Report 4, 1990

INTERPRETATION OF THE TEMPERATURE DATA OF THE ELLIDAÁR GEOTHERMAL FIELD, SW-ICELAND

Klara Bojadgieva,
UNU Geothermal Training Programme,
Orkustofnun - National Energy Authority,
Grensasvegur 9,
108 Reykjavik,
ICELAND

Permanent address:
Enterprise for Geophysical Exploration and Geological Mapping,
Bul. Hr. Kabakchiev 23,
Sofia 1505,
BULGARIA

ABSTRACT

A study of temperature data in the Ellidaár geothermal field is discussed in this report. It is one of the geothermal fields that supplies the city of Reykjavík with hot water. The cooling process taking place in this field is of particular interest. Estimates of the magnitude of the cooling at different depths have been done using a constructed average temperature graph of the initial (undisturbed) temperature, and measured or reconstructed temperature graphs of the present state. Cold water inflow to the aquifers at 600-1200 m depth was established on the basis of temperature distribution maps at different levels and cross-sections. It has a SE-NW direction with the strongest cooling effect at 800 m depth. This conclusion was confirmed by temperature data measured at the wellhead of the production boreholes, provided by Hitaveita Reykjavíkur (Reykjavík District Heating Service).

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

1.1 Scope of the work

Hitaveita Reykjavíkur (Reykjavík District Heating Service) is the biggest district heating system in Iceland and supplies about 60% of all district heating by geothermal water in Iceland. It uses three low temperature areas; the Reykir (Mosfellssveit) geothermal area is about 20 km northeast of Reykjavík, but two are inside the boundaries of the city, the Laugarnes and Ellidaár geothermal areas. These fields have been exploited for 20-50 years. In 1989, 1190 l/s of water with a temperature of 80-90°C were pumped from the Reykir area, 150 l/s of 92°C hot water from the Ellidaár area and 300 l/s of 128°C from the Laugarnes area (data from Hitaveita Reykjavíkur).

In this project, attention is primarily paid to the interpretation of temperature data from the Ellidaár area, where severe cooling has been observed for some years. Production at the Ellidaár field began in 1969 with 105°C water being pumped from it. By 1987 it had cooled considerably, or by 6-21°C (Tómasson, 1988). This is due to an inflow of cold groundwater, both at shallow levels and within the depth interval of 600-1200 m.

The present study of the Ellidaár geothermal field has been carried out on the basis of:

a) temperature measurements in 15 deep wells (up to 2200 m) in the Ellidaár area, recorded during and after the completion of drilling.
b) Hitaveita Reykjavíkur data including wellhead temperature data and production history.
c) additional information from results of spinner measurements and the isotopic composition of the water.

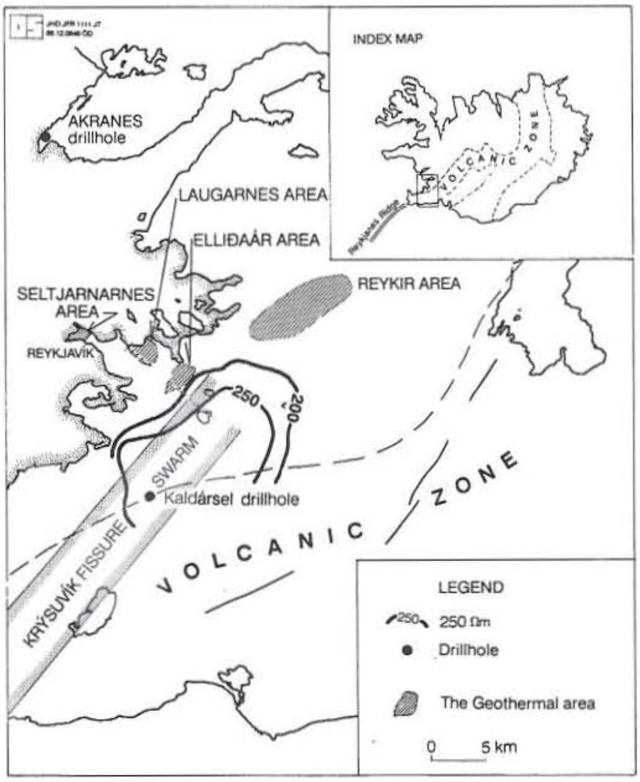


FIGURE 1: The location of the Reykjavík geothermal fields

1.2 Location of the Ellidaár area

The location of the Reykjavík geothermal fields mentioned above is shown in Figure 1. The Ellidaár area (Figure 2) is closest to the Krýsuvík fissure swarm, which is represented by a high resistivity anomaly, caused by a cold groundwater system. According to Georgsson (1985), cold water in the Krýsuvik fissure swarm reaches at least down to 750 m depth and may even reach down to 1000 m depth. These results are confirmed by the temperature graph recorded in the Kaldársel drillhole (Tómasson, 1988). This cold groundwater system in the Krýsuvík fissure swarm is probably the source for cold water inflow into the southeastern part of the Ellidaár geothermal field. The elevation of the area is 25-50 m above sea level.

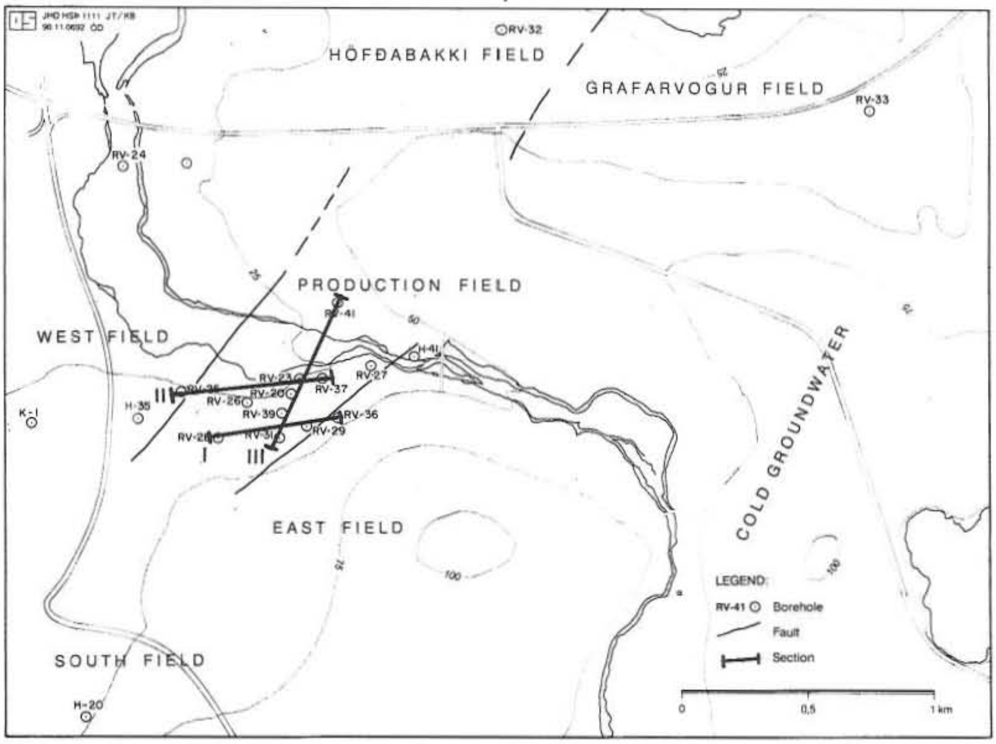


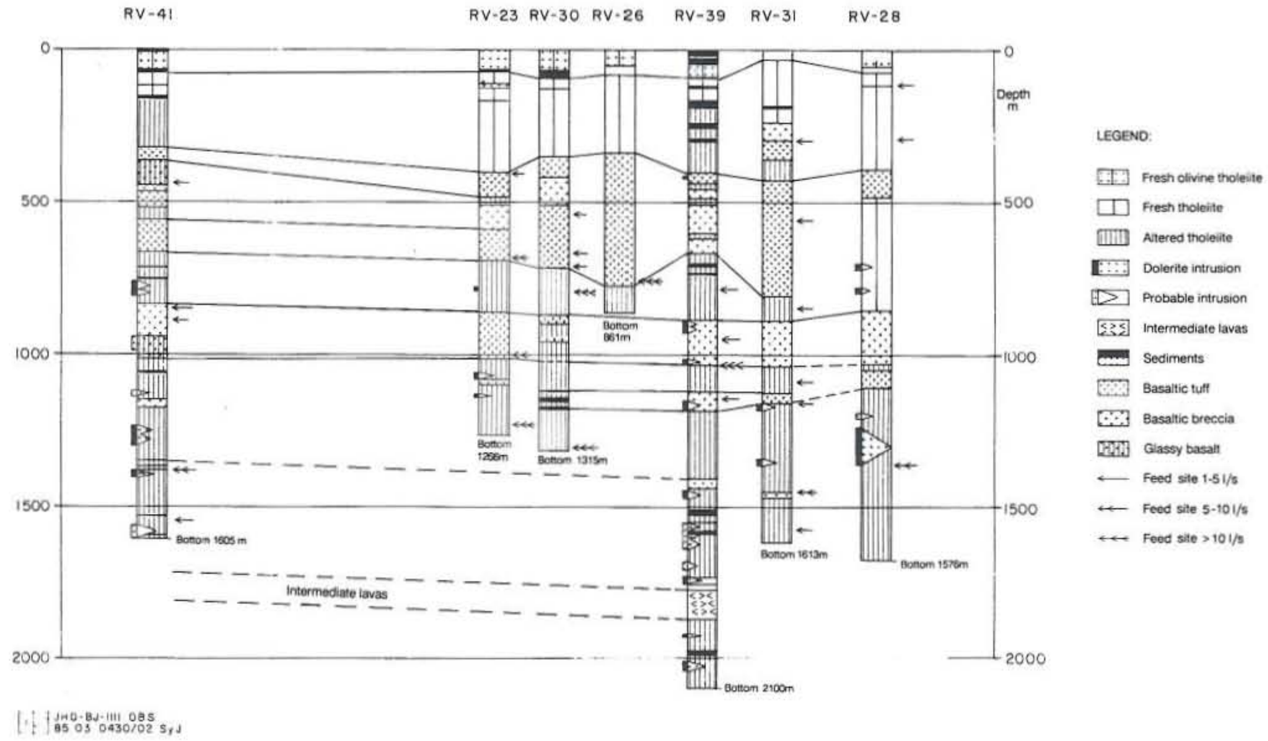
FIGURE 2: The Ellidaár geothermal area, location of wells, cross-sections and sub-fields

1.3 Geology and hydrogeology

Iceland is situated on a constructive plate boundary which crosses through the country and is marked by a zone of volcanic and tectonic activity. This zone is flanked by Quaternary rocks, mainly sequences of subaerial lava flows intercalated by hyaloclastites and morainic horizons at intervals corresponding to glacial conditions. The Quaternary formations are bordered by Tertiary subaerial flood basalts.

The low temperature areas in Iceland are characterized by temperatures lower than 150°C at 1 km depth. They are located in Quaternary and Tertiary strata, mostly in the lowlands and valleys. The strata of the Ellidaár geothermal area is of Quaternary age, about 2.8-1.8 m.y. Faults and fissures, which are part of the Krýsuvik fissure swarm, are prominent in the eastern part of the geothermal area. There are two water systems within the boundaries of the Ellidaár field, the geothermal system and a much bigger cold groundwater system. Above the geothermal field the cold groundwater is about 20 m thick, but reaches down to about 1000 m to the east of the field. There were no warm springs in the production part of the geothermal area prior to drilling, but some were found to the south of the area.

The subsurface geology is divided into three groups (Figure 3). They are the upper basalt series, the hyaloclastite series and the lower basalt series (Tómasson, 1988; 1990). The aquifers are classified in a similar way. The uppermost aquifers (A-aquifers) are found in the uppermost 300-500 m with temperatures in the range of 40-90°C. The geothermal system is hydrogeologically connected to the cold groundwater system in the upper basalt series, which is one of the main reasons for the great cooling with time in the whole area. The middle aquifers (B-aquifers) are confined to the hyaloclastite series with temperatures reaching 100-110°C at the beginning of production in 1968. The lowest aquifers (C-aquifers) are confined to the lower basalt series with temperatures of 70-115°C (Tómasson, 1988). The locations of the feedzones in the wells are shown in Figure 3.



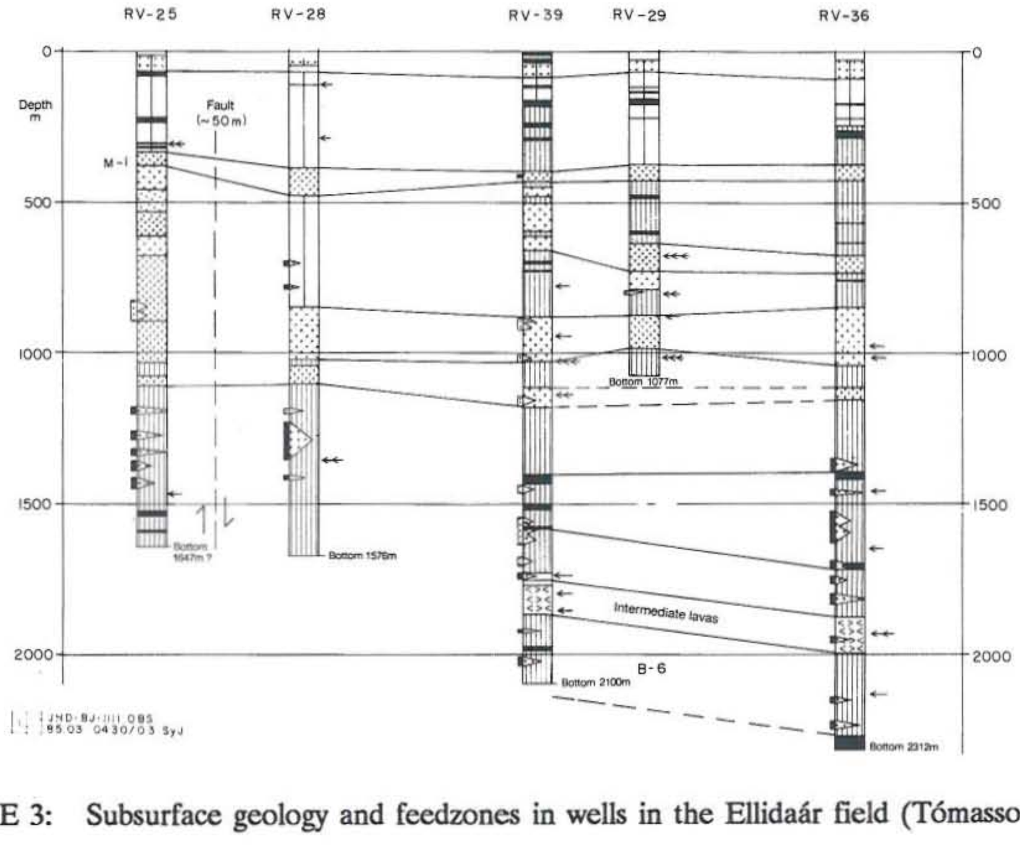


FIGURE 3: Subsurface geology and feedzones in wells in the Ellidaár field (Tómasson, 1988)

1.4 Literary references

Regional conductive heat flow in Iceland is very high and ranges from 80 to 300 mW/m² (Pálmason, 1973). Geothermal gradients measured in deep drillholes in SW-Iceland indicate increasing values towards the volcanic zone from 70°C/km in Tertiary rocks to 165°C/km in early Quaternary rocks. A schematic cross-section through the Reykjavík thermal fields is shown in Figure 4. The three areas are separated by impermeable barriers (Thorsteinsson and Elíasson, 1970). The high temperature gradient in the Ellidaár geothermal area close to the surface (200°C/km) is due to the transport of hot water at depth to the surface. Outside the thermal fields, the geothermal gradient is about 100°C/km (Tómasson et al., 1975).

According to Tómasson (1988) the main conclusions for the origin and thermal state of the Ellidaár geothermal field are:

a) The alteration mineralogy in the Laugarnes and Ellidaár areas indicate that these were originally high temperature fields with temperatures of 200-300°C.
b) The Ellidaár area can be divided into sub-fields, one of which is the present production field (Figure 2).
c) The production field is characterized by a reverse temperature curve. Hot 100-110°C water flows from the north at 400-1200 m depth, mixes with colder 72-85°C local water and thus cools down.
d) The 72-85°C warm water is assumed to come from the Krýsuvík fissure swarm with a circulation path which is less than 10 km, but the hottest water has a circulation path of 40 km or more, according to the isotopic composition of the water (Figure 4).
e) Two origins of cooling are pointed out; direct inflow of cold water into the drillholes, mostly through the A-aquifers, and temperature levelling in the hot water tongue.
f) Two types of thermal mining are taking place; natural thermal mining and mining induced by utilization of the geothermal system, much faster than the former process.

