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BOREHOLE GEOPHYSICS AND GEOLOGY OF THE URRIDAVATN GEOTHERMAL AREA, E-ICELAND

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ABSTRACT

The Urridavatn geothermal field is a low-temperature geothermal field in E-Iceland, which has been utilized for space heating since 1980. In this study the temperature conditions in the system are evaluated on the basis of 68 temperature logs from 8 wells. This evaluation reveals a near-vertical hot water up-flow intersected by the best production well in the field, well UV-8, at about 800 m depth. This thermal anomaly tilts towards well UV-5 at greater depth. It is recommended to deepen well UV-5 to at least 1500 m depth to intersect this up-flow. The lithology of the Urridavatn geothermal system is also evaluated on the basis of geophysical logs, drillcutting analysis and a core description from one of the wells. An emphasis is placed on studying the correlation between temperature logs and lithology. A method is proposed whereby lithological information may be extracted from temperature logs. It involves comparing several temperature logs from the same well and dividing the borehole into temperature units, each with similar characteristics. It is suggested that these temperature units may be used to distinguish between permeable and non-permeable lithological units.

1. INTRODUCTION

The Urridavatn geothermal field is a low-temperature field located in Tertiary rock formations, in eastern Iceland (Figure 1). Hot water production from this field started in 1980, but after only two years of production a rapid drop in the water temperature from 64 to 55°C occurred. A head-on resistivity survey located a near-vertical low-resistivity structure, not intersected by the wells. A new well which intersected this structure turned out to be a good

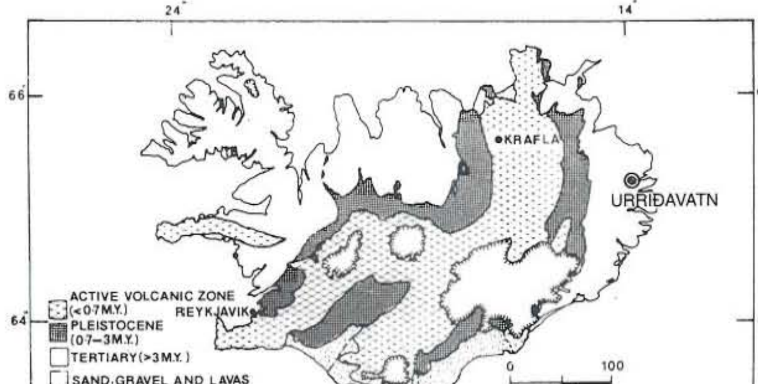

FIGURE 1: Geological map of Iceland and the location of the Urridavatn geothermal field

producer, yielding up to 40 l/s of 75°C water.

This report presents an evaluation of the temperature conditions and lithology in the Urridavatn field. It describes work carried out by the author as a part of the six month Geothermal Training Programme at the United Nation University in Iceland from May to October 1995. Its purpose was firstly to define the temperature distribution in the system on the basis of temperature logs. Sixty-eight temperature logs have been carried out in eight wells, some during and after drilling others after stimulation, discharge tests or long-term production. Temperature conditions in the Urridavatn field have not been evaluated previously in detail. Additional information on the hot water up-flow in the system is derived on the basis of this evaluation, which in turn may be used to locate new production wells in the area.

Secondly the purpose was to study the lithology of the field on the basis of caliper logs, normal resistivity logs, natural gamma-ray and neutron-neutron logs in addition to drill-cutting analyses and a core description from one shallow well. An emphasis was placed on studying the correlation between temperature logs and lithology. A method will be presented, based on studying temperature logs under different conditions, whereby different lithological units in boreholes may be distinguished.

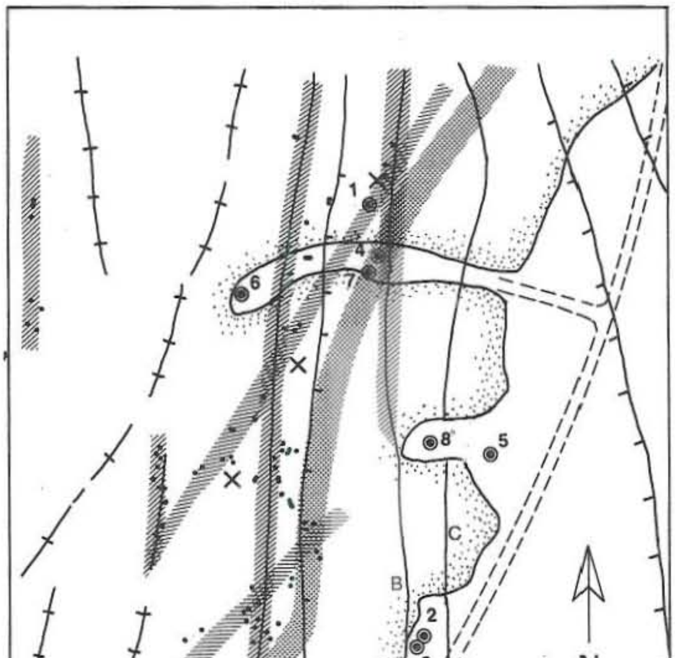

FIGURE 2: The Urridavatn geothermal field, holes in the winter ice, wells and geological and geophysical structures

2. THE URRIDAVATN GEOTHERMAL FIELD

The Urridavatn geothermal system is of the low-temperature type. Low-temperature fields are characterized by subsurface temperature less than 150°C at 1 km depth. In Iceland the low-temperature fields are mainly situated on the flanks of the active volcanic zones in Quaternary or Tertiary formations. The Urridavatn field is located in the eastern part of the country, outside the neovolcanic zone, below lake Urridavatn (see Figure 1). Prior to production, the only surface manifestations of the geothermal activity were openings in the ice of lake Urridavatn during the winter.

Exploration of the field has been described by Einarsson et al. (1983). It included temperature mapping at the bottom of the lake. The highest temperature was found to be 59.5°C. Geological exploration was done with the goal of mapping the dykes that were believed to control the upflow of hot water. In addition a magnetic survey and resistivity measurements were carried out for the same reason. These surveys showed many faults passing through the area and that Urridavatn is in fact partly in a graben (see Figure 2). The geothermal field is utilized by the District Heating Service of the town of Egilsstadir and the county of Fell (Hitaveita Egilsstada og Fella).

Production started in 1980, with only one well in operation, well UV-4, which produced 12 l/s of 64°C water, mainly from a shallow aquifer. In 1982 three wells were in operation and six wells had been drilled in the area. During the first two years of production severe cooling of the water took place and the water temperature decreased to about 55°C. As a reaction to this problem Orkustofnun reevaluated all available data concerning the geology and geophysics of the area in addition to collecting new data. An extensive geophysical survey was carried out, involving resistivity and magnetic measurements on ice or water. The purpose of this was, on one hand, to determine which geological structure controlled the upflow of hot water in the system and, on the other hand, to find the cause of the cooling. Head-on resistivity measurements were carried out and a vertical low-resistivity feature was located, which was thought to be responsible for the transport of hot water to the geothermal area. Following this two wells were drilled, well UV-7 as an exploration well and UV-8 which intersected a very good feed-zone at about 800 m depth. Initially UV-8 produced 40.5 l/s by free-flow. It has not suffered cooling since it started producing.

3. TEMPERATURE CONDITIONS IN THE URRIDAVATN FIELD

3.1 General overview

Temperature is an essential parameter in geothermal investigations. Temperature logs run during and after drilling give valuable information on location of aquifers, formation temperature distribution and flow patterns in the area. It is well known, that borehole conditions can disturb the temperature equilibrium in the formation around the well. This is due to the mud or water circulation during drilling or well stimulation as well as internal flow in the well. In permeable zones the cooling depends on the pressure condition in the well relative to the formation. If pressure conditions allow, the circulation fluid penetrates into the formation, cooling the formation even to great distances from the well. In dense formations, changes in the temperature occur due to the temperature difference between the circulation fluid and the formation, and are controlled by heat conduction. When the circulation is stopped, the temperature in and around the well recovers toward the equilibrium temperature because of energy transfer from higher to lower temperatures. Again the energy transfer is by conduction in the denser formation and by convection and conduction in the permeable zones (Stefánsson and Steingrímsson, 1980).

The interpretation of temperature conditions in geothermal systems should be based on all available temperature profiles measured in the boreholes in the area. These may be measured during drilling, during the warm-up period after drilling, and after wells have discharged. The technique which is usually applied for interpretation of temperature logs is as follows. First the undisturbed temperature profile or formation temperature is estimated for each well and then the formation temperature data are plotted on cross-sections or plan-views and isothermal maps drawn. Such maps usually indicate clearly the convective rather than the conductive nature of geothermal reservoirs. From these plots the flow pattern can be deduced. The hot water flow must be from the hotter parts of the reservoir towards its cooler parts. Temperature inversions indicate hotter permeable zones. A constant temperature zone indicates fluid movement. In all cases, maximum or minimum zonal temperatures imply some flow and hence some permeability (Grant et al., 1982).

In the Urridavatn geothermal field sixty-eight temperature logs have been carried out in eight wells, some during and after drilling, others after stimulation, discharge tests or long-term production.

UV-1 Completed in October 1963 to a depth of 116.2 m. About 12 years later, in January 1976, the only available temperature log was carried out in this well.

UV-2 Completed in November 1963 to 116.8 m depth, in 1967 it was deepened to 192.6 m. Three temperature logs, carried out between 1969 and 1976 are available from this well.

UV-3 Drilled to 1152 m depth during November 1975 to January 1976. It was deepened to 1454 m in August 1977. Eighteen temperature logs were carried out during and after drilling.

UV-4 Drilled to 1600 m depth during August to October 1977. It was cased down to 160 m with 273 mm casing diameter. Three temperature logs were carried out in the well, two of them during the drilling period and the last about a year later.

UV-5 Drilled to 851 m depth during the period from December 1979 to July 1980. It was cased with 273 mm diameter casing down to 120 m and with 254 mm diameter casing down to 180 m. Nineteen temperature logs were carried out during and after drilling, a few after injection and airlift tests.

UV-6 Drilled to 877 m depth between August 1979 and July 1980. It was cased down to 220 m with 273 mm diameter casing. Eleven temperature logs were carried out during and after drilling, a few after airlifting and injection tests.

