water (Pa^{-1})
c_r = Compressibility of rock (Pa^{-1})
c_t = Total compressibility (Pa^{-1})
g = Acceleration of gravity (m/s^2)
h = Thickness (m)
k = Permeability (m^2)
h = Thickness of the reservoir (m)
L = Length of the resistor (m)
m = Mass increase (kg)
m^* = Slope of the semilog analysis (m/cycle)

$\Delta \mathrm{P}$ = Initial pressure of the reservoir (Pa)
Δp = Pressure differential between tanks (Pa)
p = Pressure increase (Pa)
q = Flow rate (m^3/s)
q = Mass flow ($\mathrm{kg\ s}^{-1}$)
r_1 = Inner radius of 2-D resistor
r_2 = Outer radius of 2-D resistor
r = Distance between wells (feed zones) (m)
s = Storativity ($\mathrm{kg\ Pa}^{-1}$) for liquid-dominated reservoir
T = Transmissivity
T^* = Transmissivity (m^2/s)
t = Time (s)
V = Volume of tank (m^3)

κ = Mass storage coefficient (capacitance) ($\mathrm{m}^2\mathrm{s}$)
μ = Dynamic viscosity of the water (kg/ms)
ν = Kinematic viscosity of geothermal water ($\mathrm{m}^2\ \mathrm{s}^{-1}$)
ρ_w = Density of geothermal water ($\mathrm{kg/m}^3$)
ϕ = Porosity of reservoir (%)
$\sigma_{1,2}$ = Simulated flow resistance between tanks (permeability)
ρ = Density of the water ($\mathrm{kg/m}^3$)

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