These results are supported by many cross-sections within the geothermal area which are included in the report by Tómasson (1988).

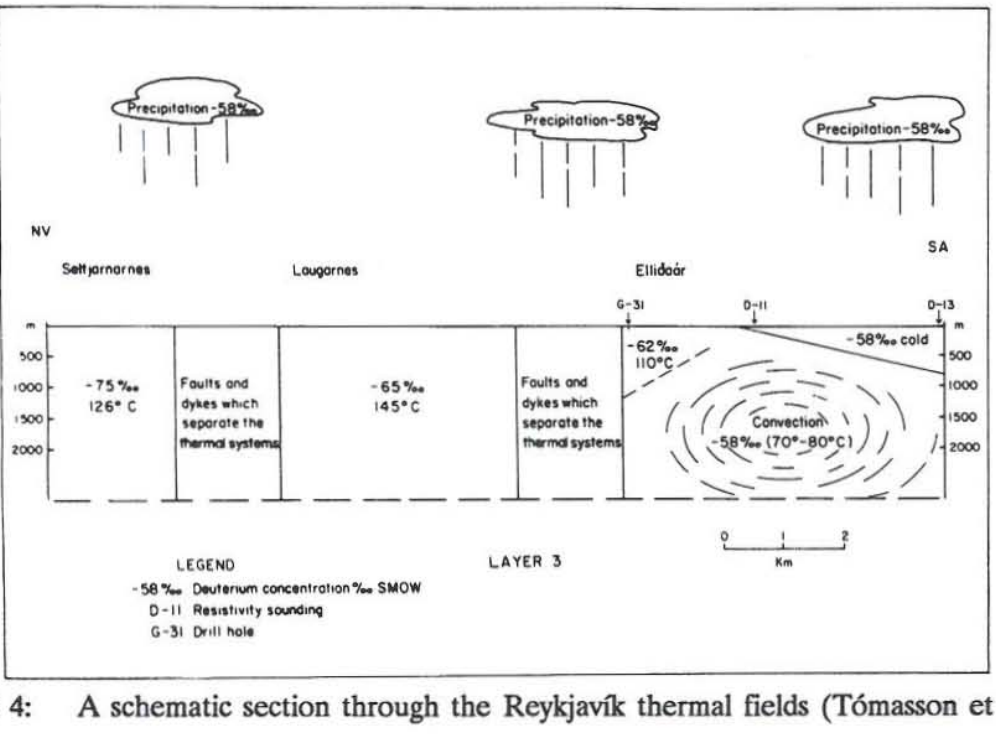


FIGURE 4: A schematic section through the Reykjavík thermal fields (Tómasson et al., 1975)

2. ANALYSIS AND INTERPRETATION OF TEMPERATURE GRAPHS

The problem under consideration is to represent the present and initial temperature states in the Ellidaár geothermal field, with emphasis on the cooling factors that influence it. The data used were recorded during drilling and for the past 20 years in productive and nonproductive wells.

2.1 Temperature measurements and distribution

Altogether, data from 15 deep wells with nearly 150 temperature graphs have been used. The temperature graphs were measured during drilling and the warm-up period and after production started. From existing temperature graphs, those were selected that included representative data for the initial (undisturbed) temperatures, the temperature changes with time and the present state of the geothermal field. The chosen graphs from each well are shown in Figures 5, 6, 7 and 8. For most of wells, the last temperature measurement before completion of drilling was used. It should provide information on the initial bottom hole temperature, which is not much disturbed by the drilling process. However, measurements that do not reach the bottom or give additional information have not been included (wells RV-23, 28, 29 and 33).

The main conclusions from the analysis of the selected temperature curves are as follows:

Representative graphs showing the nature of the Ellidaár field are reverse temperature curves, such as were recorded in wells RV-36 (13.9.1980) and RV-37 (6.5.1981) (Figures 7d and 8a). RV-36 is located to the east of the production field and RV-37 is a production well near the eastern boundary of the field (Figure 2). Both wells were drilled later (1980-1981) than most of the production wells (1968-1969). Cooling as a result of production is not observed in RV-37. The temperature curve in RV-39 from 22.8.1984 (Figure 8b), is similar in character to the ones in RV-36 and RV-37, but is disturbed by vertical upflow. Temperatures measured after the warm-up period for all wells mentioned above, represent the true formation temperatures around the wells. All other temperature graphs are strongly influenced by the internal flow in the wells.

Based on the latest temperature measurement in the wells, the present temperature distribution in the production field is as follows:

1. Temperatures higher than 90 °C are still measured in the production field in wells RV-23, 31, 37 and 39 (in the B-aquifers).
2. Temperatures have dropped below 90°C after nearly 20 years of production in wells RV-26, 29 and 30.

There are two factors causing this cooling:

1. A-aquifers connected to the groundwater system. Cold water flows into the geothermal system, due to a pressure drop in the aquifers. This cooling can be seen in well RV-23 in the depth interval 350-500 m (Figure 5a). It also exists in well RV-26 (Figure 5d), but here a downflow from the A-aquifers causes cooling both in the A-aquifers and below them. No cooling has been observed in well RV-27, which has no A-aquifers (Figure 6a).
2. Cold flow into the B-aquifers, caused by a pressure drop due to production. This can be observed in wells RV-29 and 30 (Figures 6c and d). This inflow has a SE-NW

JHD HSÞ 1111 KB
90.11.0660 T

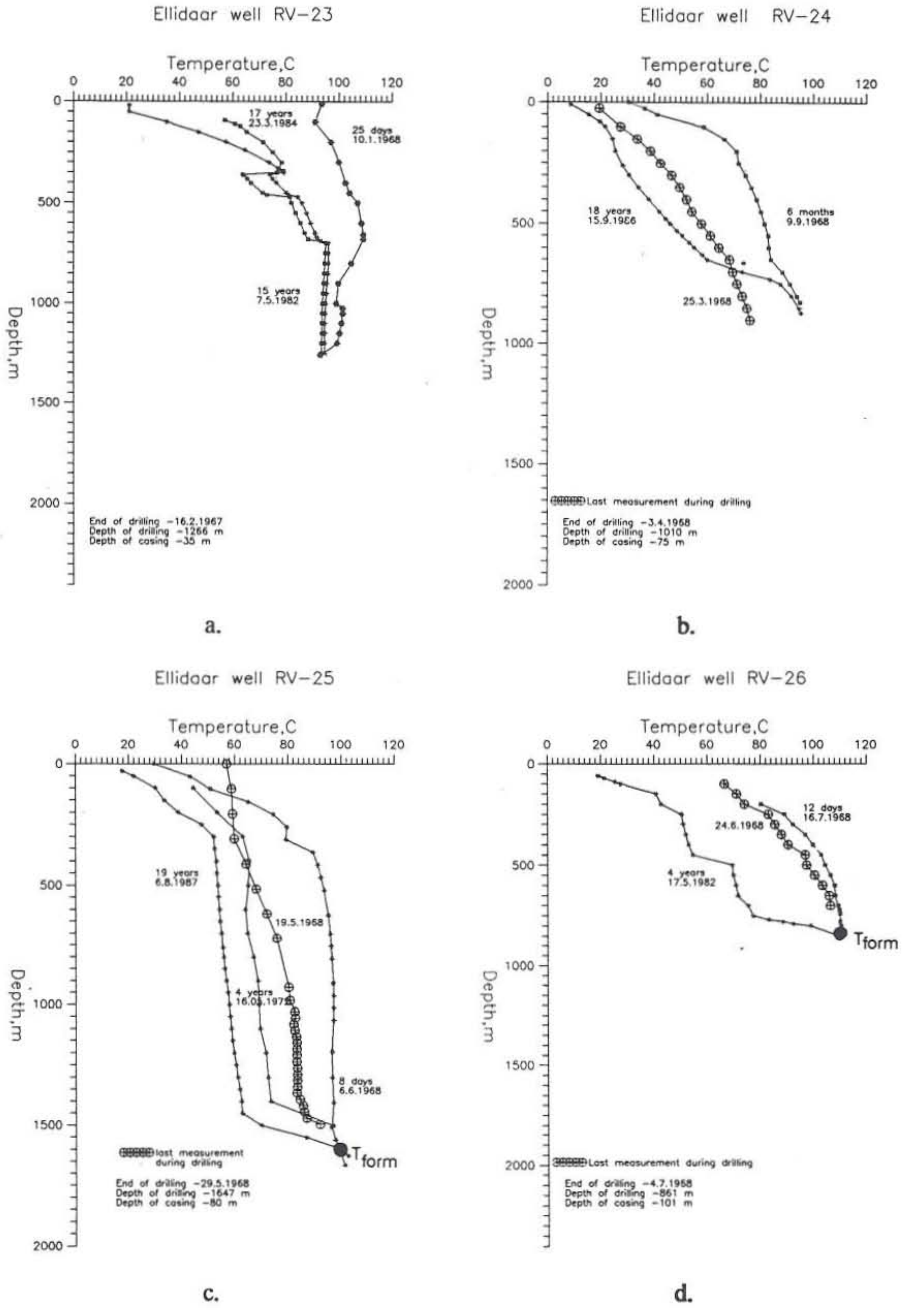


FIGURE 5: Selected temperature graphs from wells RV-23, 24, 25 and 26. Time periods on the graphs are after completion of drilling. T_{form} is the estimated undisturbed formation temperature