UV-7 Drilled to 344.7 m depth between April 1983 and May 1983, with the purpose of getting information on the tilt and inclination of the up-flow zone and additional geological information (a core was taken from the whole well). Twenty-four temperature measurements are available from the well, measured during and after drilling. The first temperature log during drilling, was performed on 12-04-1983 and the last on 09-05-1983. Eight years later, on 18-07-1991, the last temperature log was measured.

UV-8 Drilled to 1006.6 m depth from July 1983 to November 1983. Four temperature logs have been carried out in the well, the last one was performed one week after drilling was stopped.

3.2 Location of aquifers

Convection so dominates conduction that a minor flow from an aquifer can produce a major thermal feature. If the well only penetrates dense formations, the temperature increases linearly with depth. The slope of a temperature log is called the thermal gradient. As soon as aquifers are penetrated by the well, the temperature can increase or decrease irrespective of the depth but depending on the aquifer temperatures. Such irregularities in the log indicate aquifers. If temperature logs are carried out during artesian discharging, the true temperatures will be masked by the temperature of these aquifers. The locations of aquifers derived from the temperature logs are listed in Table 1.

3.3 Formation temperature

Formation temperature is defined as the undisturbed temperature of a geological formation prior to drilling. It is most important in geothermal applications for creating a conceptual model of the system in question, in particular regarding the temperature distribution and flow patterns. Determination of the static formation temperature may also be required for the following reasons (Dowdle and Cobb, 1975):

a) For the interpretation of resistivity logs, which requires knowledge on formation water resistivity that depends on temperature;
b) Due to the design of deep-well cementing programmes;
c) For the estimation of temperature at greater depth by extrapolating bottom hole geothermal gradients.

TABLE 1: Location of aquifers in the Urridavatn wells

Well	Depth of aquifer (m)	Temperature (°C)	Well	Depth of aquifer (m)	Temperature (°C)
UV-1	25-30	>57	UV-5	560-620	65
	116	53		720-800	75
UV-2	150	34	UV-6	60	35-40
UV-3	70	30		100	42
	150-170	40		360	61
	420	66		760	72
	480-490	70	UV-7	20	48
	940-900	72		800	41
	1050-1075	74		110	52
	1450	78		260	61
UV-4	250-300	50-52	UV-8	100	28
	450	58		250	50
	950	72		500	72
	1600	78		740	88
UV-5	40-80	26		1000	80
	220	50			

Measured subsurface temperature is usually lower than the true formation temperature until the well has reached equilibrium after drilling. Cooling takes place during drilling due to the circulation of the colder drilling fluids. It takes the formation around the well up to several months to reach temperature equilibrium, especially if drilled by water or mud. To measure the formation temperature directly a long waiting time is therefore required. A few methods are available to shorten this time and estimate the formation temperature. One is the so-called Horner method. It requires that the temperature is measured several times at the same depth, preferably at the bottom of the hole, during the warm up period. This method cannot be used close to aquifers or feedzones or if there have been several periods of cooling down and heating up during drilling. To get an estimate of the formation temperature the measured temperature is plotted against log $((t_0+\Delta t)/\Delta t)$, where t_0 is the circulation time (cooling time) and Δt is the time since cooling stopped. The basic concept is the straight-line relationship, i.e. the assumption that extrapolation of the straight-line to a ratio of $(t_0+\Delta t)/\Delta t=1$ will determine the true formation temperature.

When the Horner method is not applicable the formation temperature has to be estimated from the temperature logs during and after drilling. There, the bottom hole temperature (BHT) is the most reliable. This is because the bottom of the well, at the time of each measurement, has undergone less cooling than any part of the well above. Therefore it gives a temperature close to the formation temperature, but usually slightly lower. Sometimes a segment of the log can, in addition, be assumed to be close to the formation temperature. After the well has started flowing, or when there is flow between aquifers in the well, the flow masks the true formation temperature.

In the Urridavatn field the temperature logs were carried out over a long period in time, in some wells longer then ten years, so a temperature equilibrium was clearly achieved. In such cases the last temperature log measured is assumed to show the formation temperature. Where there is flow from the well, or internal flow, bottom hole temperature and selected segments of the log that seem to have achieved equilibrium, were used. In general some touch of artistry and experience is needed in interpretation of temperature logs and estimation of the static formation temperatures.

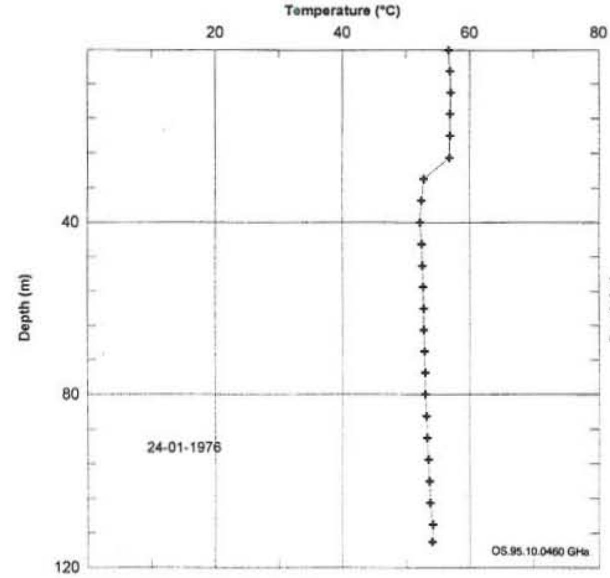

FIGURE 3: Temperature log in well UV-1

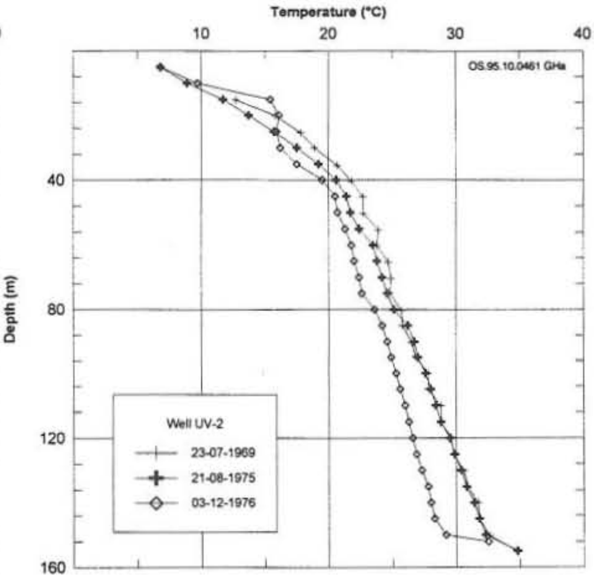

FIGURE 4: Temperature logs in well UV-2

UV-1 Only one log exists from this well, during which the well was flowing (see Figure 3). The flow is from the bottom of the well at 110 m with a formation temperature of 53°C. Another aquifer is at a 30-35 m depth with a temperature greater than 60°C, which means an inversion in temperature in this well.

UV-2 The formation temperature profile is based on the bottom hole temperature measured on 23-07-1967 and 21-08-1975 (same temperature). From there a smooth line is drawn up through a point at the depth of 15 m to the surface temperature of 4.5°C (see Figure 4). The formation temperature is assumed to be a little higher than the measured one.

UV-3 The formation temperature profile is based mainly on the bottom hole temperature measured on 27-08-1978 at a depth of 1450 m (Figure 5) and the bottom hole temperature when the well was only 1160 m in depth, measured on 11-03-1976. Also, on a segment (30-100 m) of the log measured on 27-08-1978 (Figure 5).

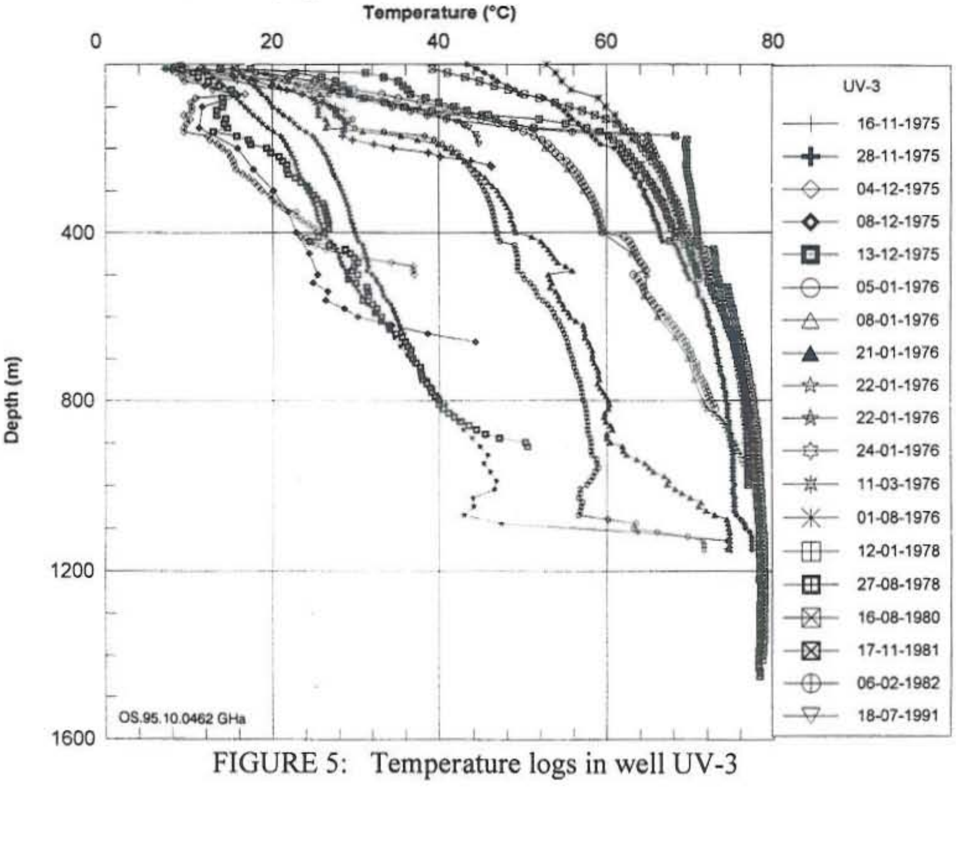

FIGURE 5: Temperature logs in well UV-3

UV-4 The suggested formation temperature profile is based on the bottom hole temperatures at 1580 m depth measured on 28-08-1978, at 800 m measured on 11-09-1978 and the segment from 270 m depth up to the surface measured 10-10-1977 (see Figure 6).

UV-5 The suggested formation temperature in the upper part down to 200 m is based mainly on the log performed on 04-09-1991. Below this the log is disturbed by flow from the aquifer at 240 m down to 600 m. The segment 700-840 m from the same log is also used. Following this the whole curve was smoothed (see Figure 7).

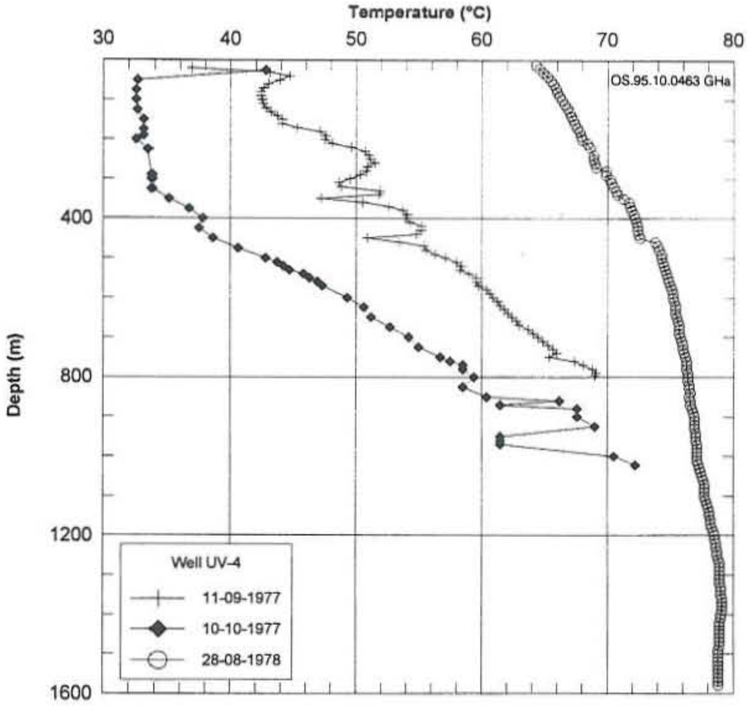

FIGURE 6: Temperature logs in well UV-4

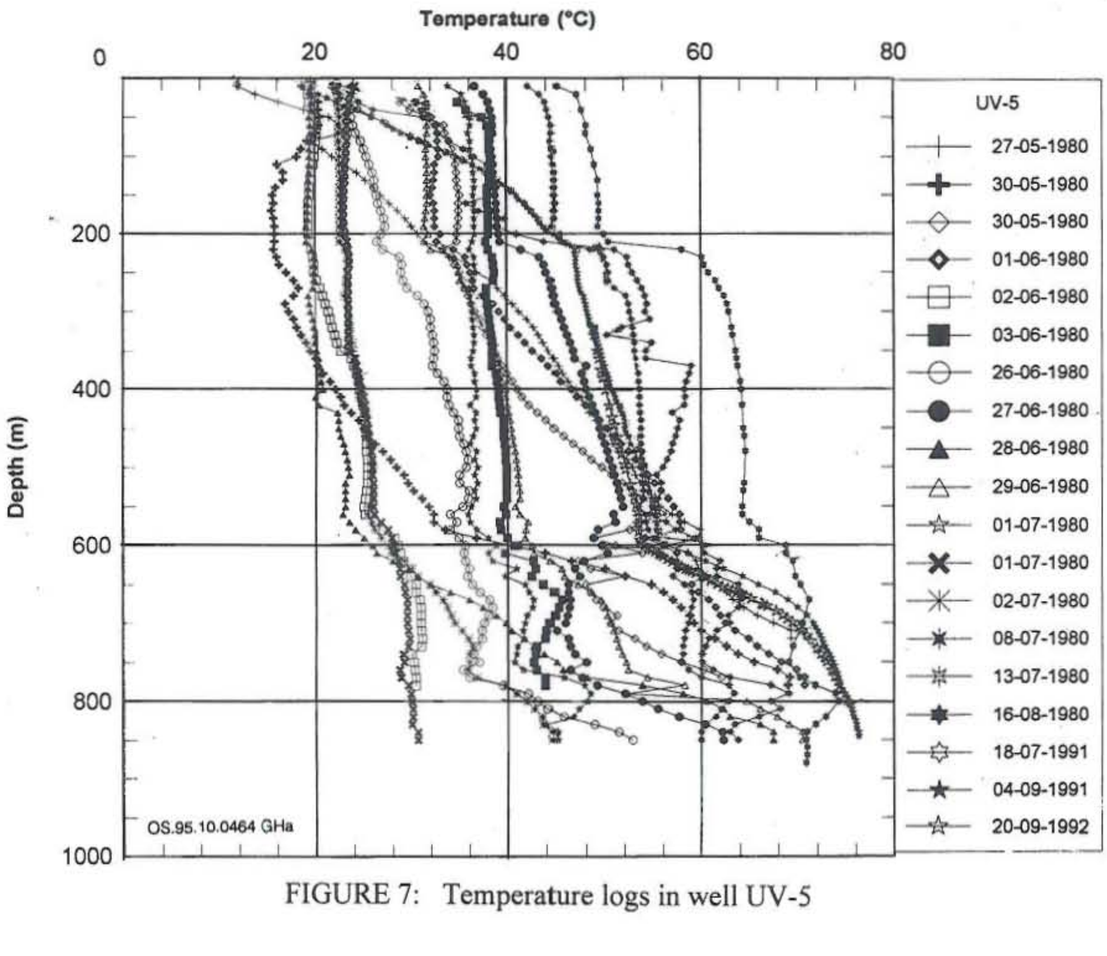

FIGURE 7: Temperature logs in well UV-5

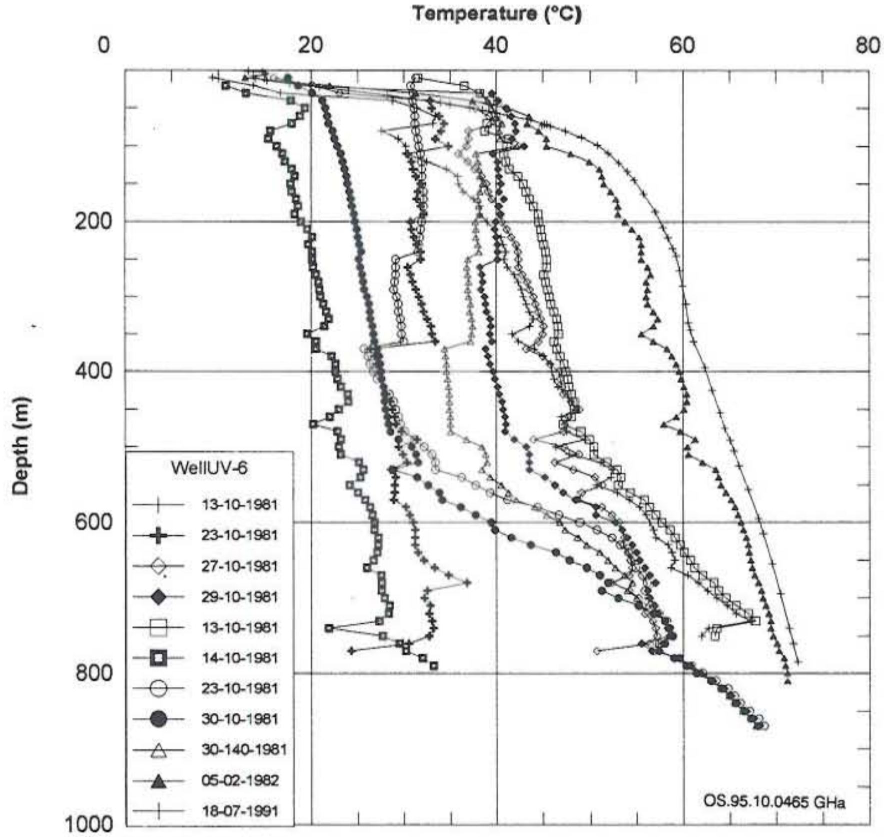

FIGURE 8: Temperature logs in well UV-6

UV-6 The temperature log performed on 18-07-1991 is assumed to be close to the formation temperature (see Figure 8). It was carried out 10 years after drilling. No cooling seems to have occurred during this period.

UV-7 The temperature log carried out on 18-07-1991 is assumed to be the formation temperature (see Figure 9).

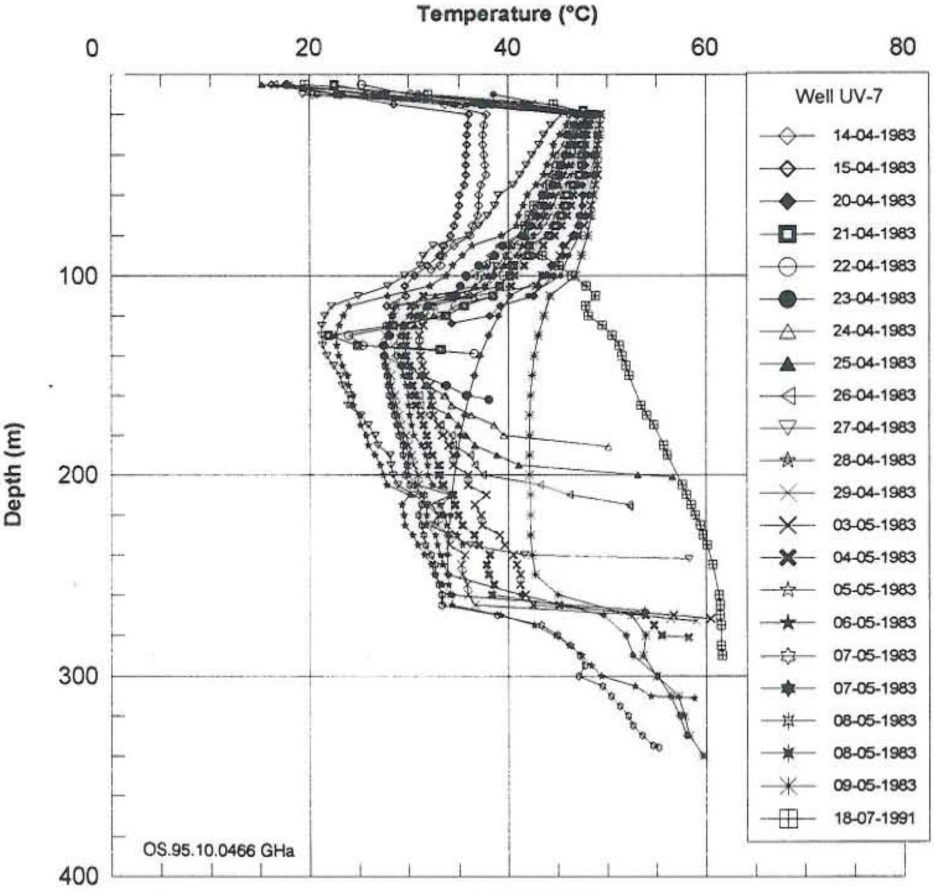

FIGURE 9: Temperature logs in well UV-7

UV-8 The formation temperature profile is based on the bottom hole temperature at 1000 m depth measured on 23-11-1983, at 750 m measured on 28-10-1983, the segment from 320 to 380 m from the log measured on 04-10-1983 and the segment from 15 to 20 m measured on 14-09-1983 and 04-10-1983 (see Figure 10).