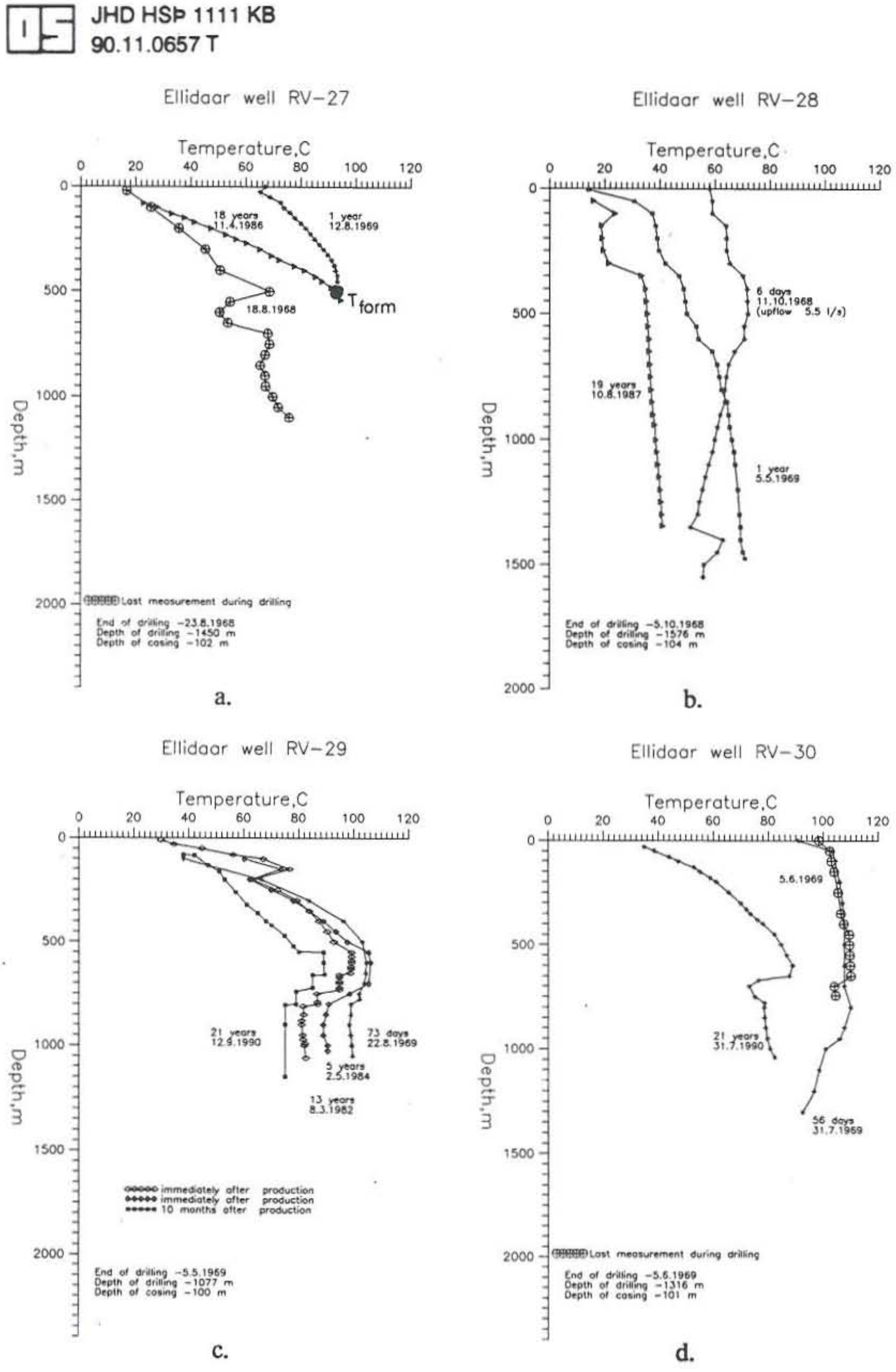


FIGURE 6: Selected temperature graphs in wells RV-27, 28, 29 and 30

JHD HSÞ 1111 KB
90.11.0655 T

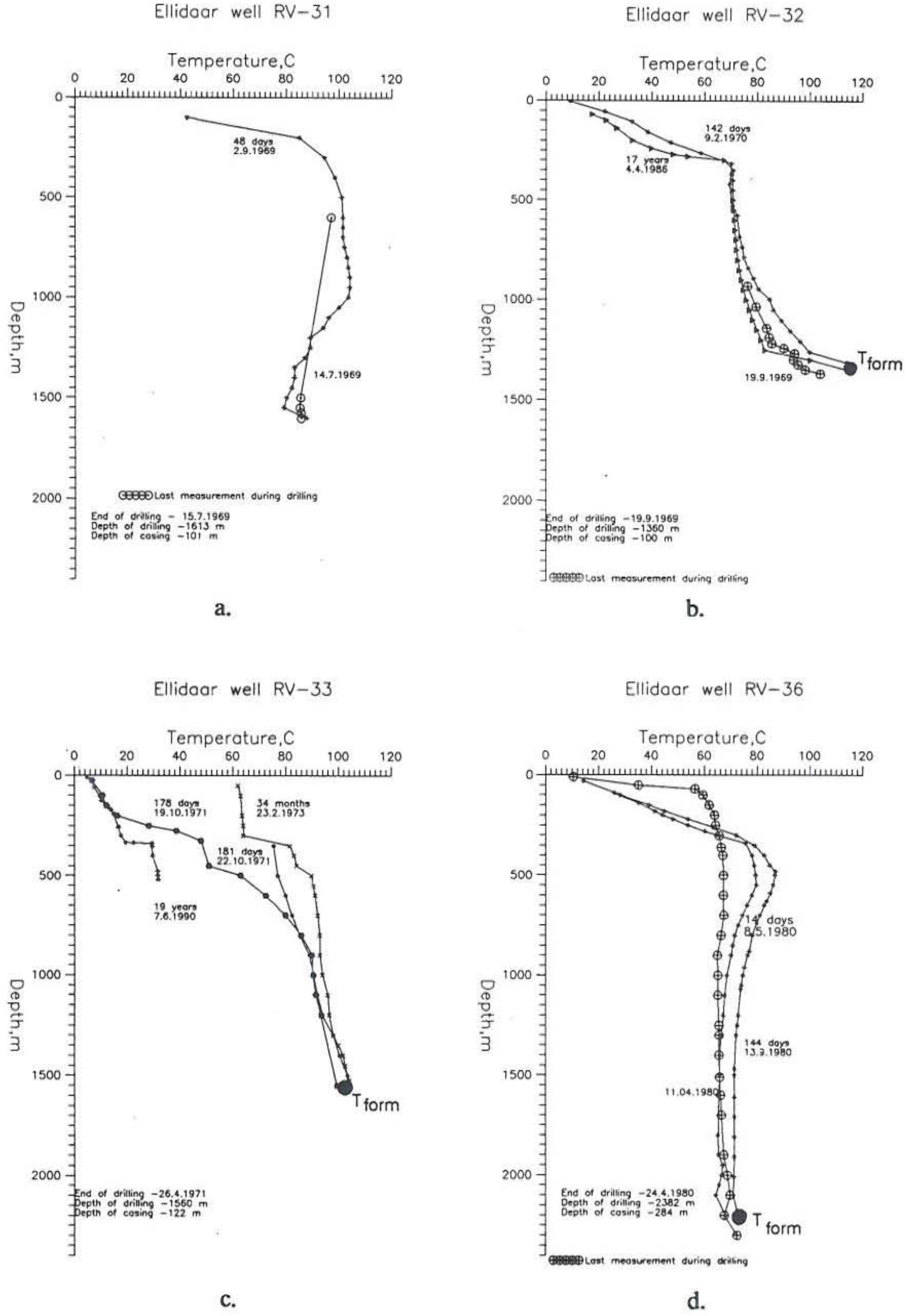


FIGURE 7: Selected temperature graphs in wells RV-31, 32, 33 and 36

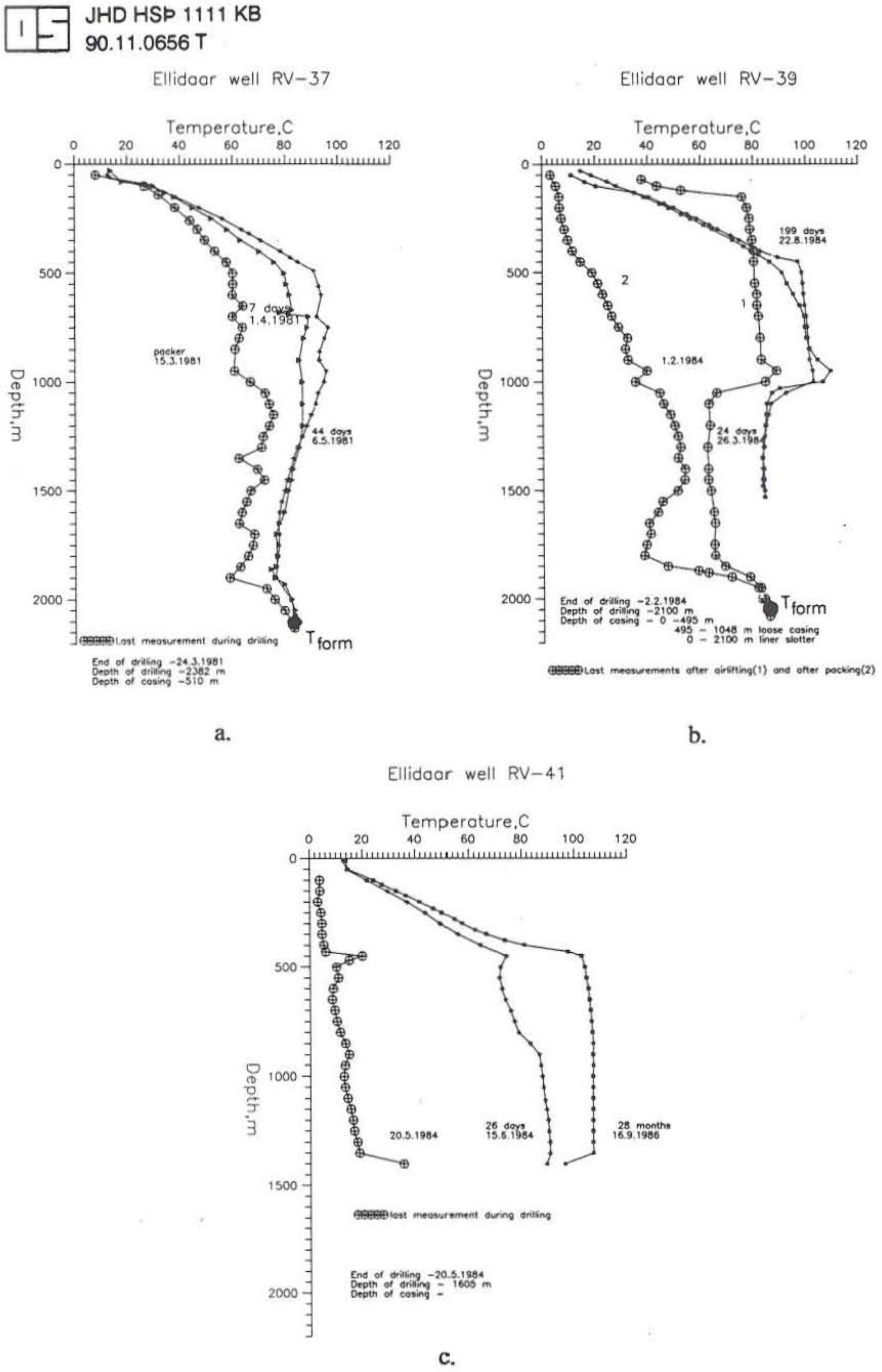


FIGURE 8: Selected temperature graphs in wells RV-37, 39 and 41

direction. It probably originates from the thick cold groundwater system to the east of the field (Krýsuvík fissure swarm). The cold inflow predominantly takes place between 600 and 1200 m, with the strongest influence on temperature at 800 m depth. According to data from circulation losses and gains during the drilling process, high temperatures measured in RV-31, 37 and 39 (Figures 7a, 8a and 8b) are explained by the intake of water mainly from the C-aquifers (Tómasson, 1988). There is no indication of cooling in the C-aquifers. All new graphs, maps and cross-sections included in this report confirm this statement.

Great cooling is observed in wells outside the production part of the field.

1. Well RV-25 is located to the west of the production field. A cooling of 10°C in the depth interval of 300-500 m has occurred over a period of 15 years (1972-1987) because of a downflow in it (Figure 9). The same cooling effect, 30°C in 18 years, is observed in well RV-28 to the southwest of the production field (Figure 9).
2. Well RV-24 (northwest of the production field) has cooled up to 40°C over 18 years (1969-1987) (Figure 10). The magnitude of the drawdown in well RV-24 implies a hydrological barrier between the western field and the production field (Tómasson, 1988).

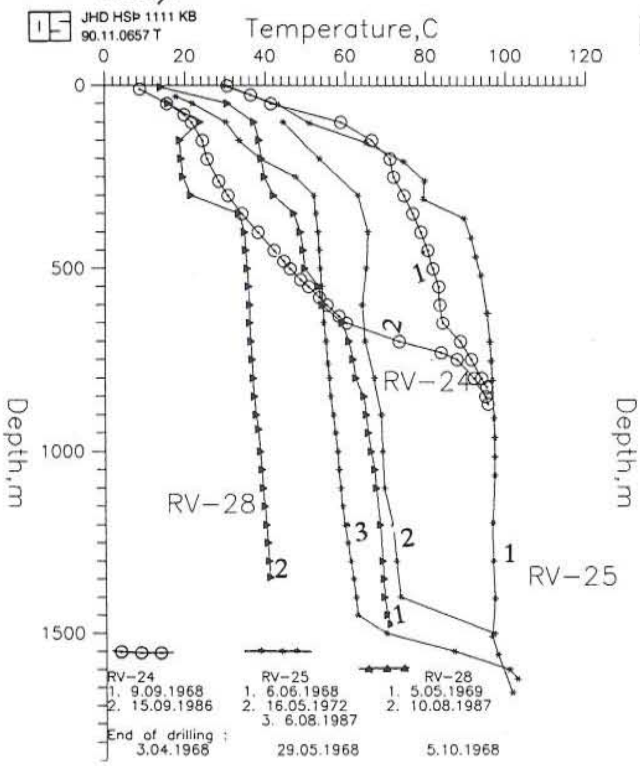


FIGURE 9: Temperature decrease with time in wells RV-24, 25 and 28

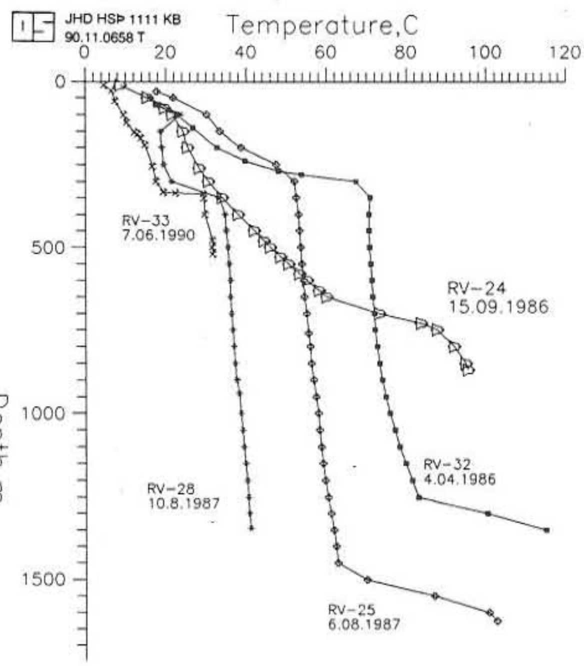


FIGURE 10: Wells affected by cooling, because of downflow from A-aquifers

2.2 Estimation of the initial (undisturbed) temperatures

In order to study the cooling effect, the initial temperature field must be known. To get information on the initial temperature in the Ellidaár geothermal field, all temperature measurements during drilling and the warm-up period have been studied. The wells which were drilled at the beginning of the exploitation of the field have undergone more temperature changes than wells drilled later.

At least one temperature value could be taken as representative of undisturbed (initial) temperature for most of the wells. It is usually the bottomhole temperature of the well. These points show a constant temperature value with time, which means that they could be considered as true formation temperatures. During drilling, the least cooling is at the bottom of a well. These points are indicated on selected graphs with T_{form} (formation temperature).

T_{form} is not defined in some wells because of an internal flow in them, e.g. RV-23, 28 and 29 (Figures 5a, 6b and 6c). For example, a downflow measured in well RV-29 of maximum 7.8 l/s at 804 m depth (Figure 11) masks the formation temperature (Josef Holmjarn, pers. com.) The values in the other three wells RV-30, 31 and 41 (Figures 6d, 7a and 8a) are influenced by the presence of aquifers at the bottom of the wells and T_{form} are not available for them.

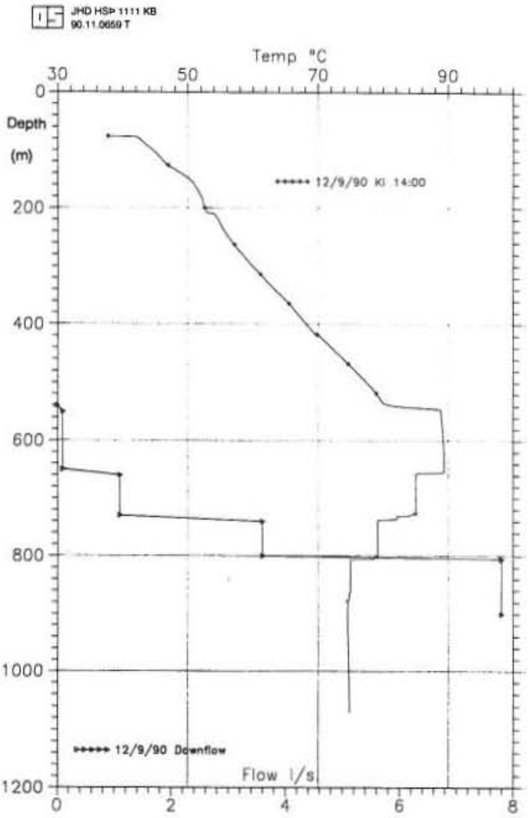


FIGURE 11: Temperature graph in well RV-29 and flow rate based on spinner measurement.

The data for T_{form} from the rest of the wells were plotted on a graph, marked as T_{in} (Figure 12) and represent the estimated average temperatures in the Ellidaár geothermal field. Temperatures from well RV-36 have been used for shallow depths (100, 220 and 350 m) because, as was mentioned earlier, temperatures in wells RV-36, 37 and 39 are close to the undisturbed temperatures, particularly at the upper layers to a depth of 400 m. T_{in} in Figure 12 can be represented by a polynomial approximation with the equation:

$$T=7.88+0.24H-1.67*10^{-4}H^2+3.17*10^{-8}H^3,$$

where T is temperature (°C) and H is depth (m). All temperature curves representing the current state of the field were compared with this polynomial approximation in order to estimate the temperature changes in the area.

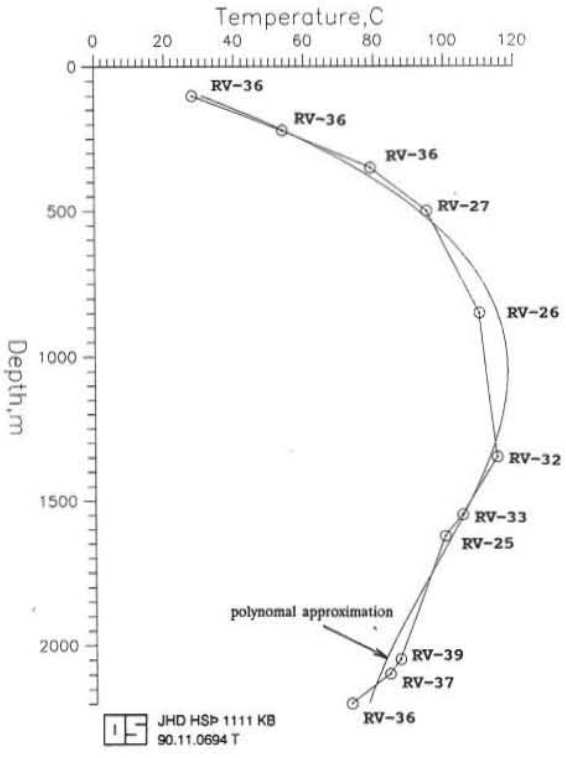


FIGURE 12: Average initial temperature, T_{in}, in the Ellidaár geothermal field

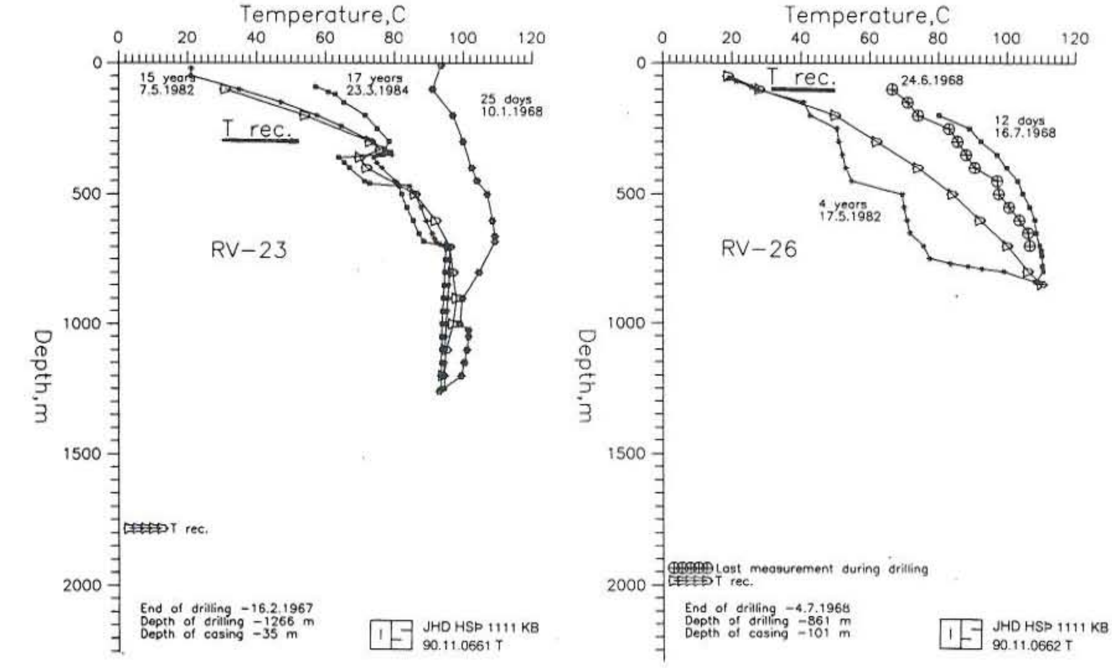


FIGURE 13: Present temperature in wells RV-23 and 26

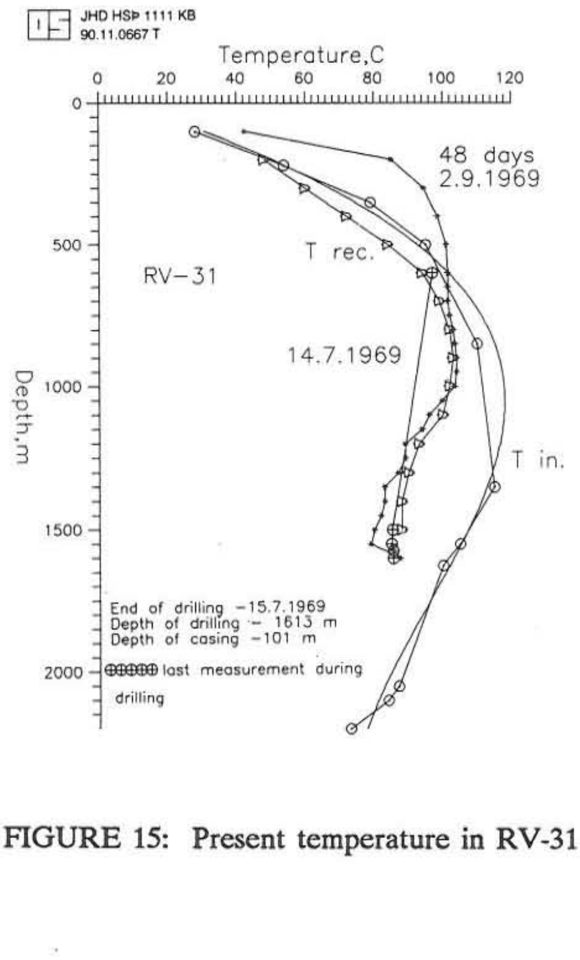


FIGURE 15: Present temperature in RV-31

2.3 Reconstruction of temperature curves

In order to estimate the temperature changes in the field, the present temperature distribution has to be known. Measured temperature profiles in most of the wells in the productive field are not representative for the present distribution of the temperature around the wells, because of internal flow in the wells.