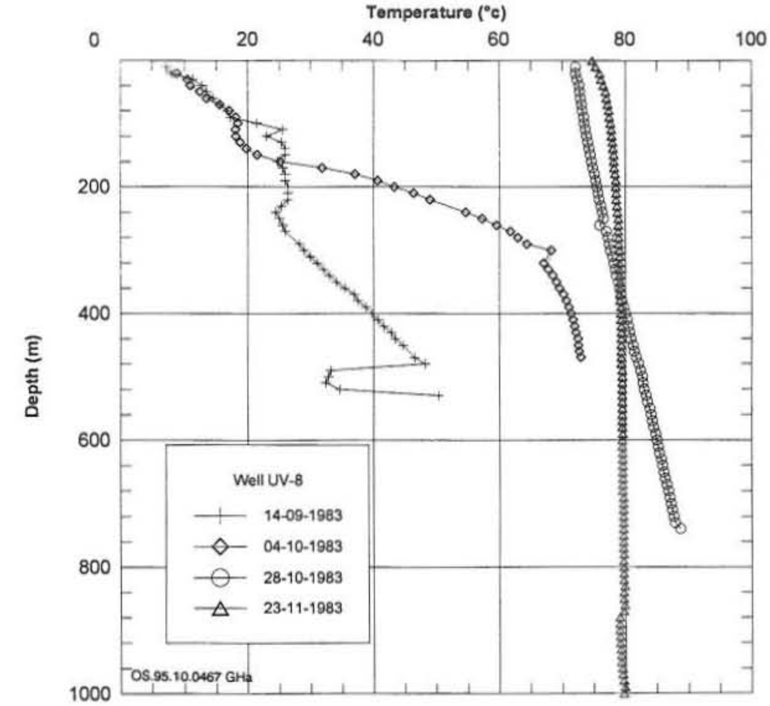

FIGURE 10: Temperature logs in UV-8

The formation temperature is plotted on two cross-sections, one E-W and the other N-S (Figure 11). Furthermore, four iso-temperature maps were drawn, at 100, 300, 500 and 800 m depth (see Figure 12). These figures show a temperature anomaly near well UV-8 with the maximum temperature of 88.5°C at 800 m depth. The temperature anomaly is believed to be due to a near-vertical fracture, which was identified by head-on resistivity profiling and intersected by well UV-8 at about 800 m depth. It is possible that the near-vertical fracture tilts toward well UV-5. The temperature distribution below 700 m depth gives a weak indication of this. At 800 m depth, the temperature is about 75°C in well UV-5, 73°C in well UV-6, 71°C in well UV-3 and 69°C in well UV-4.

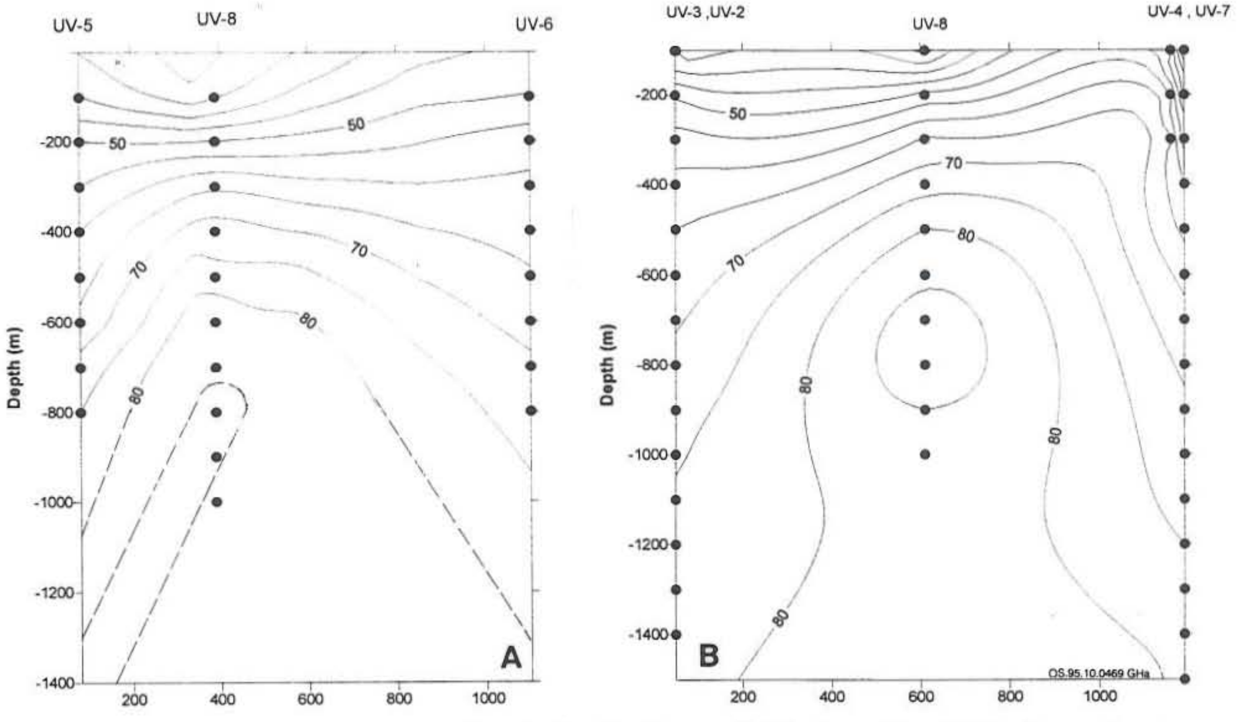

FIGURE 11: Temperature cross-sections in the Urridavatn field, a) trending W-E; b) trending S-N

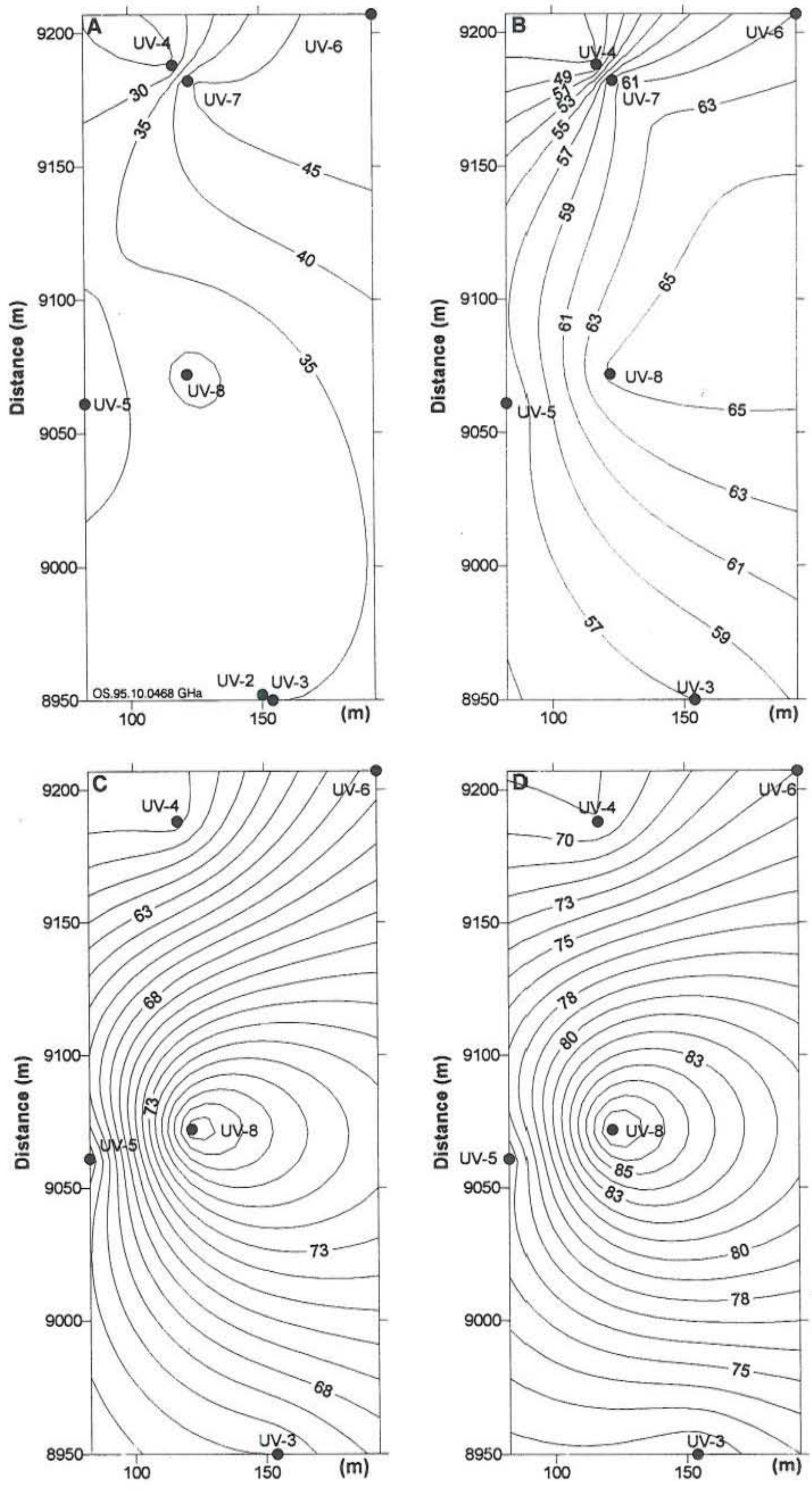

FIGURE 12: Iso-temperature maps of the Urridavatn field, at the depth of a) 100 m; b) 300 m; c) 500 m; d) 800 m

3.4 Bottom hole temperature (BHT) measurements during drilling

The bottom hole temperatures measured during drilling in the wells are listed in Table 2. The most reliable measurements are those in well UV-7. This well was core drilled, drilling stopped overnight, and the temperature logged each morning. Figure 13a shows the bottom hole temperatures and the formation temperature profiles for wells UV-3, 4, 7, and 8 in the S-N cross-section (Figure 11) who are on both sides of dyke B (Figure 2). Figure 13b shows the same for wells UV-5, 6, and 8 which are in the W-E cross-section. All bottom hole temperatures for well UV-4 are close to the formation temperature. The bottom hole temperature at 796 and 1022 m depth were measured 2 days after drilling reached that depth, while the last one at 1580 m depth was measured about one year later. The bottom hole temperature of well UV-3 at 110, 243, 1150, and at 1450 m are also close to the formation temperature, while those measured at 240, 243, 500, 660,

TABLE 2: Results of measurements of bottom hole temperature (BHT) in the Urridavatn wells

Well No.	Depth (m)	BHT (°C)	Conditions before logging
UV-3	110	28.6	3-hour circulation, logged after one day warm-up
	243	46.2	After 8 day warm-up
	500	37	3-hour circulation, logged after 4 hour warm-up
	660	44.2	0.5-hour circulation, logged after 4.5 hours
	910	50.0	5.5-hour circulation, logged after 7 hours
	980	77.3	---
	1150	74.7	3.5-hour circulation, logged after 3 days
	1450	78.3	1 year after end of drilling
UV-4	796	69.0	4 days after drilling stopped
	1022	72.2	2 days after drilling stopped
	1580	78.8	10.5 months after end of drilling
UV-5	720	69.3	4 hours after drilling stopped
	780	69.0	40 minutes after airlifting
	850	52.9	2-hour circulation, logged after 14 hours
	880	70.9	38 days after end of drilling
UV-6	750	62.0	4 days after drilling stopped
	790	33.2	6-hour circulation, logged after 20 hours
	870	68.7	8 hours after end of drilling
UV-7	58	44.8	After a night´s stop
	83	28.2	After a night´s stop
	97	32.3	After a night´s stop
	115	27.8	After a night´s stop
	124	34.2	After a night´s stop
	137	33.2	After a night´s stop
	139	36.5	After a night´s stop
	162	38	After a night´s stop
	186	50.1	After a night´s stop
	201	56.6	---
	216	52.3	After a night´s stop
	242	58.3	After a night´s stop
	268	53.8	After a night´s stop
	273	69	After a night´s stop
	281	58.2	---
	294	54.3	1 day after drilling stopped
	311	58.8	0.5-hour circulation, logged after 4.5 hours
	336	55.2	---
	340	59.7	---
UV-8	530	50.3	---
	740	88.7	---
	1000	79.8	---

and 910 m are much lower than the formation temperature, being measured right after circulation was stopped (see Table 2). While the bottom hole temperature at 58 m depth in well UV-7 shows temperature close to the formation temperature, all the other bottom hole temperature measurements in that well show a variation around the average formation temperature of the other wells. It is obvious that the bottom hole temperatures below 225 m depth are much closer to the formation temperature, than those above this depth.

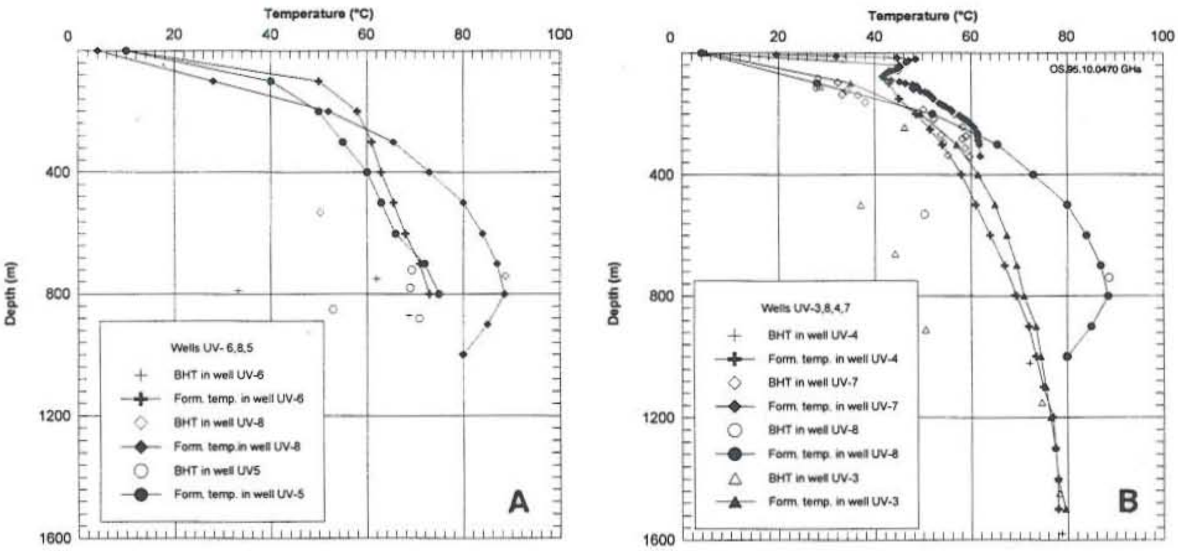

FIGURE 13: Bottom hole temperatures (BHT) and formation temperatures in a) wells UV-5, UV-6 and UV-8; b) UV-3, UV-4, UV-7 and UV-8

In general it may be concluded that the bottom hole temperature is always lower than the static formation temperature. How much lower, depends on borehole conditions, circulation time, the properties of the drilling mud and how much time has elapsed at the time of measurement since drilling stopped.

3.5 Flow patterns in the Urridavatn geothermal system

The temperature cross-sections (see Figure 11) show a near-vertical up-flow close to well UV-8, which the well intersects at 800 m depth. It is possible that this fracture, which is believed to conduit the hot water from below, tilts towards well UV-5. Close to the surface an E-W horizontal flow of hot water is obvious. In addition the reservoir is linked to the lake by dykes and faults. Because of the formation pressure decline after the production started cold water from the lake now flows down into the reservoir.

The formation temperature profiles (see Figure 13) also show a slight temperature inversions in well UV-8 at 800 m depth and close to the surface in wells UV-4 and 7, which indicate a hotter permeable layer. If the formation temperature suggested for well UV-4 is reliable, then it is obvious that the formation temperature in that well is lower than in wells UV-6 and 7, except at the surface. The comparison between formation temperature in these three wells shows a temperature anomaly close to the surface in wells UV-4 and 7. From 100 m down to 340 m depth in wells UV-6 and 7, the temperature is very similar, while well UV-4 is about 5-10°C colder. Well UV-4 is in general a little bit colder than the others down to 1000 m depth.

In well UV-5 a cooling of 3°C in one year occurred, possibly because of down-flow of colder water from the aquifer at 220 m depth to the one at 560-620 m and some of it to the lower aquifer at 720-800 m depth. There is a connection between well UV-5 and 8, according to the tracer injection test, done in this well (Axelsson et al., 1995). The available temperature logs do not allow an exact interpretation of the cooling mechanism in the geothermal field.

According to the result of the hydrological study, the geothermal reservoir can be divided into two parts. A low-permeability upper part, with a permeability thickness of about 10-11 Dm, extending down to 500 m, and a high-permeability thickness of about 1.1-10 Dm, below 500 m depth (Axelsson, 1987).

3.6 Lithological information from temperature logs

High precision temperature measurements in boreholes may be used to correlate with lithology. Near the liquid-gas interface in petroleum wells, discrepancies of several degrees occur between downhole and uphole logs (Reiter et al., 1980). Conaway and Beck (1977) identified a calcium carbonate layer and thin middlelayers by temperature gradients. Temperature gradients generally increase when other logs indicate that the formation is becoming shaly or clayey. Reiter et al. (1980) showed correlation between gamma-ray and temperature-gradient logs. A gamma-ray increase suggests more shaly (or clayey) formation and correlates with the temperature-gradient logs because of lower thermal conductivity. Generally temperature-gradients log qualitatively correlate best with induction-conductivity logs, because an increase in induction conductivity implies a more shaly formation that will have a lower thermal conductivity and therefore a higher temperature-gradient. As the formation becomes more dense temperature-gradients decrease, which permits correlation with the gamma-gamma log.

In the following a method will be proposed, whereby lithological information may be extracted from temperature logs. It is based on studying the change of temperature versus depth under different conditions. The temperature profile in a well is recorded at various times under different conditions. By plotting several temperature logs on the same figure, it is possible to distinguish parts of the borehole with uniform temperature behaviour.