An attempt to remove the effects of these disturbances was made for wells RV-23, 26, 29, 30, 39 and 41 (Figures 13 and 14). All existing temperature measurements in each well were taken into consideration for the reconstruction. The main reference points used were: temperatures in the upper layers where there is a conductive heat flow only, indications of temperature at the feed zones, and T_{form}. RV-31 has not been measured since 1969. An attempt was made to estimate the present temperature in the well (Figure 15). A comparison with T_{in} gave very good information about the upflow in the upper layers. However, the proposed reconstructive graph for RV-31 is not well defined, due to the lack of new temperature measurements.

The effect of water flow along the casing is removed in well RV-39 (Figure 15). The vertical part on the last temperature measurement (22.8.1984), 490-1050 m, is caused by inflow into this well at 1000 m depth, and its movement along the loose casing up to a depth of 500 m.

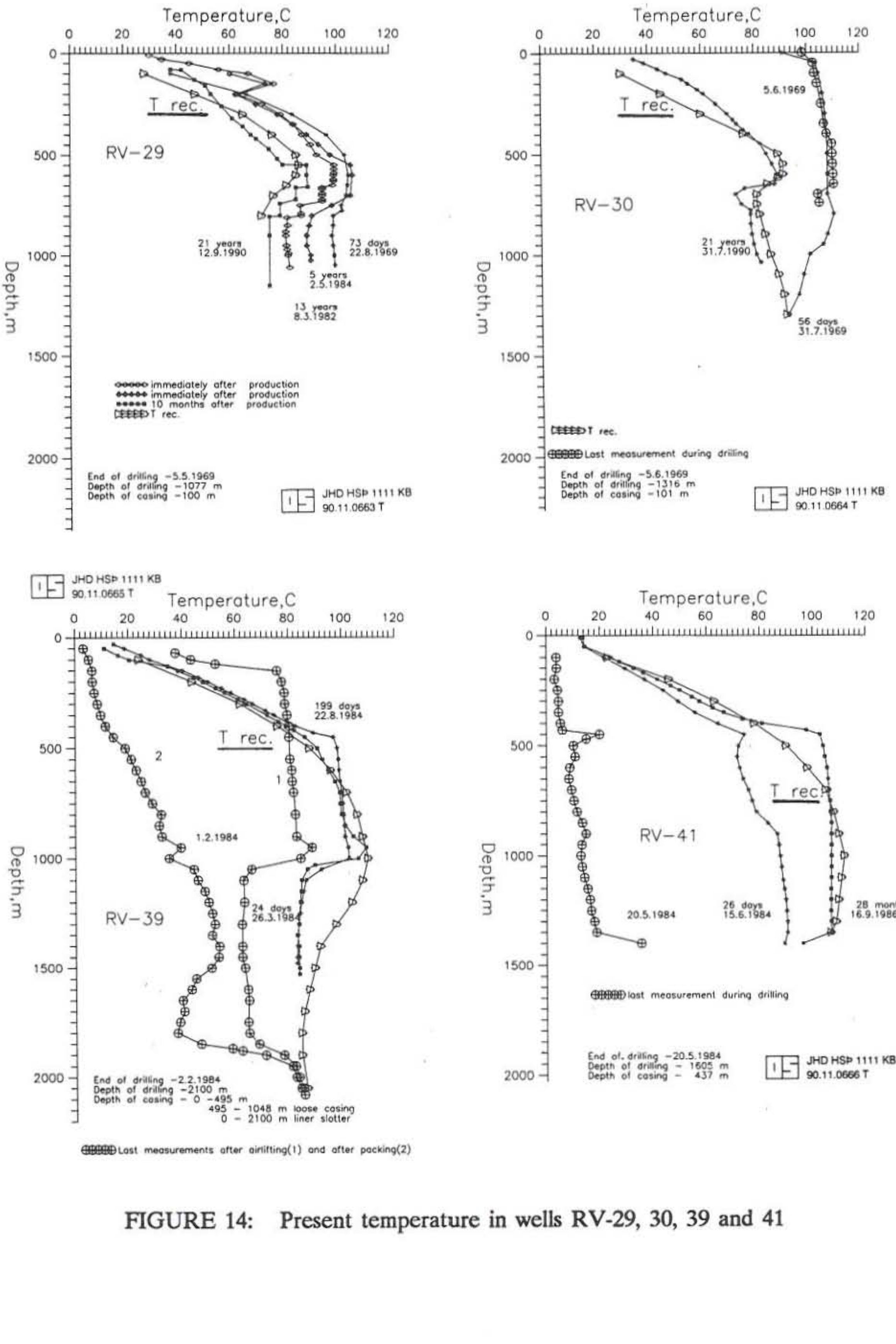


FIGURE 14: Present temperature in wells RV-29, 30, 39 and 41

3. COOLING PROCESSES IN THE GEOTHERMAL FIELD

3.1 Comparison of present and initial temperatures

All graphs showing the present temperatures in the field (Figures 13-15) were subtracted from the graphs showing initial temperatures (Figures 5-9) in order to estimate the cooling in the geothermal field after more than 20 years' production. The differences are plotted in Figure 16. The greatest cooling is observed in the wells outside the production field (RV-28, 25, 32 and 33). The cooling in these wells is caused by continuous downflow from the A-aquifers. Within the production field the greatest cooling is observed in wells RV-29 and RV-30 at 600-1000 m depth. An analysis of the temperature decrease in the Ellidaár field is done separately for the productive and nonproductive parts of the area.

3.1.1 Cooling in the production field

In order to estimate the cooling in the production field, the reconstructed temperature curves were used with the assumption that they show the present state of the geothermal field, and plotted together with the average initital temperature curve (T_{in}) from Figure 12 (Figure 17). Only measured data is used for well RV-37, as no internal flow was indicated there. This comparison shows fairly well the degree and depth penetration of cooling in the production field, as well as the temperature distribution in it. The temperature changes are small at shallow depths (down to 500 m) but increase at deeper levels. The greatest cooling is seen in well RV-29, where it amounts to 40°C at 800 m depth (Figure 18a). Well RV-30 also shows a cooling of 30°C in the depth interval 800-1000 m (Figure 18b). The difference lies in the origin of the water these wells take in. Well RV-29 takes all of its water from the B-aquifers, which have cooled down considerably during production. Well RV-30, on the other hand, takes only 70% of its water from the B-aquifers; the remaining 30% comes from C-aquifers. Cooling has not been observed in the C-aquifers (Tómasson, 1988).

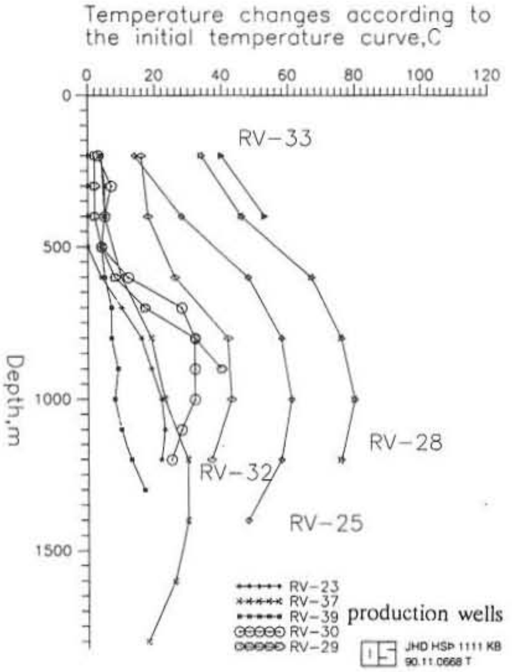


FIGURE 16: Cooling curves for the wells in the Ellidaár field

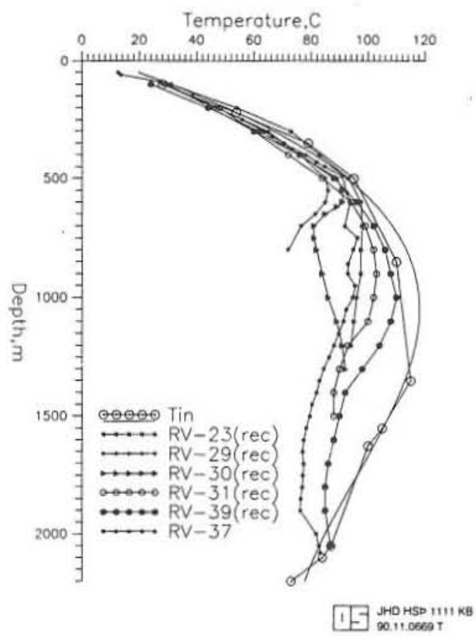


FIGURE 17: Present temperature in the production field compared to T_{in}

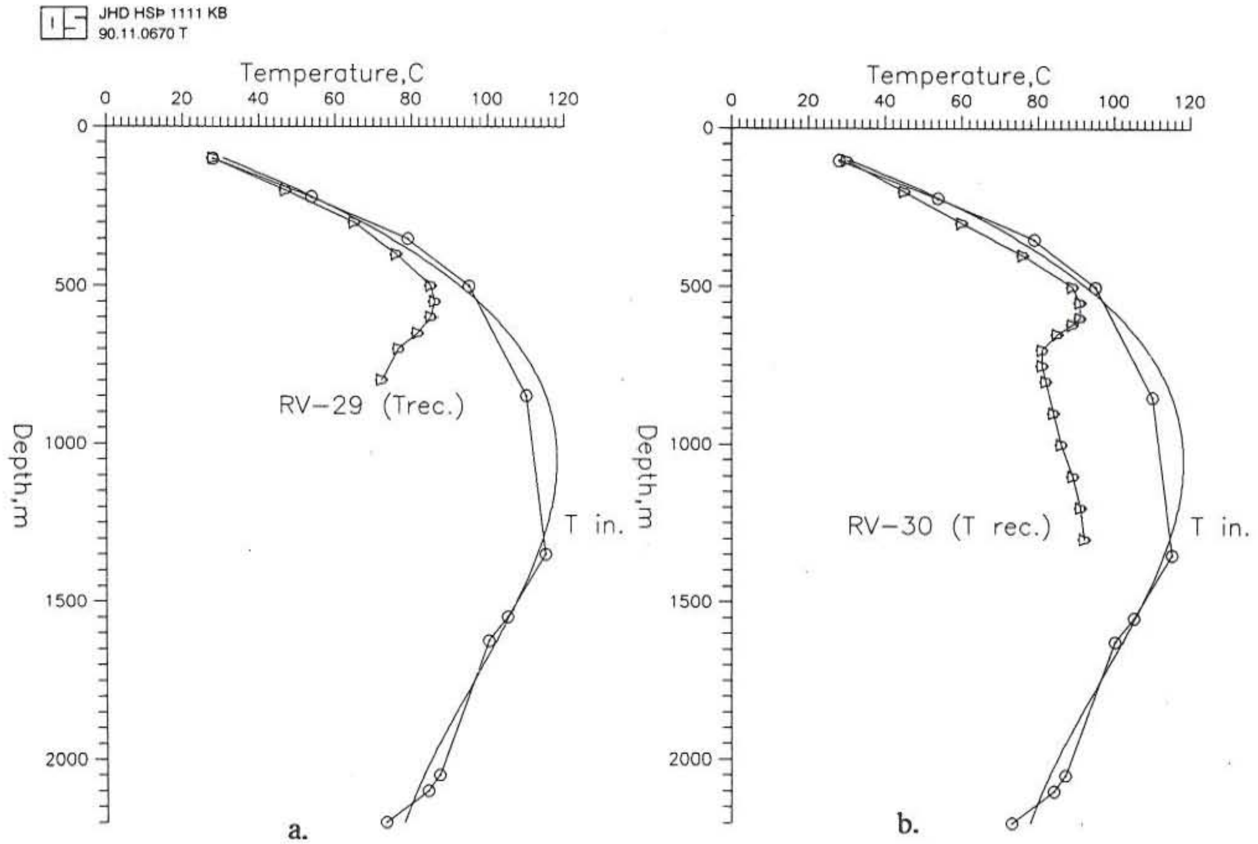


FIGURE 18: Comparison of the present temperature and T_{in} in wells RV-29 and 30

There are smaller temperature changes observed in wells RV-23 and RV-31 (up to 25°C) (Figures 19a and b) which can also be explained by a greater portion of the water coming from the C-aquifers. In RV-23 it is 52% and in RV-31 90%, according to data on circulation losses and gains during drilling (Tómasson, 1988). The smallest changes within the production field are observed in well RV-39 (Figure 19c).

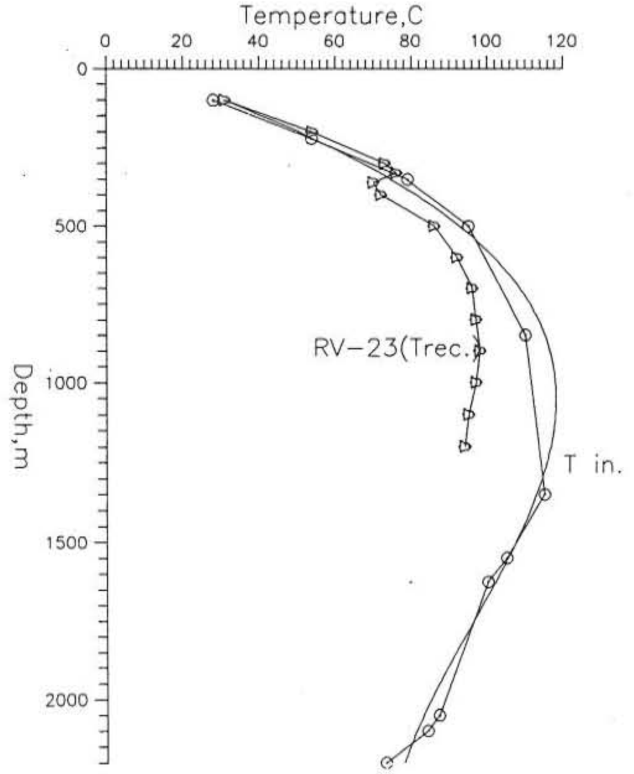
3.1.2 Cooling in nonproductive wells

The greatest cooling outside the production field is observed in wells RV-25 and RV-28 (Figure 19). It is caused by a downflow from the A-aquifers. This downflow has cooled the wells for most of the interval measured. Consequently, it is difficult to ascertain whether other causes are contributing to cooling in the vicinity of these wells.