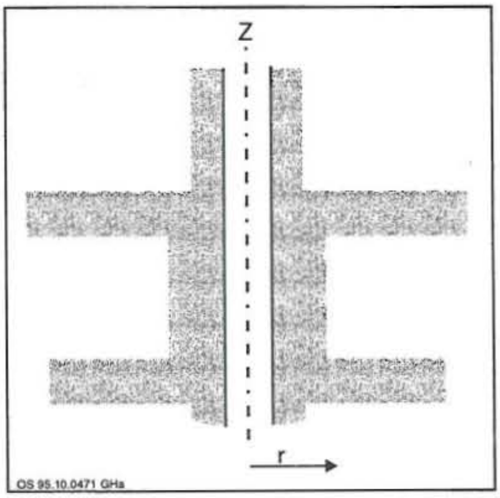

FIGURE 14: A schematic figure showing cooling (shaded area) around a well after drilling (Alm, 1985)

Heat transfer by conduction is always present in the wells. If a permeable layer or fracture is intersected by the well, heat transfer by convection will also take place. The response of a low-permeability layer to temperature change is controlled by conduction through the thermal diffusivity. During drilling or injection, the circulation water causes cooling in the well, if its temperature is less than the static formation temperature. Since the heat transfer by conduction is a slow process compared to convection, a much smaller volume of an impermeable zone is cooled down compared with the permeable one during the same amount of time. Figure 14 schematically shows cooling around a well after drilling (Alm, 1985). How large the volume is, that is affected by conductive cooling in an impermeable layer, depends on the circulation time, while in a permeable layer the volume depends also on pressure conditions, permeability and porosity of the formation (Dresser Atlas, 1982). If there is no fluid movement either in the well or in the formation, the time it takes to achieve the static formation temperature depends on the volume which has been affected. The temperature of impermeable zones will reach the formation temperature much faster than in permeable zones, because the cooling volume is much smaller than for the permeable ones. Temperature logs recorded at different times will be parallel to each other since the whole impermeable interval should be cooled and heated the same. This will be called parallel shift. If there is an inflow in the well, the recovery time may be quite variable, depending on the pressures in the layers. Temperature logs recorded at different times will be non-uniformly displaced (not parallel shift). Therefore, when temperature logs are run, time is of great importance for the interpretation.

In the Urridavatn geothermal field temperature logs have been carried out under different conditions, over a long period of time. To simplify the analyses, logs from each well are divided into three groups, including logs measured during warm-up, after airlifting, and after injection. The logs from each group are plotted on separate figures. Consequently, depending on the response of the formation, it can be divided into different units, called temperature units (Figure 15c):

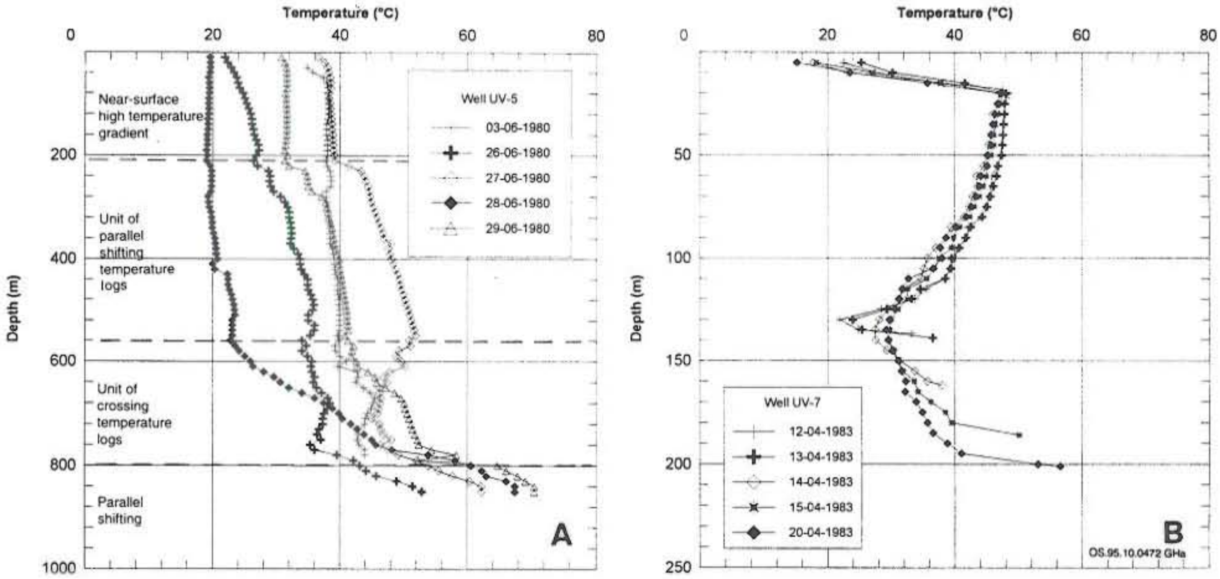

FIGURE 15: a) Different temperature units in well UV-5; b) crossing behaviour of temperature logs in well UV-7

1. Parallel shifting: This is the dominant behaviour of the logs at impermeable layers (Figure 15a);
2. Crossing units: These are segments where two or more of the logs cross each other at certain depths. Some intervals in the logs are characterized by several crosses in front of permeable layers and lithological boundaries. Figure 15b shows the location where three curves or more cross each other at the same depth, i.e. at 124, 134 and 149 m depth. By correlation with the lithology, these locations show a boundary between fresh and altered basalt, a thin layer of scoria and a dyke boundary, respectively. Figure 9 shows a lot of crosses at about 100-115 and 260-265 m depth, which seem to correspond to the boundary of impermeable dense formations. The log carried out eight years later crosses at 100 m depth;
3. High-gradient unit: A typical high-gradient unit is observed close to the surface. The highest values of the near-surface temperature gradients are found above the geothermal systems (Flóvenz and Saemundsson, 1993);
4. In addition to the above units, one log sometimes shows high-temperature anomalies, e.g. after airlifting, while another one shows low-temperature anomalies at the same depth, e.g. after injection. This is called opposite behaviour.

The Urridavatn geothermal system can be divided into four units as shown in Figure 15a.

Unit 1 Characterized by the near-surface high temperature gradient, it reaches down to 200 m depth in well UV-7, and down to about 320 m in UV-8.

Unit 2 Mainly characterized by parallel shifting behaviour of the temperature logs. This unit can be subdivided into two parts, upper and lower. It extends down to 410, 560, and 470 m in wells UV-3, 5 and 6, respectively.

Unit 3 Mainly characterized by a crossing behaviour of the temperature logs, extending down to 620, 800, and 760 m depth in wells UV-3, 5 and 6, respectively.

Unit 4 Mainly characterized by parallel shifting of the temperature logs, as seen in wells UV-3 and 5.

In well UV-6, from 760 m depth down to the bottom of the hole, the temperature logs, carried out on 28-30 October 1981 after injection with a packer at 281 m depth, after airlifting and after injection with a packer at 427 m depth, respectively, are overlapped. There are two explanations possible. Firstly this part is not affected by the injection and airlifting, i.e. it is below the lowest aquifer. Secondly the recovery time, in this segment is very short. If the second explanation is reliable, it would mean there is a high heat flow, which indicates the well is very close to a hot permeable zone.

4. LITHOLOGICAL LOGS

4.1 General

Lithological logs are acquired to aid in subsurface geologic correlation and lithologic studies in wells in a geothermal field. The classification of a geothermal reservoir according to the lithological type, sedimentary, metamorphic, igneous (crystalline and glassy), volcanic ash and associated sediments, tuff, breccia and hydrothermally altered (Sanyal and Matthews, 1982) determines which combination of tools is to be used. In Iceland the combination caliper, neutron-neutron, gamma-ray, short and long normal resistivity is usually used.

The caliper is used to measure the borehole diameter. It gives information on, porous or permeable layers (presence of mud cake (Dresser Atlas, 1982)), hole volume, estimation of cement volume, location of zones for installing packers for well testing, and location of lithology fractures.

Neutron-neutron tool response can be related to the apparent hydrogen content of the formation, and therefore, it is used for evaluation of porosity, and identification of lithology in correlation with other logs. It can both be used in open and cased boreholes.

Natural gamma-ray measures gamma radiation, from natural radioactive isotopes. Some rocks contain radioactive minerals such as, uranium, thorium, and potassium, which emit natural gamma radiation. Radioactivity in igneous rocks is high in granite, rhyolite, and trachyte. The gamma-ray can be used in any borehole condition to obtain information on, lithology-stratigraphy, and can distinguish rock units based on the contents of the radioactive elements.

Resistivity measurements (short and long normal) send electrical current, into the formation. A receiver electrode measures the response of the formation at a certain distance from the emitter. Generally, an increase in the span (distance between sender and emitter) results in higher depth readings into the formation. The response of the formation depends on porosity, temperature, total dissolved solids (TDS) of the fluid, and electrical conductivity of the matrix.

4.2 Evaluation of the well logs

In the Urridavatn wells, well caliper, short and long normal resistivity, neutron-neutron and gamma-ray logs have been carried out. Based on these the Urridavatn geothermal system can be divided into five lithological units in the uppermost 800 m, with four additional units at deeper levels. The correlation between the wells is based on two well defined layers penetrated by the wells. The first layer can be seen in gamma-ray logs at 260-440 m depth, below this layer the second one, which is a few metres thick, is seen in the resistivity logs. These two layers were traced in wells UV-3, 5 and 6. Table 3 shows the correlation between the wells in the uppermost 800 m based on the well logs. Examples of logs in well UV-3 are shown in Figure 16. The characteristic horizons are emphasized.

There is a very good correlation between wells UV-3, 5, and 6, based on the well logs interpretation, except for a part of the intrusion at 460-510 m depth in well UV-5 and the intrusion in well UV-3 at 680-855 m. It is easy to correlate between the wells down to about 570 m depth, but below it is more difficult. There is no correlation with well UV-8, which is located in between wells UV-3, 5, and 6. The short and long resistivity logs in well UV-8 are different from the other wells, which indicates a lateral lithological disruption around well UV-8. The geological strata in this well is different from the other wells (see Chapter 5.1).

TABLE 3: Correlation between the uppermost 800 m in the wells based on well logs

Well depth (m)	Resistivity (Ωm)	Gamma-ray (API)	Neutron-neutron	Caliper (mm)	Differential temperature
UV-3					
0-260	High (~120), very high at 100-120 and 160-260 m	Mostly ~20	Low	160-200	
260-440	Low-500	~35, characteristic layer	Very low	170 to 380 m, 150 to 440 m	
440-460	High	Low, ~20	High	~ constant	
460-570	Increases with depth from 10 to 300	Decreases with depth, 40 to 20	Very low	Decreases a little, 170-150	
570-670	High (600) at top and bottom, else 50	About 30	Low	150-170	
670-800	Medium (~80)	~30	Low	170-160	
UV-5					
0-260	Casing	20 down to 100 m, 15 to 260 m	Low	230 below casing (180 m)	High values 180-230 m
260-445	Low-500	Average 35, characteristic layer	Very low	~200 to 360 m then ~170	Low negative values
445-560	Top resistive (500), characteristic layer, then increa.20 to 250	~35	Very low	~170	Low negative values
560-640	~40	~30	Low	Cave at 640 m	Big variations
640-800	Low-200	~30	Low	Cave (250) at 745 m	High positive value at 640 & 780-790 m
UV-6					
0-230	Casing	25 at 0-90 m, then 15 to bottom of casing	Low		High values, especially at 100-130 m
230-420	Low-400, slightly decreasing	~35, characteristic layer	Low	Caves (200) at top, 330-360, and 390-420 m	Variable
420-570	At top high/very high faults, then variable	At top 20, ~30 at 450-500 m, then lower	Low	Big cave 470 m	Very high pos. value at 470 m
570-680	20-250	~30	Low	150-170	Close to 0
680-(800)	Variable	~30	Low	Big cave 745 m	Close to 0
UV-8					
0-200	Variable		Low	Variable	
200-500	Mainly low, slightly decreas. with depth		Low		
500-680	~150 at 500-590 m, ~50 down to 680 m		Low		
680-880	Highest value in well		Low		
880-(1000)	Increasing 50 to 250		Low		

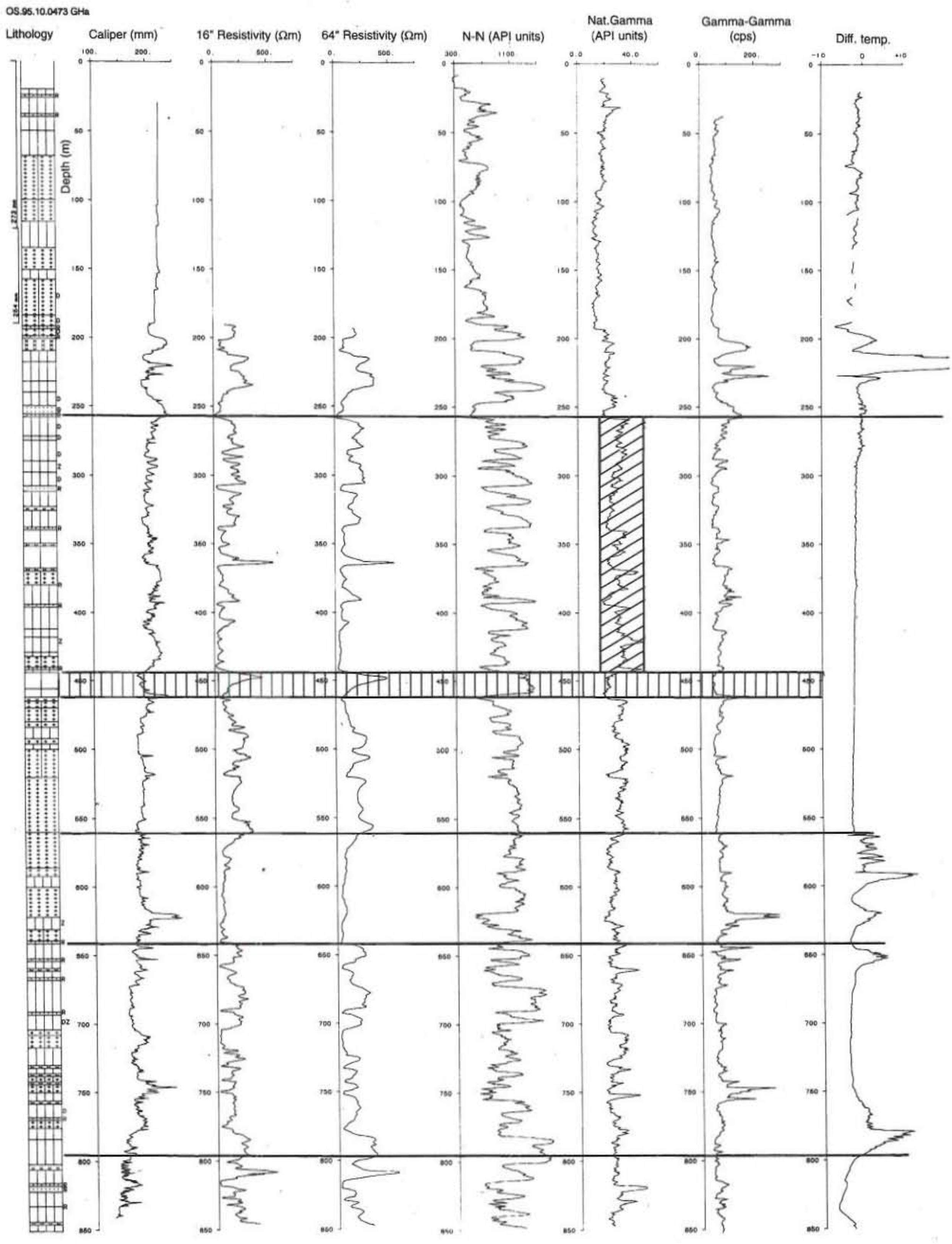

FIGURE 16: Well UV-3 in the Urridavatn geothermal field, stratigraphic column together with caliper, short and long normal resistivity, gamma ray, N-N and differentatial temperature logs (modified after Einarsson et al., 1983)

5. BOREHOLE GEOLOGY

5.1 Well stratigraphy

The geological strata at Urridavatn is a typical Tertiary lava formation with thin middlelayers. The description of the strata, which is intersected by the wells, is based on analysis of cuttings taken every two metres during drilling. The geological strata in the wells have been divided into nine units, according to the dominant rocks (Einarsson et al., 1983). The youngest layers (units) are described first. It often proved very difficult to decide where the exact connection between the geological strata was, though the wells are not far apart. With the aid of well logging this task has become easier. According to the cutting analysis the main alteration minerals indicate a mesolite/scolecite belt above 300 m and the laumontite belt there below. The stratigraphy of well UV-3 is shown in Figure 16.

Unit 1 The thickness of this unit is 130-160 m in the wells. It covers the interval 4-159 m in well UV-3, 12-150 m in UV-4, 20-151 m in UV-5, and 30-132 m in UV-6. This unit consists of altered, fine-grained basalt layers, some porphyritic plagioclase, and medium to coarse-grained and less altered tholeiite basalt layers. There are some red middlelayers. The fresh tholeiite is found almost only in wells UV-5 and 6. A dolerite dyke is intersected by UV-3 at 90 m depth, while a fresh dolerite dyke is intersected by UV-5 at 135-150 m depth.

Unit 2 The unit is 100-110 m thick. It is at 159-271 m in UV-3, 150-256 m in UV-4, 151-258 m in UV-5, and 132-234 m depth in UV-6. The formation is characterized by altered plagioclase- and pyroxene porphyritic basalt and thick sedimentary layers. At the centre of the unit is a 10 m thick sediment layer. At the bottom of this unit there is about a 10 m thick sediment bed in UV-4. Slightly altered olivine grains were found in UV-6. Some layers correlate very well between the wells.

Unit 3 The unit is 75-85 m thick. It is at 271-353 m in UV-3, 256-330 m in UV4, 258-340 m in UV-5, and at 234-320 m depth in UV-6. The unit consists of porphyritic plagioclase, usually fine-grained basalt without middlelayers. At the bottom of this unit is porphyritic basalt. In wells UV-3, 5, and 6 it is especially rich of plagioclase and therefore a good permeable layer. It is very possible that well UV-6 intersects a dyke at 234-257 m depth. In this unit, the correlation between the layers in the wells is good.

Unit 4 The thickness of this unit varies between 125 and 145 m in the wells. It is intersected at 353-480 m in UV-3, 330-460 m in UV-4, 340-484 m in UV-5, and 320-466 m depth in UV-6. The formation mostly consists of medium to coarse-grained basalt, but also a few fine-grained basalt layers, fresh or altered. Sediment beds intercalated the fine-grained basalt. In UV-4 coarse-grained basalt is the most common, a part of it identified as a dolerite dyke, and the altered, fine-grained basalt is missing. A characteristic layer in this unit is a very little altered, fine-grained basalt. It is likely that well UV-4 intersects a 20 m thick fault at 300-400 m depth and UV-3 intersects another 10-15 m fault at 400-450 m depth.

Unit 5 This unit is about 125 m thick. It is at 480-604 m in UV-3, 460-587 m in UV-4, 484-(622) in UV-5, and 466-591 m depth in UV-6. The unit consists of altered, fine-grained basalt with oxidised breccias and red sediment middlelayers. There is altered, coarse-grained olivine tholeiite at 518-531 m in UV-3. Well UV-5 intersected slightly altered dolerite dyke at 520-622 m depth. It also intersects a 10-15 m fault at 450-650 m depth.

Unit 6 The thickness of this unit is 105-110 m. It is intersected by well UV-3 at 604-(682) m, at 587-692 m in UV-4, (622)-704 m in UV-5, and 591-699 m in UV-6. The main substance of this unit is altered, fine-grained basalt intercalated with red scoria and sediment middlelayers. The characteristic layers are two olivine-tholeiite layers, with cavity full of basalt between them, at the top of the unit. At 670-690 m and in the lowest layer in well UV-5 the rock is coarse-grained, while in UV-6 there are totally fresh olivine crystals in olivine tholeiite-layers.

Unit 7 This unit is about 460 m thick. It is at (682)-1184 m in UV-3, 692-1150 m in UV-4, 704-(851) in UV-5 and 699-(877) m in UV-6. It consists of altered, fine-grained basalt layers and altered, coarse-grained tholeiite layers, without substantial middlelayers. Characteristic are two layers of olivine-tholeiite at the top of this unit. At 820 m depth in well UV-5 and 6 there is a 6 m sediment layer, which is missing in UV-4. Well UV-6 intersects faults at 470 m and 745 m depth, which are filled to some extent with laumontite. While UV-3 intersects an altered dolerite dyke at 682-858 m depth, UV-4 intersects a thick quite altered dolerite dyke at 850-936 m depth. In the center of the dyke there is a 20 m thick part where the rock is fine-grained with very strange texture.