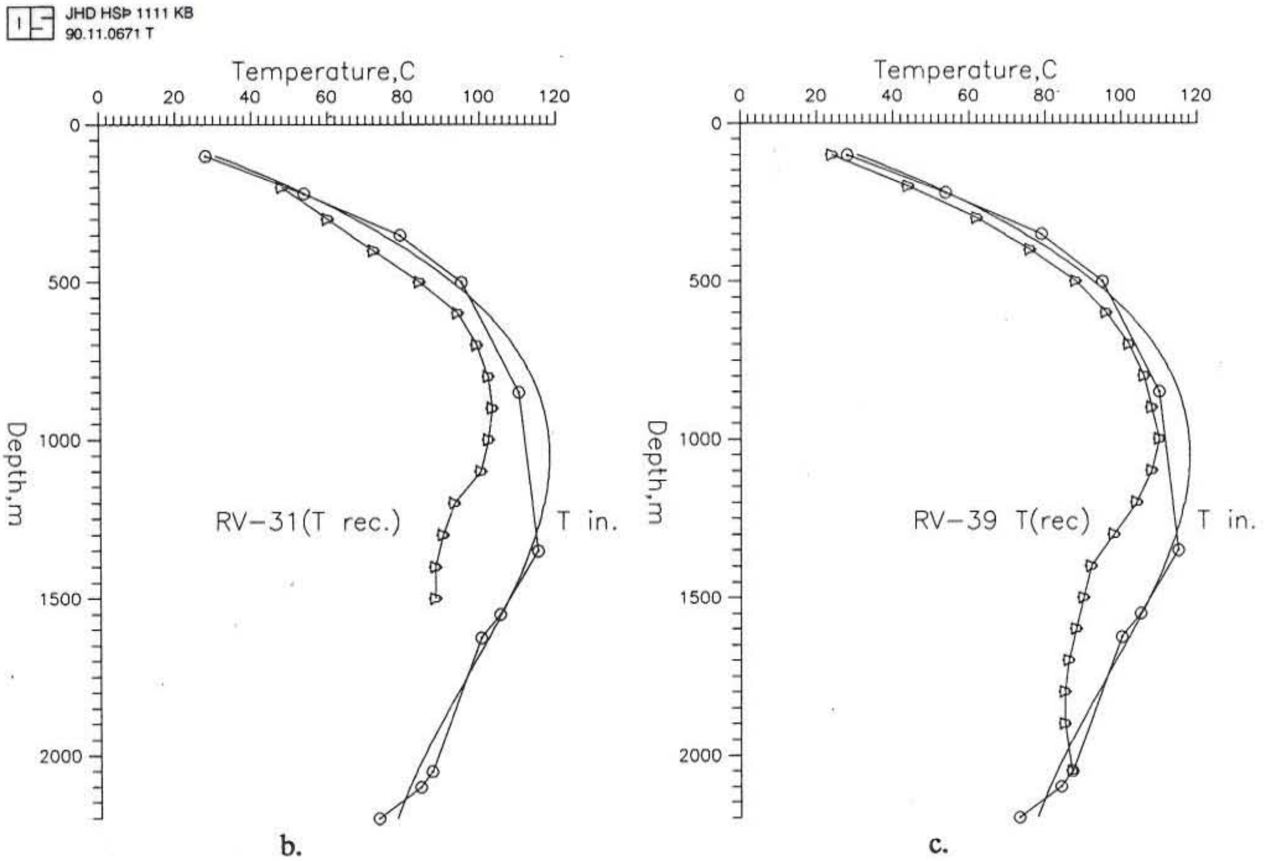
Well RV-27 is northeast of the field. No cooling is observed in it, and the measured temperature down to 500 m depth in 1986, 18 years after drilling, agrees with T_{in} (Figure 21a). The main reason for this is the location of well RV-27 close to where the hot water enters the field from the northeast, and it has no A-aquifers. Temperatures in well RV-41 are also close to T_{in}, but a slight cooling in B-aquifers is observed (Figure 21b).

Temperatures in most of the wells are disturbed by internal flow. Wells RV-36 and RV-37 are the only ones with no internal flow, and they still have reverse temperature profiles. As mentioned earlier, they were both drilled a few years after production started in the field. Well RV-36 is to the east of the production area, but RV-37 is within the production field.

Both were measured during the warm up period but the last measurements were taken after only 144 days (RV-36) and 44 days (RV-37), when the wells had not yet recovered after drilling. All existing temperature measurements were used to estimate the initial temperatures in these wells (Figure 22). The temperatures in RV-37 are much higher than in RV-36 and comparison with T_{in} shows greater cooling in RV-36 (Figure 23). This difference can be explained by cold inflow from the southeast, which affects well RV-36 more than well RV-37 and must have already started before these wells were drilled.



a.



b. c.

FIGURE 19: Comparison of present temperature and T_{in} in wells RV-23, 31 and 39

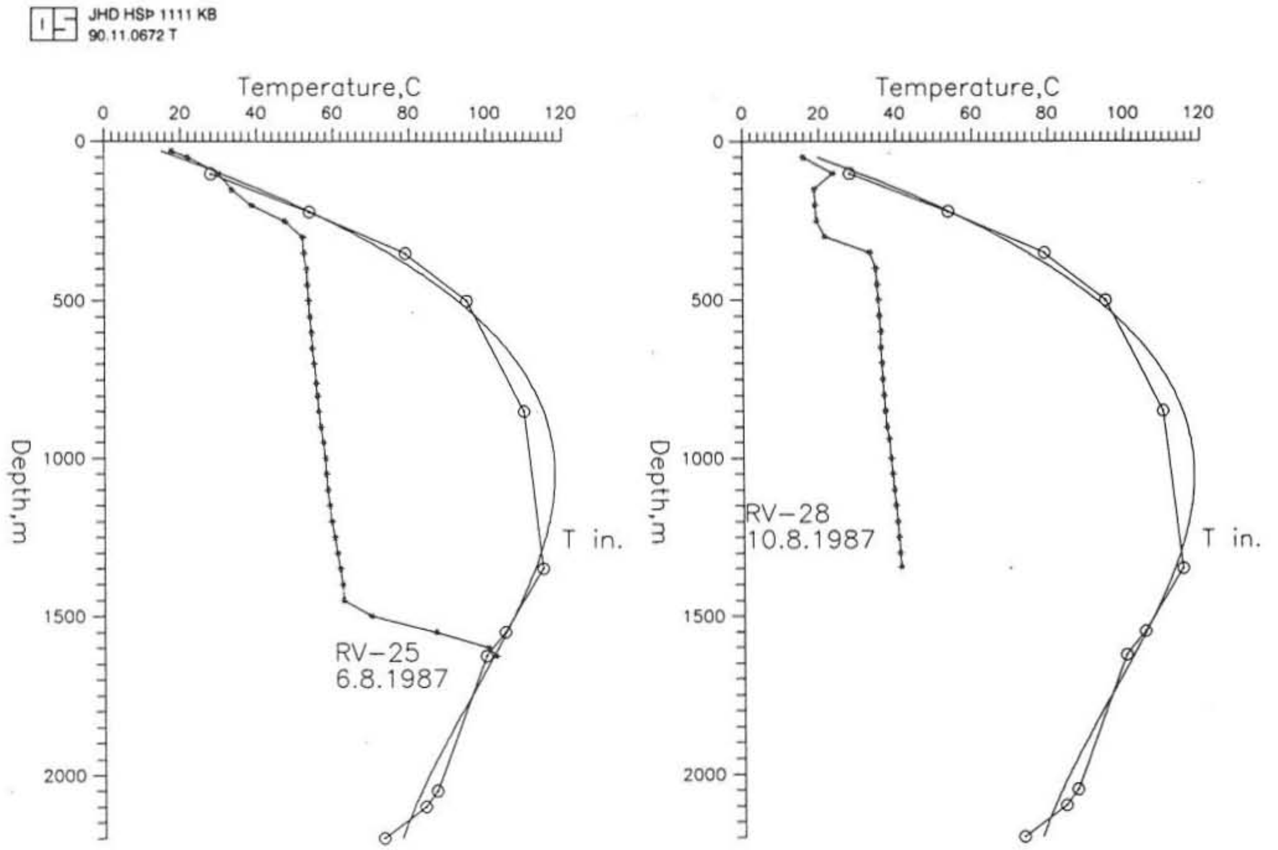


FIGURE 20: Comparison of latest temperature curves with T_{in} for RV-25 and 28

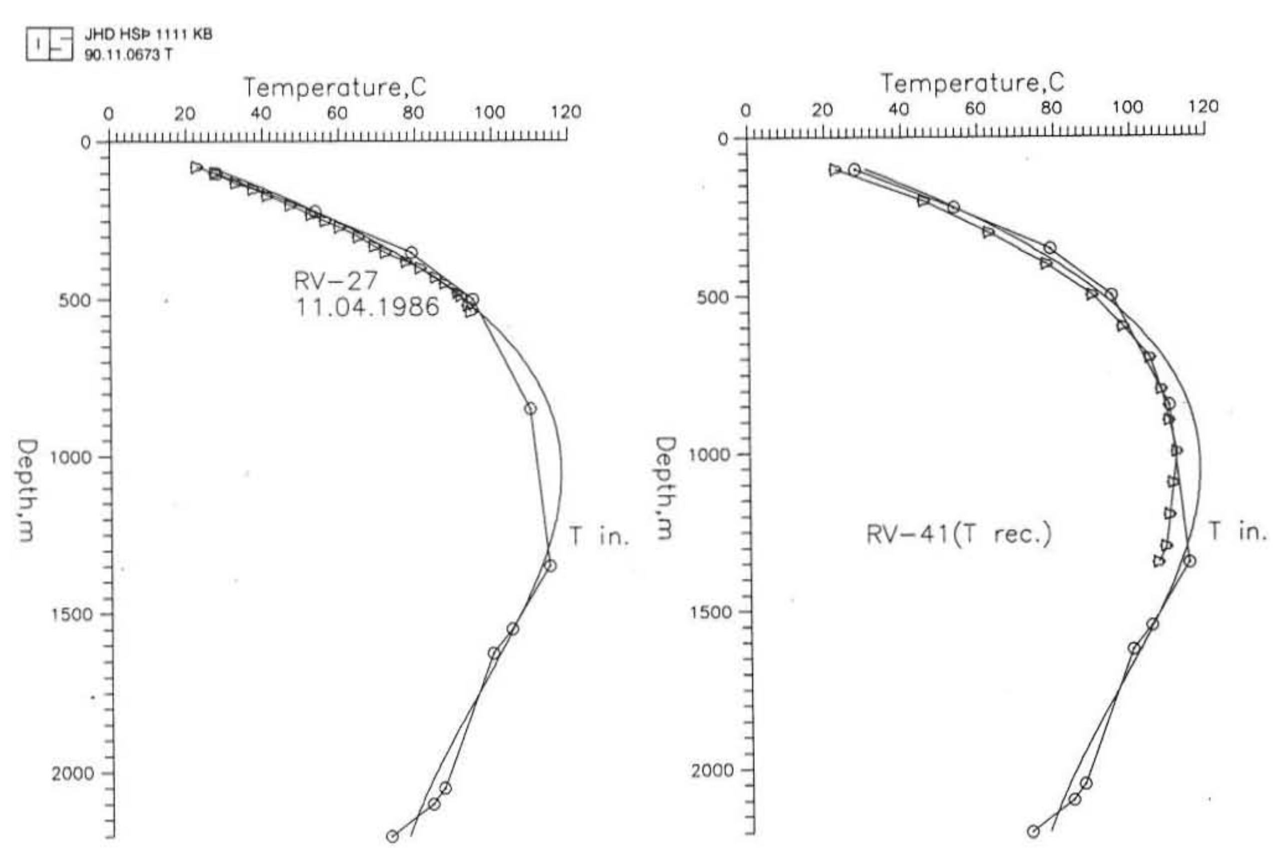


FIGURE 21: Comparison of present temperature and T_{in} for RV-27 and RV-41

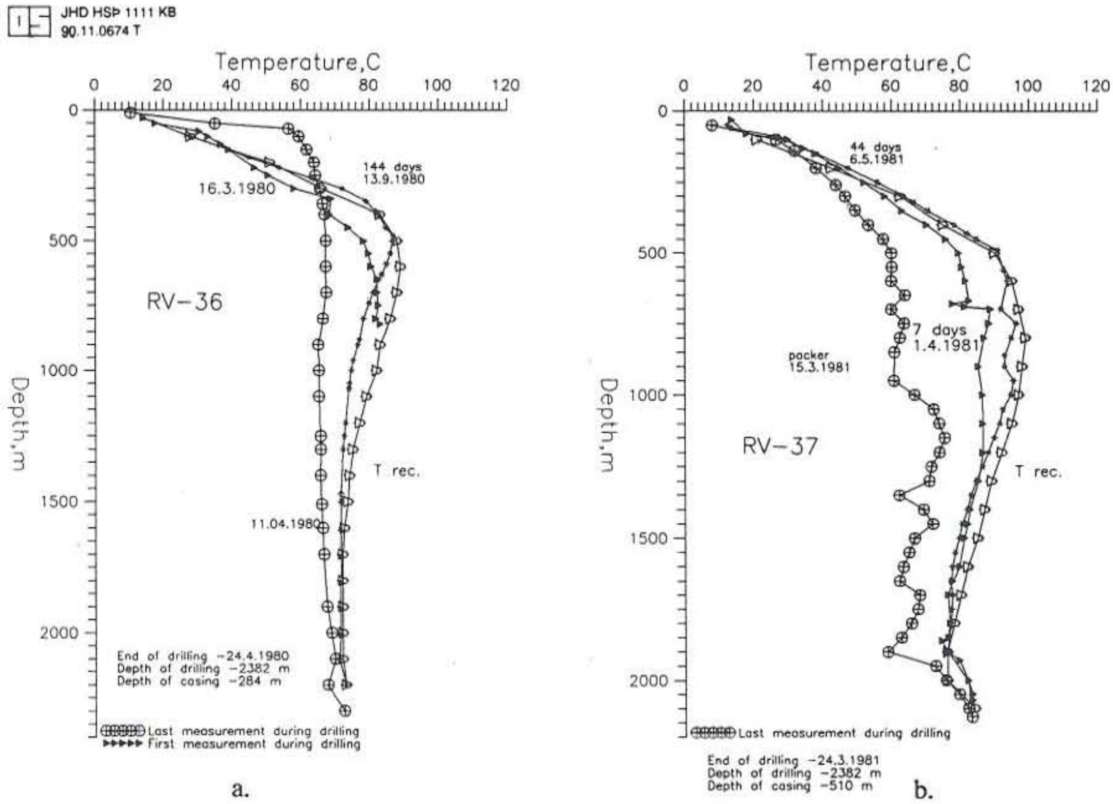


FIGURE 22: Estimate on initial temperature in wells RV-36 and 37

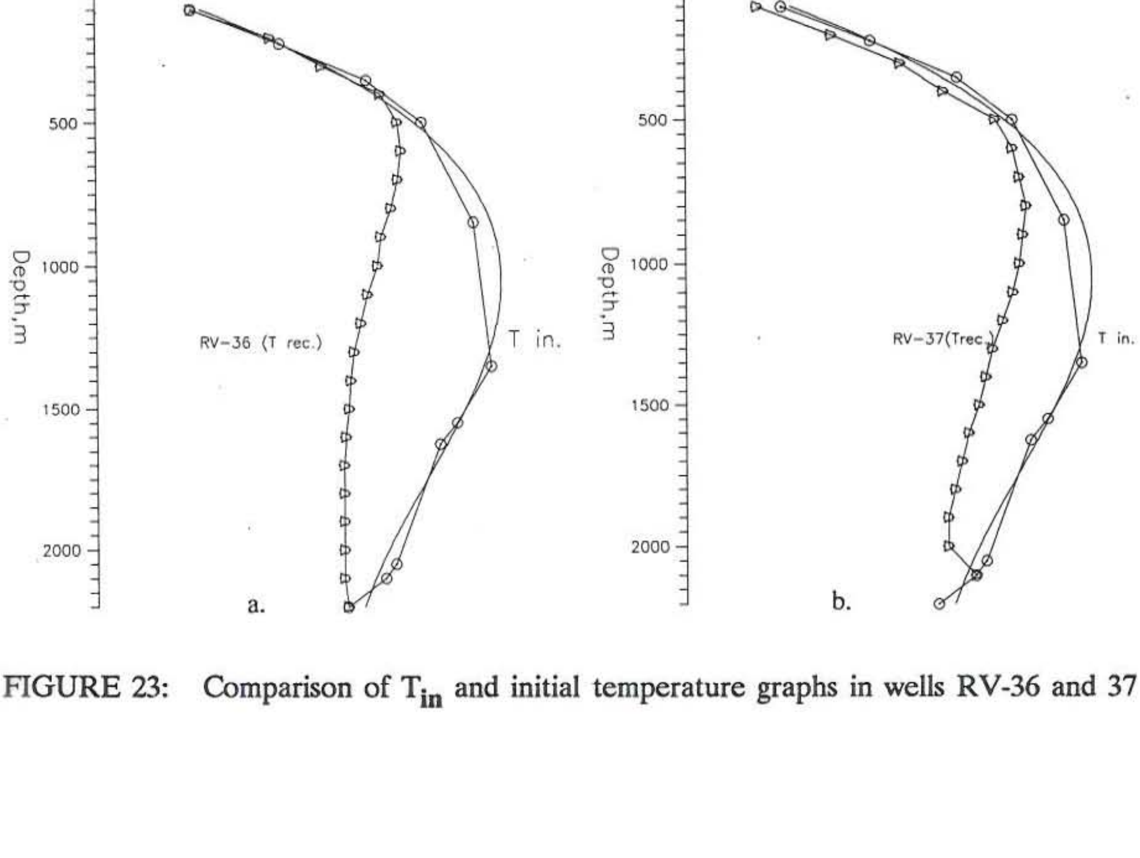


FIGURE 23: Comparison of T_{in} and initial temperature graphs in wells RV-36 and 37

3.2 Temperature distribution maps

Maps of the present temperature distribution at 200, 400, 600, 800, 1000 and 1200 m depth have been drawn up (Figures 24-29). The last temperature measurements were used where possible, otherwise reconstructed curves were used. Similarly, maps of the difference between present temperatures and T_{in} were drawn for the same levels (Figures 30-35). All these maps and cross-sections presented in the report have been drawn up using the programme SURFER, installed on a PC computer.

The lowest temperatures are measured to the west and southwest of the field down to 1500 m in wells RV-25 and RV-28. They are cooled by cold water inflow from the A-aquifers. The highest temperatures are related to a hot water flow into the geothermal field from northeast to southwest. The temperature map at 200 m depth (Figure 24) shows a comparatively uniform temperature with values between 40 and 50°C. Slightly higher values are found in wells RV-23 and 36. At a depth of 400 m (Figure 25), a northeast orientation is evident on the 80°C isoline. This originates from the hot water inflow into the field between 400 and 1200 m depth.

Three main zones can be distinguished on all other maps (Figures 26-29). They are:

a) a zone of low temperatures to the west and southwest, caused by downflow in wells RV-25 and RV-28.

b) a zone of high temperatures, marked by the 90 and 100°C isolines, outlining the NE-SW flow direction of hot water.

c) a colder zone in the southeast, where cooling is taking place in the B-aquifers (wells RV-29, 30 and 36).

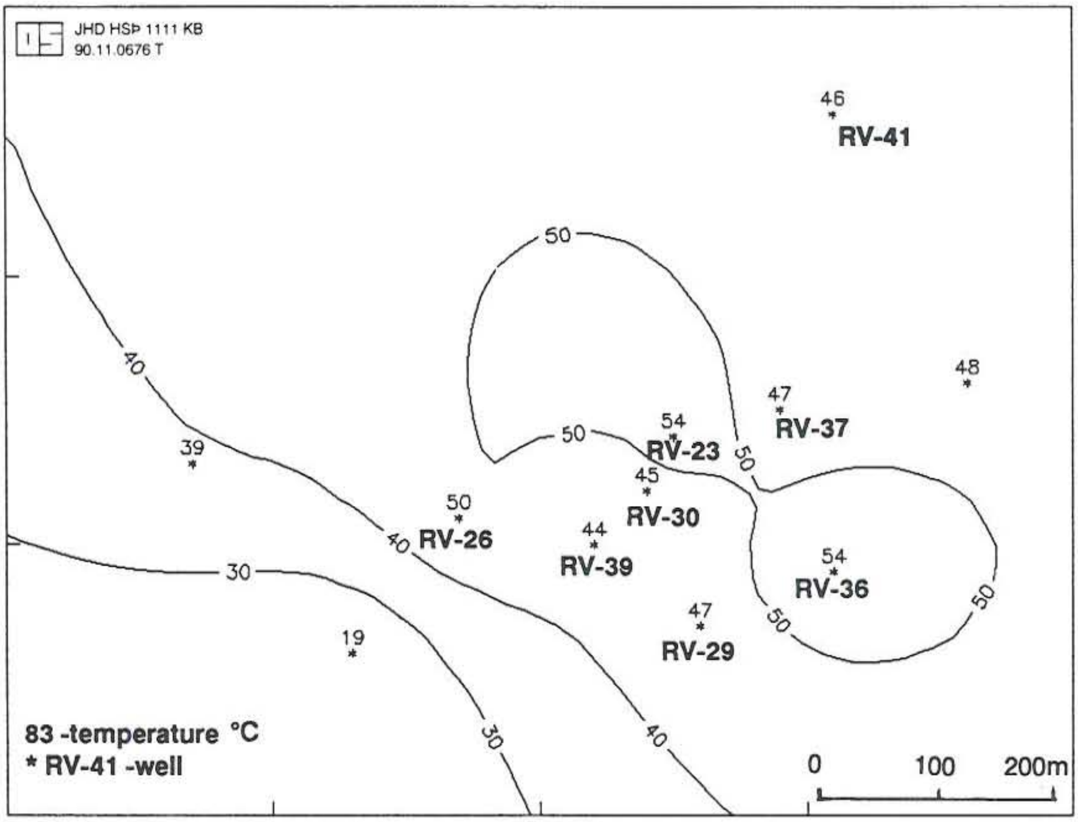


FIGURE 24: Temperature map at 200 m depth

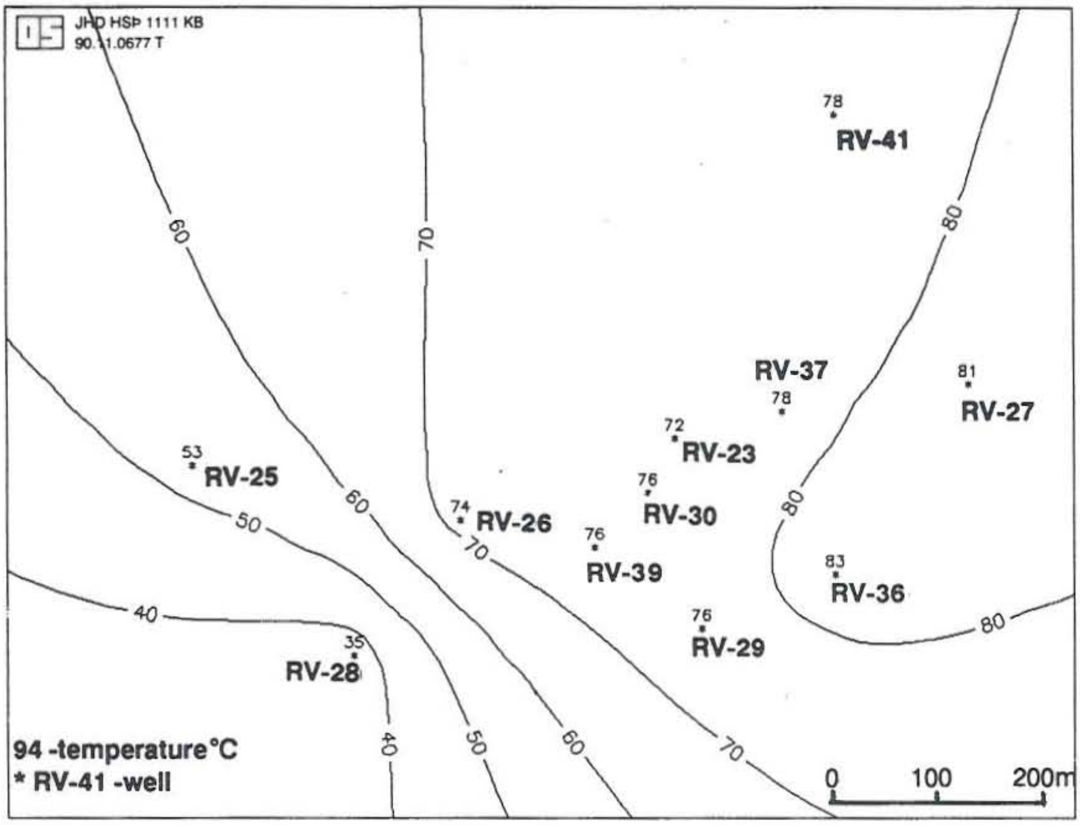


FIGURE 25: Temperature map at 400 m depth

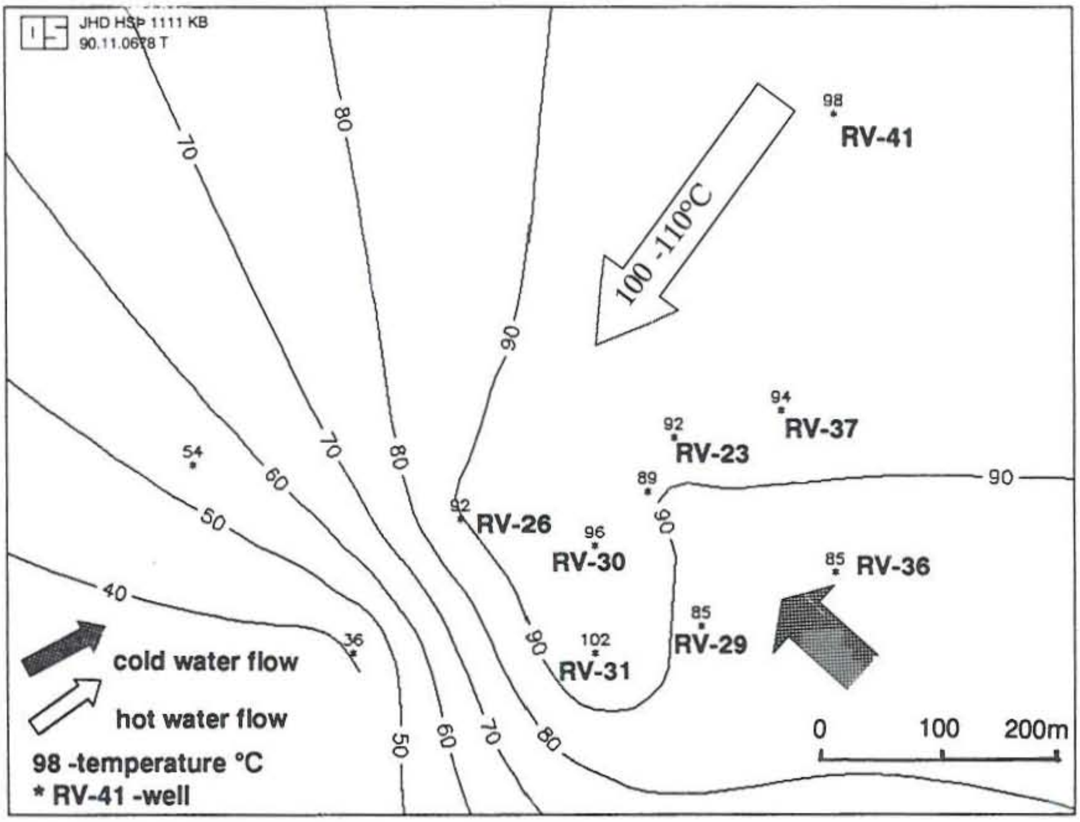


FIGURE 26: Temperature map at 600 m depth

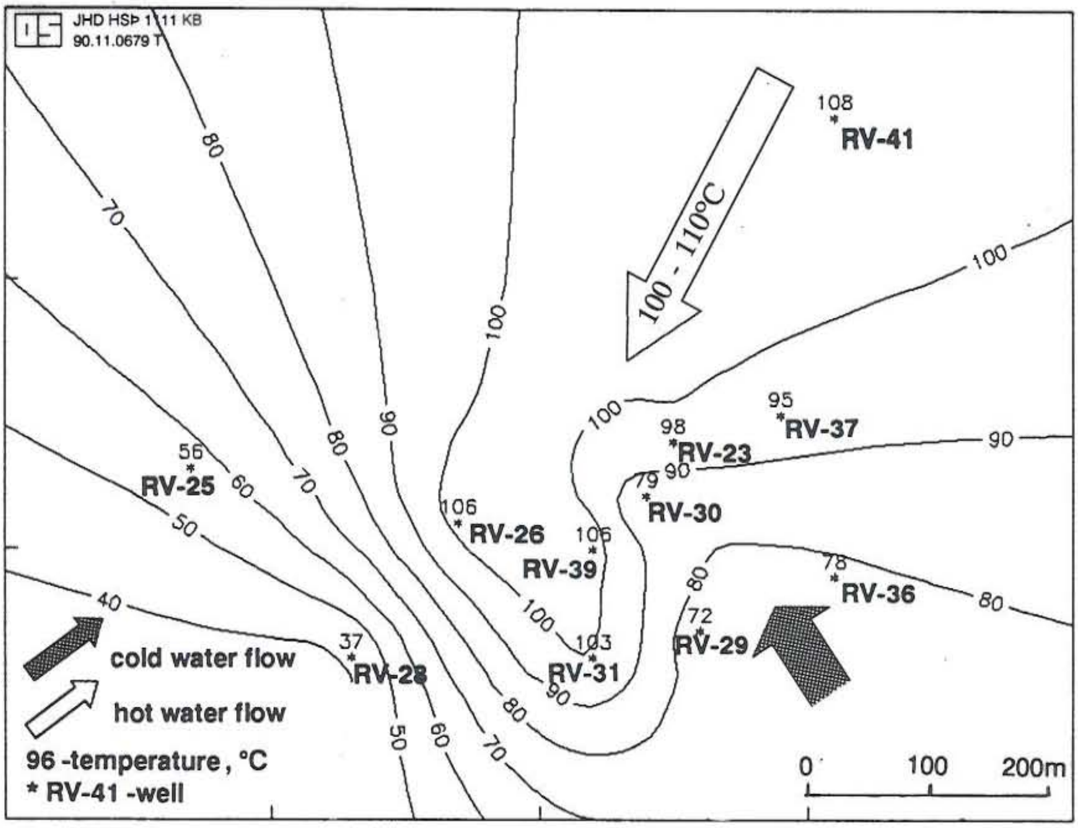


FIGURE 27: Temperature map at 800 m depth

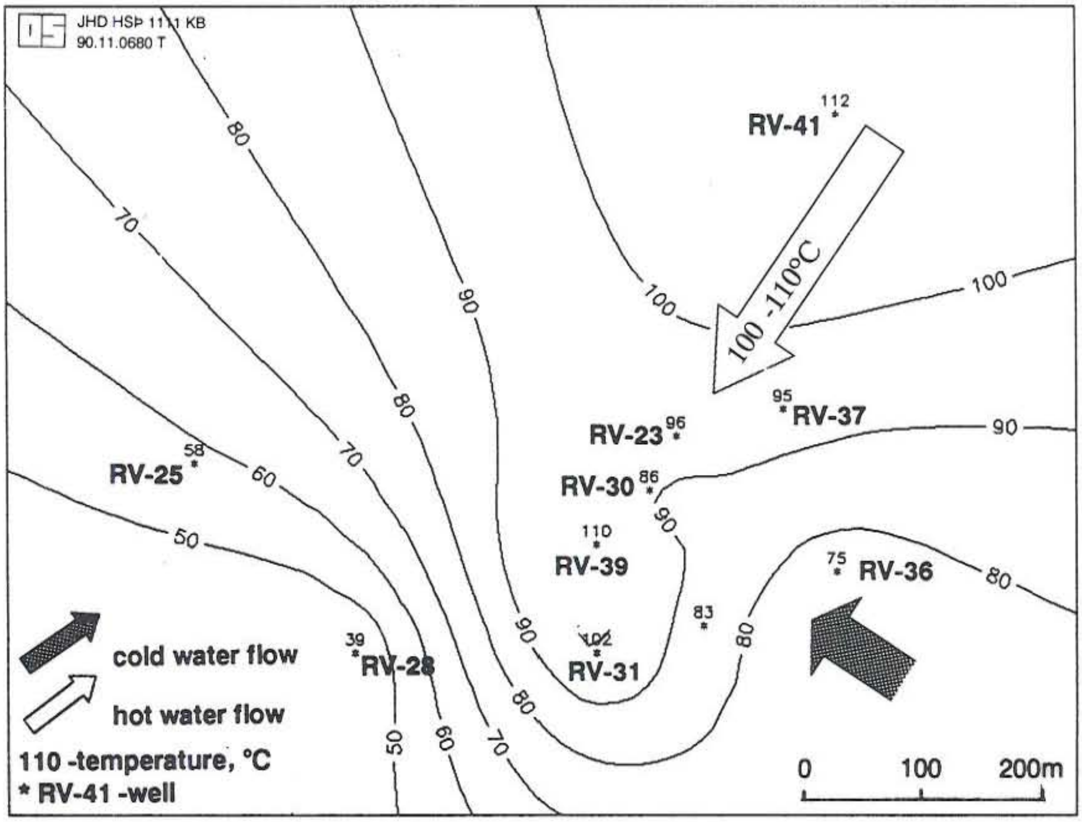


FIGURE 28: Temperature map at 1000 m depth

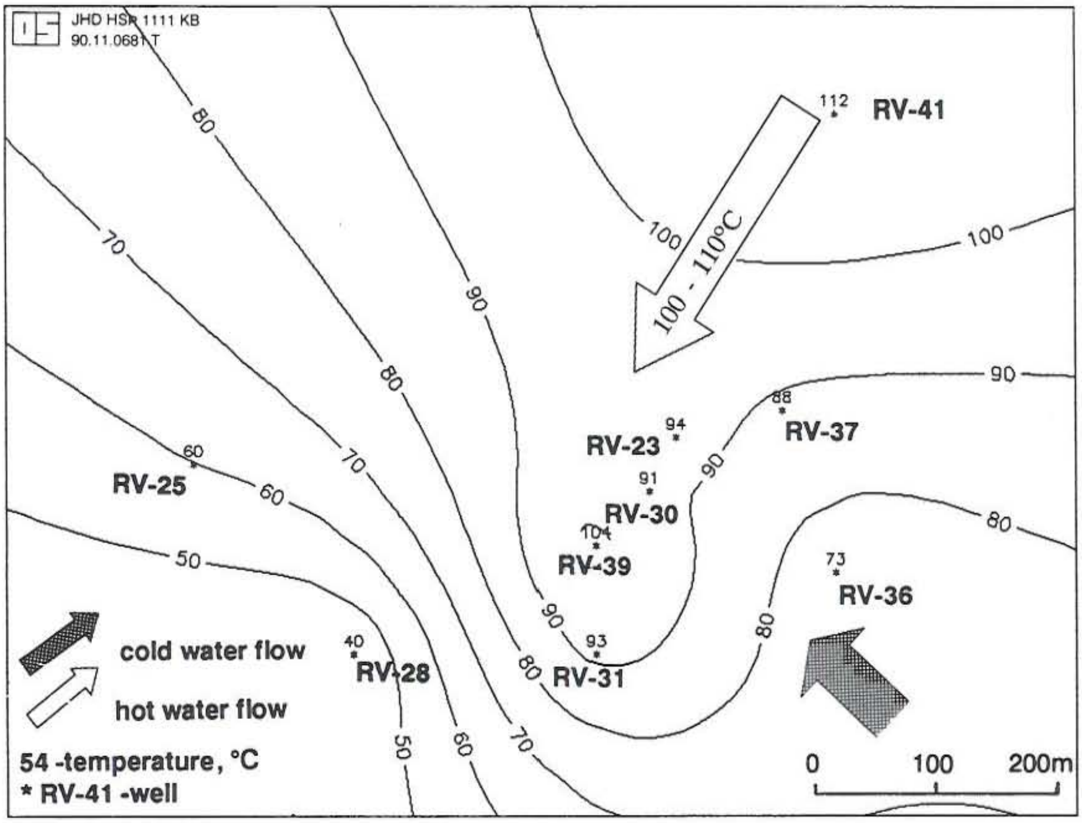


FIGURE 29: Temperature map at 1200 m depth

Cooling in the southeastern part of the area is observed at 600 m depth (Figure 26), but the influence is strongest at 800 m (Figure 27). At depths of 1000 and 1200 m, the cooling effect is decreasing (Figures 33 and 34). The reason for this cooling is believed to be infiltration of water from the cold water system within the Krýsuvík fissure swarm (Figure 1) and a probable horizontal fracture zone, placed at 800 m depth, through which the cold water reaches the Ellidaár area. A temperature map for 1400 m depth was not drawn due to lack of data.