Unit 8 The thickness of this unit is about 105 m. It is at 1184-1290 m in UV-3 and at 1151-1258 m depth in UV-4. It consists of porphyritic plagioclase basalt, which contains a lot of cavity fillings. There are middlelayers of oxidized scoria. At the bottom of the wells there is a 20 m thick hyaloclastite sediment, which is more altered in UV-3 and contains a lot of basalt fragments.

Unit 9 This formation is at least 340 m thick. It is at 1290-(1454) m depth in UV-3, and at 1258-1594 m depth in UV-4. It mostly consists of altered, fine-grained basalt layers with oxidized scoria and filled cavities, and less altered, medium to coarse-grained basalt, often porphyritic plagioclase. The correlation between the layers in this unit is not possible. There is an altered hyaloclastite sediment in the last four metres in well UV-4, while the last 22 m of well UV-3 are in an altered dolerite dyke.

The geological strata in well UV-8 appears to be different from the other wells. Even though it is situated in between them. Down to 200 m depth is altered, fine-grained basalt and fresh, medium to coarse-grained basalt with only one layer of scoria and one layer of sediment. At 200-500 m depth altered, fine-grained basalt is dominant with fresh, medium to coarse-grained basalt, and middlelayers include scoria and sediments. The rock at 500-695 m depth consists of altered, fine-grained basalt and fresh, medium to coarse-grained basalt with two layers of sediments. From 695-850 m depth is a dolerite intrusion (dyke) with a layer of altered, fine-grained basalt. From 850-(1000) m depth the rocks are mainly altered, fine-grained basalt with fresh, medium to coarse-grained basalt, dolerite intrusion, and middlelayers of scoria. The geological strata in well UV-8 is totally different from the strata in the other wells as regards the distribution of the middlelayers, but down to 850 m depth no noticeable middlelayers exist. Below 850 m depth there appear a lot of middlelayers of scoria. The altered, fine-grained basalt in well UV-8 is much thicker than in the other wells.

5.2 Dykes and faults

The geological formation in Urridavatn can be divided into two main types, Tertiary basaltic lava flows and basaltic dykes. According to geological and geophysical survey of the area, reported by Einarsson et al. (1982), there are several dykes and faults running through the area and the lake appears to be a part of a graben, see Figure 2. Three dykes, marked A, B, and C, on Figure 2, are running N-S along lake Urridavatn, and the inclination of the dykes is generally 6° to the east from vertical. Two of them, dykes A and B, controlled the upflow of hot water into the bottom of the lake before production started.

6. DISCUSSION AND CONCLUSIONS

The main result of this study may be summarized as follows:

The temperature distribution in the Urridavatn geothermal system shows a temperature anomaly, which is intersected by well UV-8 at 800 m depth. This seems to be a near-vertical hot water flow. This is also believed to be characterized by the low-resistivity structure which was identified by head-on resistivity measurements. The temperature distribution below 700 m depth indicates a higher temperature in well UV-5 than in the other wells, by about 3-6°C. This indicates that the up-flow may tilt towards well UV-5 at deeper levels. Well UV-6 is assumed to lie outside the main reservoir, e.g. on the basis of a hydrological study. Yet the temperature at the bottom of the borehole is very high, which should warrant a future study. A horizontal hot water flow is identified near the surface in wells UV-4 and 7.

A cooling of 3°C in well UV-5 is seen in two temperature logs measured one year apart, possibly because of down flow of colder water from an aquifer at 220 m depth to an aquifer at 560-620 m, and some even to a lower aquifer at 720-800 m depth. This is in agreement with a clear connection between well UV-5 and the production well UV-8, which was established by a test in 1992 (Axelsson, et al., 1995). This may contribute to the cooling of the reservoir in the future. Otherwise, the available temperature logs do not allow an exact interpretation of the cooling mechanism in the geothermal system.

A method is proposed in this report, whereby lithological information may be extracted from temperature logs. It is based on studying the change of temperature versus the depth, under different conditions. By plotting several temperature logs in the same figure, it is possible to divide the borehole into different units, each with uniform temperature behaviour (See Chapter 3.6, and Figure 17).

In the Urridavatn system the near-surface high gradients extend down to 320 m, followed by parallel shifting units, which indicate low-permeability formation. Below this is the crossing unit extending down to 410-570 m, indicating permeable layers and lithological boundaries. This is in good agreement with the results of a hydrological study, which indicates a low permeability down to approximately 500 m depth, with higher permeability below. This is also in good agreement with the results of the borehole geology, which indicate a more dense geological strata in the upper part of the geothermal system. In addition, there is a layer of mesolite-scolecite alteration and a laumontite belt at 300 m depth, at the top of the system, according to the alteration studies.

Geophysical well logs show a good correlation between the wells in the upper part of the geothermal field, some layers may be easily traced. The correlation is not as clear below 570 m depth. A lateral interruption of the horizontal layering appears in well UV-8, which makes it difficult to correlate between this well and the other wells. Figure 17 summarizes the results of the study of temperature logs, lithological logs and borehole geology, and how they are used to correlate the stratigraphy in the wells.

7. RECOMMENDATIONS

1. The temperature distribution in the Urridavatn geothermal field indicates an up-flow intersected by well UV-8 at 800 m depth tilting towards well UV-5. It is therefore recommended to deepen well UV-5 to at least 1500 m in the hope of intersecting the up-flow at greater depth.
2. The high temperature at the bottom of well UV-6, which is considered to lie outside the main reservoir warrants further study.
3. In geothermal systems such as at Lake Urridavatn where the formation consists of Tertiary basaltic units, differing in permeability, the presentation of temperature logs in terms of temperature units may be a useful method to distinguish between permeable and nonpermeable lithological units.

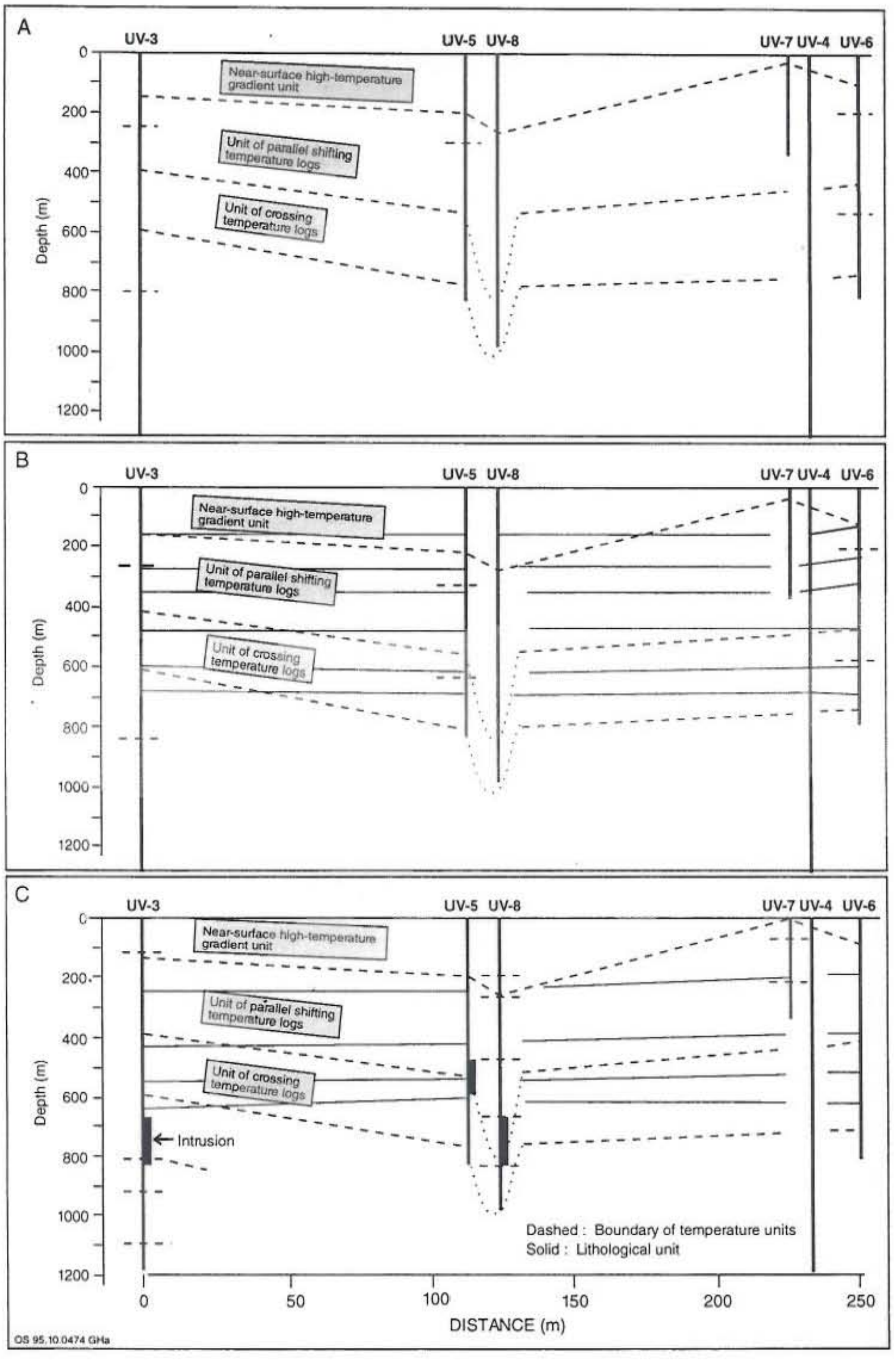

FIGURE 17: The Urridavatn geothermal field, results of the study of temperature and lithological logs and the stratigraphy in the wells, a) temperature units; b) temperature units and lithological well log correlation; c) the same with added information from borehole geology

4. Well UV-5 appears to have cooled down by 3°C because of down-flow of colder water in the well. Because of the connection with the production well UV-8, there is a risk of cooling in well UV-8. It is therefore recommended that the feed-zones at 220 m depth in well UV-5 be cemented or cased off.

5. The apparent interruption of the geological strata around well UV-8 needs further study.

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