Maps of cooling give additional information on the rate of cooling with time taking place in the field. Analysis of the maps (Figures 30-35) shows that the smallest changes are observed at shallow levels. Figure 30 clearly shows the cooling at 200 m depth to be within 4°C, and Figure 31 shows a maximum value of 10°C at 400 m. The greatest changes are at 800-1200 m depth (Figures 33-35) where values in excess of 40°C are observed (in the vicinity of RV-36). The temperatures at 200 m (Figure 30) are still close to the initial values, with a less than 2°C difference in wells RV-26, 31, 29, 27 and 36 (Figure 30). The cooling effect increases from 4°C in the east (RV-36) to 10°C in the west (RV-26) at a depth of 400 m (Figure 31). The temperature change distribution is similar for all deeper levels. It shows cold inflow from the southeast, which has already reached wells RV-36, 29 and 30 (Figures 32-35).

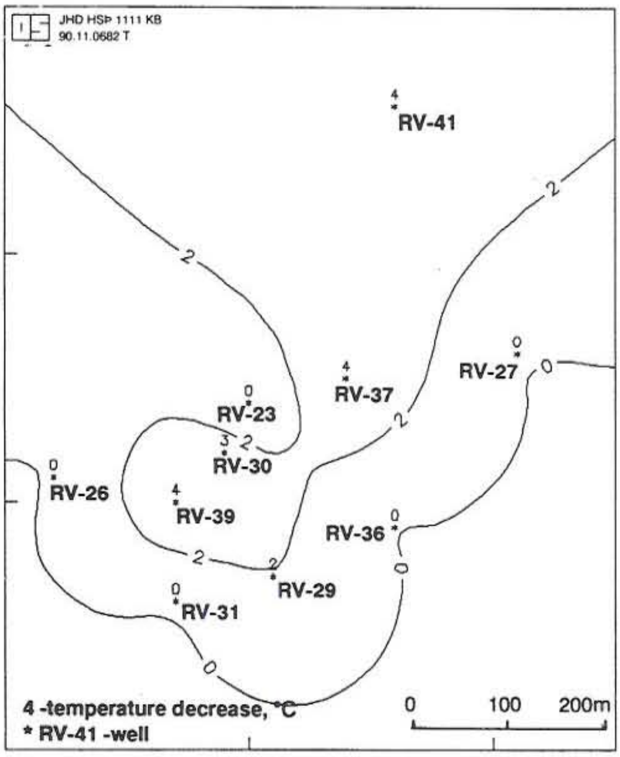


FIGURE 30: Cooling in the production field at 200 m depth

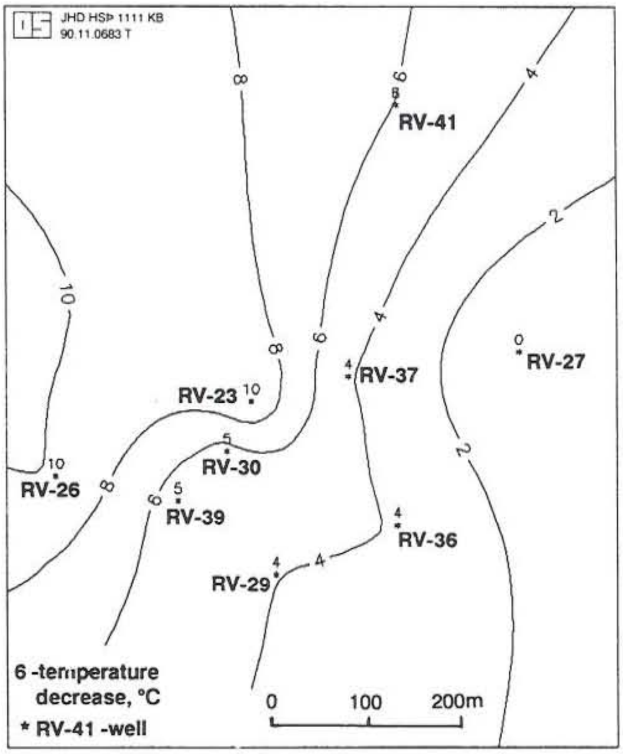


FIGURE 31: Cooling in the production field at 400 m depth

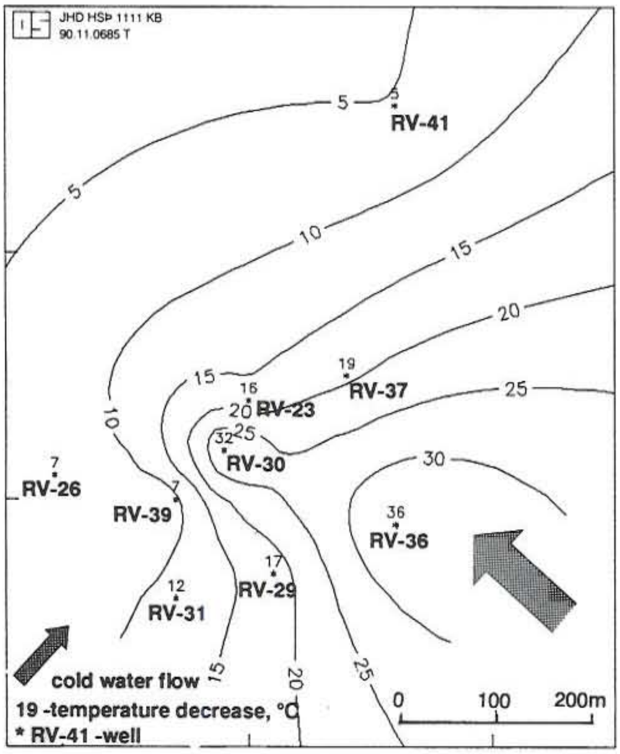


FIGURE 32: Cooling in the production field at 600 m depth

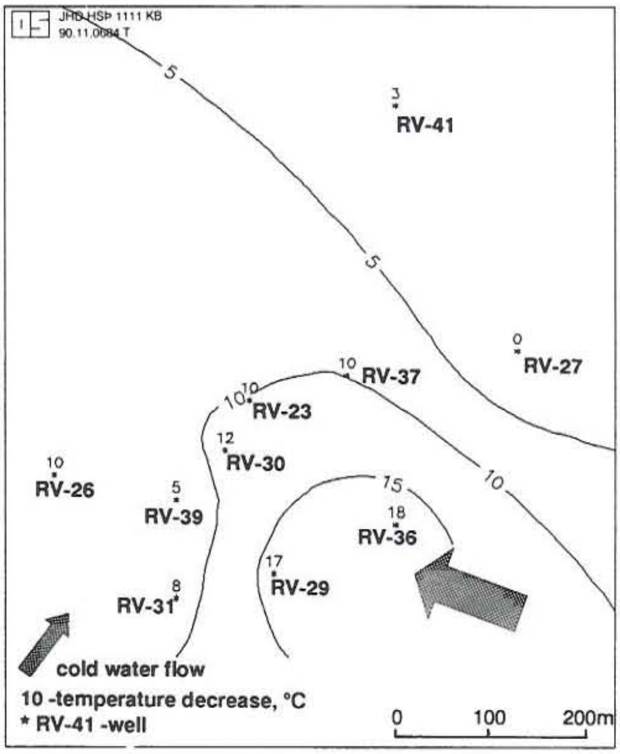


FIGURE 33: Cooling in the production field at 800 m depth

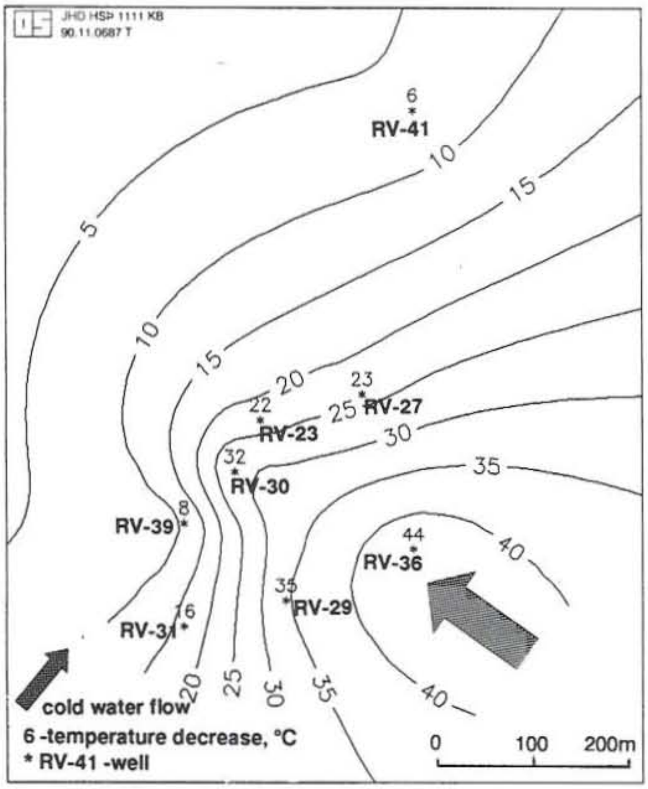


FIGURE 34: Cooling in the production field at 100 m depth

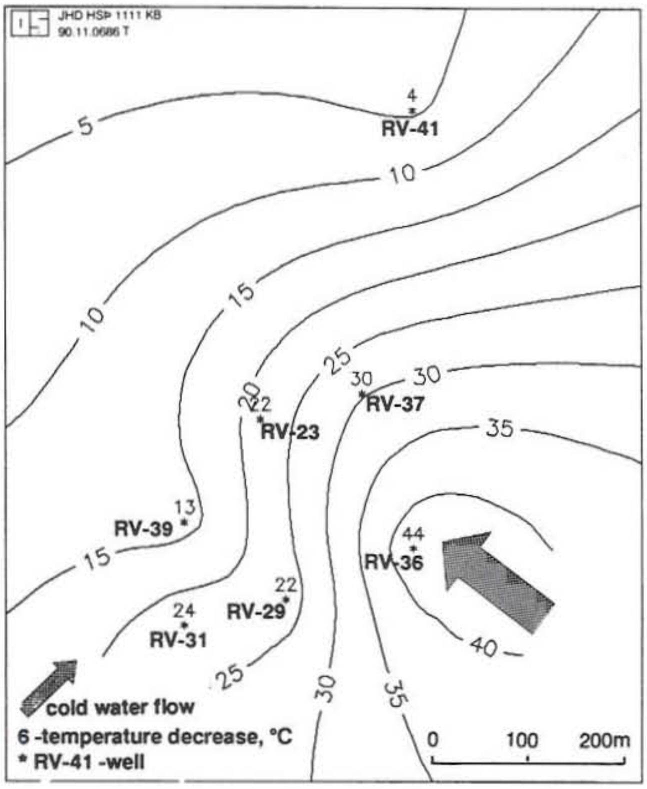


FIGURE 35: Cooling in the production field at 1200 m depth

3.3 Temperature cross-sections

To better understand the flow pattern in the geothermal field, three temperature cross-sections were drawn up. The locations are shown in Figure 2, where the cross-sections are marked as I, II and III. Cross-section I is shown in Figure 36. The highest temperatures are registered in well RV-39 (90 and 100°C isolines). Cooling due to downflow in well RV-28 is noticeable, and local cooling at 600-800 m depth can also be seen in well RV-36.

Cross-section II, which is parallel to I, is shown in Figure 37a. Deep local cooling in RV-30 is reflected in the 90°C isoline. The same cross-section was drawn up, excluding well RV-30 (Figure 37b). The existence of a hot water flow is clearly outlined by the 90 and 100°C isolines.

Cross-section III transects the other cross-sections. As Figure 38 shows, the prominent local cooling in wells RV-29 and RV-30 is confirmed in the shape of the 90 and 100°C isolines. The cross-sections show the location of a zone of high temperatures caused by a flow of hot water into the production field and also where cooling takes place within it. On the other hand, the direction of the hot water flow cannot be seen from the cross-sections due to their orientation and the small area they cover.

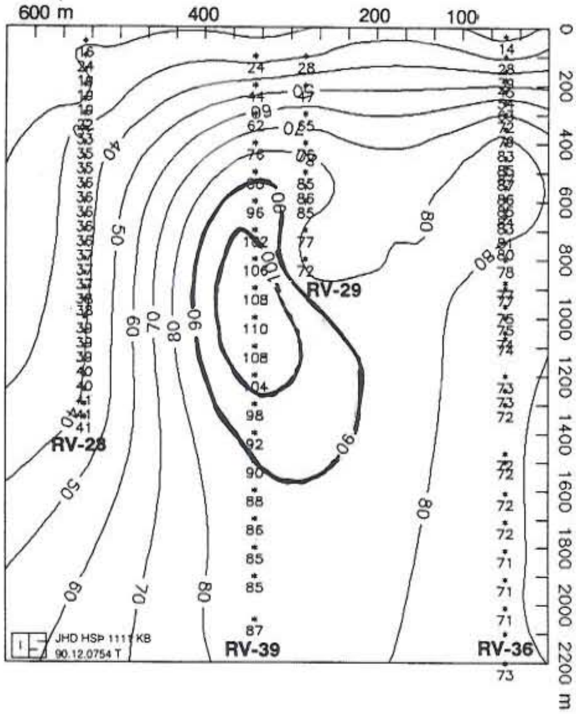


FIGURE 36: Temperature cross-section I, including wells RV-28, 39, 29 and 36

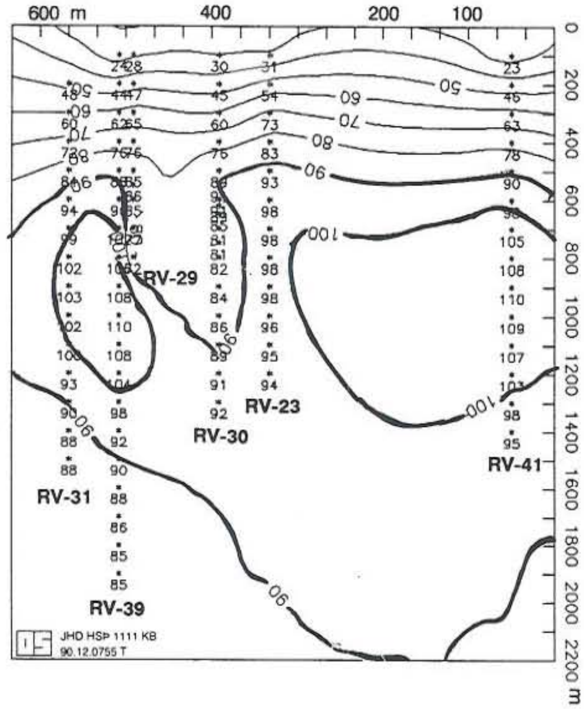


FIGURE 38: Temperature cross-section III, including wells RV-31, 39, 29, 30, 23 and 41

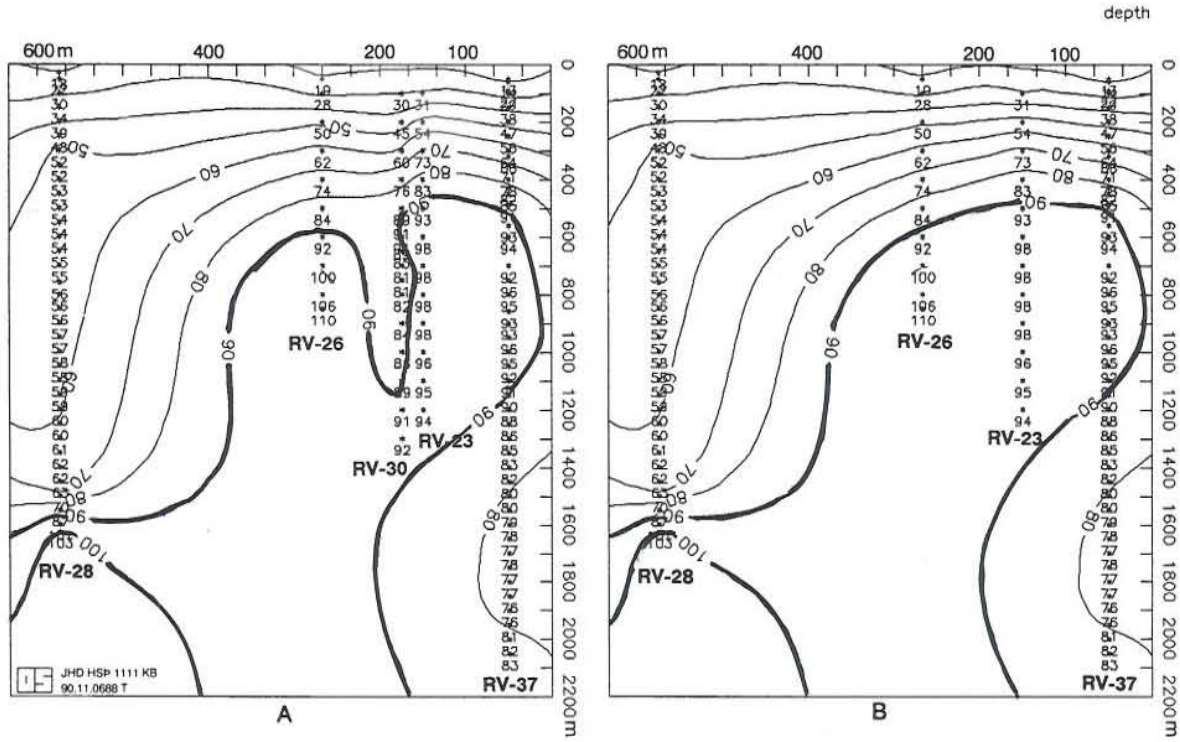


FIGURE 37: Temperature cross-section II, including wells RV-28, 26, 30, 23 and 37; in b) well RV-30 is excluded

3.4 Wellhead temperatures

Temperatures measured at the wellhead and production history data for the production wells were available from Hitaveita Reykjavíkur. Average temperatures over a two year period were calculated, and based on that three temperature maps were plotted (Figure 39). They show the average production temperature for the periods 1984-1986, 1986-1988 and 1988-1990. Based on these, a map was drawn that shows the total change in temperature for the six year period in question (1984-1990) (Figure 40). These maps confirm that cold water infiltrates the geothermal system from the southeast. In the last two years, cooling increased in wells RV-29 and RV-30. Thus, the temperature in well RV-30 decreased from 91 to 88°C, and for well RV-29 from 90 to 84°C (Figures 39b and c). Similar cooling occurred two years earlier for well RV-36. This confirms that cold water infiltrates the geothermal system from the southeast and with time the cold water front has moved from RV-36 to RV-29 and 30. According to these maps, the area covering wells RV-36, 29 and 30 is most affected and cooling amounts to 6°C in 6 years (Figure 40). A probable area of future cooling could be between the 2 and 4°C isolines, noteably in well RV-39.

Chemical and isotopic changes observed in the area (Hettling, 1984) also confirm the cooling process. According to this data, a decrease in the concentration of silica, fluoride and totally dissolved solids is measured for wells RV-30 and RV-31. The silica decreases by 30 ppm, and fluoride reaches a minimum of 0.25 ppm in RV-31 and 0.2 ppm in RV-30. These values are close to the fluoride content in local precipitation. The total dissolved solids have decreased by

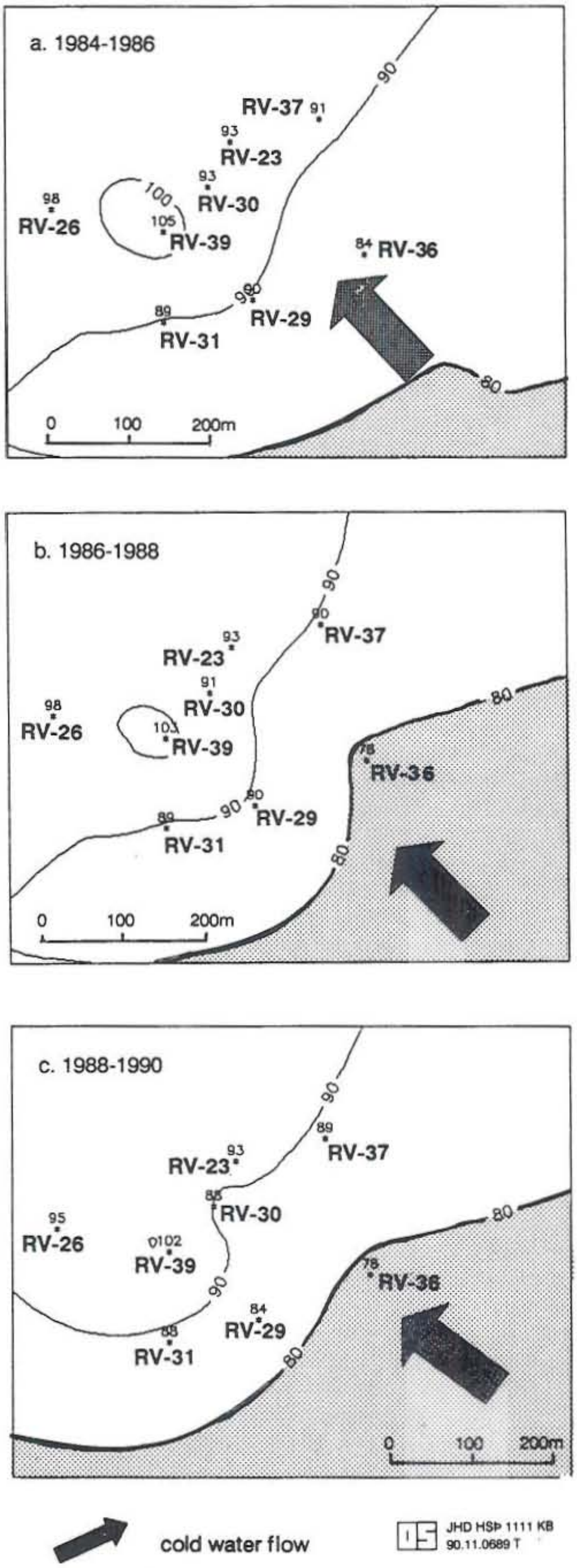


FIGURE 39: Average production temperature for the periods a) 1984-1986, b) 1986-1988, c) 1988-1990

15 ppm, which is interpreted as dilution of the geothermal water by cold water. The chloride concentration is increasing, which most likely means that the cold water is local groundwater. That cooling was taking place is pointed out in the report by Hettling (1984), but its direction had not been defined due to a lack of data. All results in the present report show that the direction of the cold inflow is from southeast to northwest.

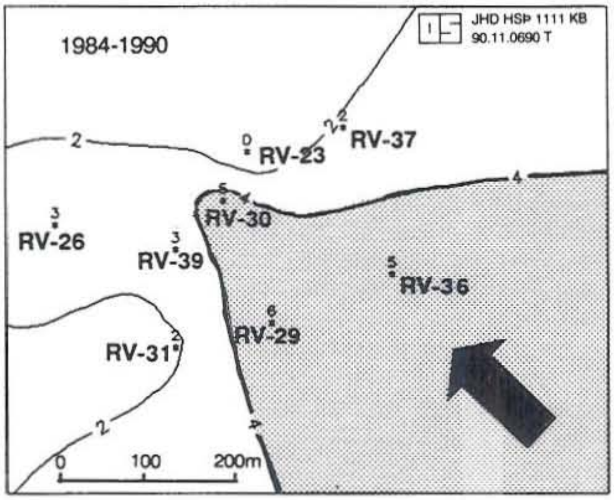


FIGURE 40: Cooling in production wells for the period of 1984-1990

3.5 Three dimensional presentation of the Ellidaár geothermal field

Temperature surfaces at a depth of 400, 600, 800 and 1200 m have been drawn up, using the programme SURFER (Figure 41). They show the main features of the temperature distribution. The lowest temperatures are related to the downflow in wells RV-25 and RV-28, and the highest temperatures are due to hot water flow coming from the northeast. Cooling in the depth interval of 600 to 1200 m is well expressed with lower temperature values in the southeastern margin of the area.

JHD HSÞ 1111 KB
90.11.0691 T

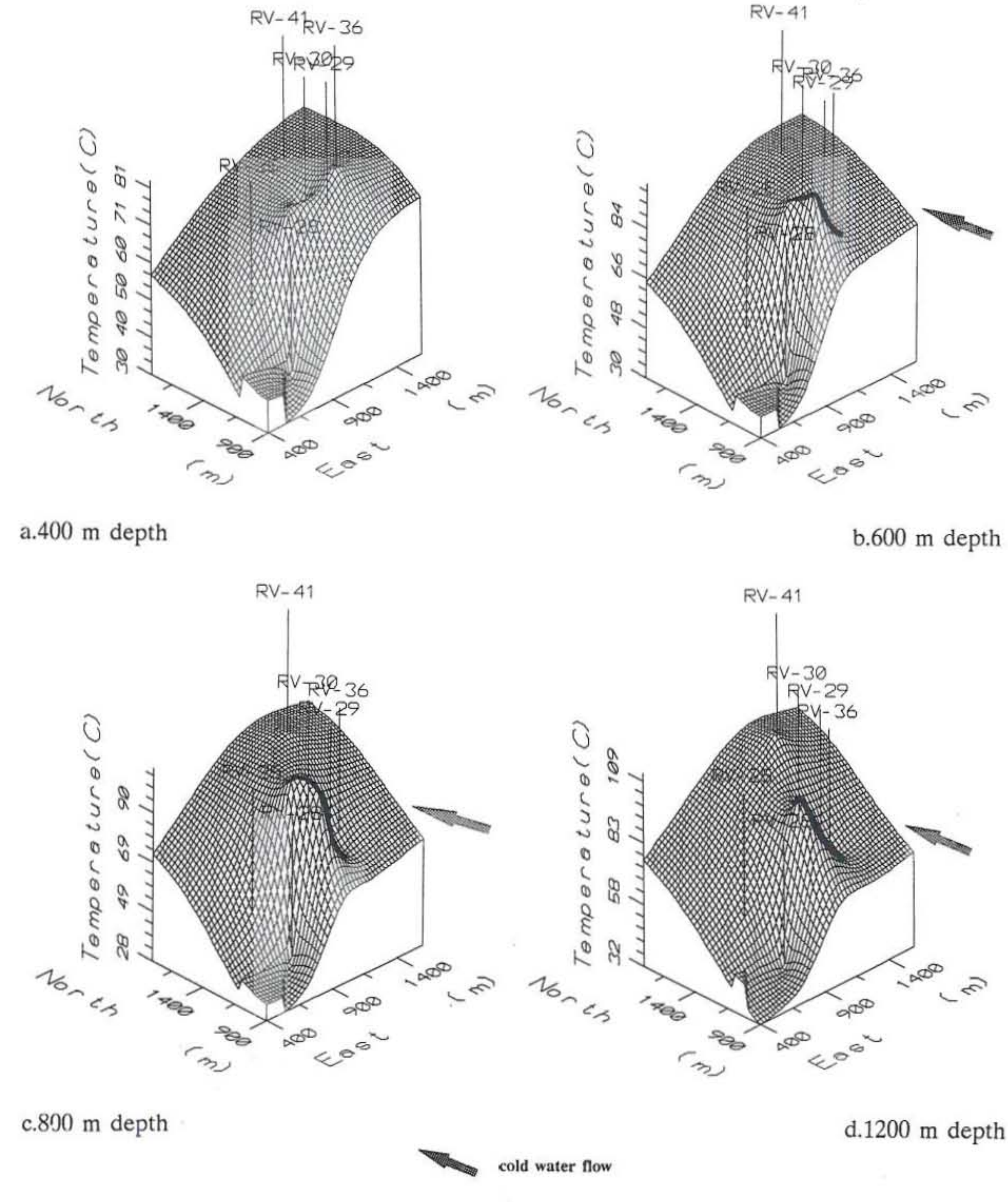


FIGURE 41: Three dimensional presentation of temperature surfaces in the Ellidaár field a) at 400, b) at 600, c) at 800 and d) at 1200 m depth

4. RESULTS AND CONCLUSIONS

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

1. Temperatures over 90°C are still measured in the productive part of the field in wells RV-23, 31, 37 and 39, which can be compared to temperatures of about 105°C at the beginning of production from the field.

2. Temperature has decreased below 90°C in wells RV-26, 29 and 30 after 20 years of production.

3. A temperature graph for the undisturbed (initial) field conditions (T_{in}) was constructed for the Ellidaár geothermal area.

4. The present temperature distribution in the field was estimated.

5. An evaluation of the magnitude of cooling taking place in the field was done by comparing the present temperature distribution with the initial one at different depths. The smallest changes are observed at 200 and 400 m depths and amount to 4 and 10°C respectively. For the production field, the greatest cooling is observed in wells RV-29 and RV-30, where it amounts to 40°C.

6. The main factors causing the cooling are
   a) cold water inflow in the shallow A-aquifers
   b) cold water infiltration into the B-aquifers from the southeast at 600-1200 m depth with the strongest effect at 800 m.

7. The cooling in the B-aquifers is seen in wells RV-36, 29 and 30 and is confirmed by wellhead temperature maps.

8. In the future, infiltration from the cold water front from the southeast can be expected to reach well RV-39, as indicated from the cooling measured at wellhead in wells RV-29 and RV-30 during the last six years (1984-1990). RV-37 is another well which at present only shows small cooling in the depth interval 700-950 m. Combined chemical and temperature measurements in these wells could provide useful information on the advance of the cold water front in the Ellidaár geothermal field.

ACKNOWLEDGEMENTS

The author wishes to thank Dr.Ingvar B. Fridleifsson for giving her the possibility to attend the UNU Geothermal Training Programme in Reykjavík. Furthermore, thanks go to Helga Tulinius, my advisor, for her assistance during all stages of data analysis and preparation of this report. I am very greatful to Dr. Valgardur Stefansson for his patience and critical discussions and to Dr. Hjalti Franzson for encouraging me in my conclusions.

Special thanks go to Dr. Einar Gunnlaugsson for the data from Hitaveita Reykjavíkur put at my disposal. Further thanks to Ludvik S. Georgsson and Marcia Kjartansson for editing the report.

REFERENCES

Georgsson, L. S., 1985: The Reykjavík - Borgarfjördur area, results of resistivity soundings. Orkustofnun, Reykjavík, report OS-85111/JHD-14 (in Icelandic), 41 pp.

Hettling, H. K., 1984: The chemical and isotopic changes in the low temperature areas of Laugarnes, Ellidaár and Reykir. UNU G.T.P., Iceland, report 3, 52 pp.

Pálmason, G., 1973: Kinetics and heat flow in a volcanic rift zone, with application to Iceland. Geophys. J. R. Astr. Soc., 33, 451-481.

Thorsteinsson, T. and Elíasson, J., 1970: Geohydrology of Laugarnes hydrothermal system in Reykjavík, UN symposium on the development and utilization of geothermal resources, Pisa, Proceedings - Geothermics Spec. iss. 2, 2, 1191-1204.

Tómasson, J., 1988: The Ellidaár area, origin and nature of the geothermal system. Orkustofnun, Reykjavík, report OS-88027/JHD-03 (in Icelandic), 67 pp.

Tómasson, J., 1990: The Ellidaár geothermal area, nature and response to production. Report, unpublished.

Tómasson, J., Fridleifsson, I. B. and Stefánsson, V., 1975: A hydrological model of the flow of thermal water in southwesthern Iceland with special reference to the Reykir and Reykjavík thermal areas. 2nd UN symposium on the development and use of geothermal resources., San Francisco, Proceedings, 643-648.