THE ELLIÐAÁR GEOTHERMAL AREA

Nature and Response to Production

by

Jens Tómasson

National Energy Authority

Reykjavík

Iceland

ABSTRACT

The Elliðaár low-temperature area is situated in the Quaternary strata of SW-Iceland, and is utilized for district heating in Reykjavík. There are two groundwater systems in the area; the geothermal system and a cold groundwater system. The latter is zero to some tens of meters thick at Elliðaár but thickens to up to 1000 m to the east of the area.

When pumping commenced an inflow of cold groundwater started into the geothermal system replacing the pumped geothermal water. This has caused cooling of the geothermal system in the range of 6-21°C in the period 1969-1987.

The Elliðaár area is divided into six fields of which one is the production field with an inverted temperature gradient. The temperature in the easternmost drillhole is 72°C at 2000 m depth, but the temperature increases towards the Laugarnes area, some 4 km to the west, where the temperature is 146°C at same depth. The conductive gradient indicates temperature as high as 300°C at 2000 m depth. It is concluded that thermal mining is taking place, and that it is greatest in the easternmost part of the system.

1. INTRODUCTION

The structure and the response of the Elliðaár geothermal system to utilization, can be explained by the geological structures both within the reservoir and outside of it. Iceland is situated on a constructive plate boundary which crosses the country from SW to NE and is marked with an active volcanic zone. The volcanic zone is divided into several fissure swarms which are termed volcanic systems and may contain a central volcano (Jakobsson 1979; Saemundsson 1978; Walker 1963). The volcanic zone is flanked by Quaternary rocks, which are characterized by sequences of subaerial lava flows intercalated with hyaloclastites and morainic horizons at intervals, corresponding to glacial conditions. The quaternary formations are flanked by tertiary flood basalts (Walker 1959, 1963).

Geothermal activity is widespread in Iceland. Thermal areas are divided into two groups on the basis of subsurface temperature in the geothermal system (Böðvarsson 1961). By definition the base temperature is higher than 200°C in the high-temperature areas and lower than 150°C in the low-temperature areas.

The high-temperature areas are located in the active volcanic zone, whereas low-temperature areas are situated in the quaternary and tertiary strata mostly in lowlands and valleys. The low-temperature areas are widespread and about 250 low-temperature areas are known, but the high-temperature areas are about 30. The low-temperature areas are suitable for direct district heating because the chemical composition of the low-temperature water is low in dissolved solids and can therefore be piped directly into the radiators for space heating. The main part of the water used for district heating is therefore from the low-temperature areas.

The use of geothermal energy in 1988 was 31% of the gross energy consumption in Iceland, or 757000 oil equivalents tonnes. The biggest part of this energy production is for space heating, where about 85% of houses are heated by geothermal water. The geothermal water is mainly distributed by public district heating services.

The oldest and by far the biggest district heating service is Hitaveita Reykjavíkur (HR) (Reykjavík Municipal District Heating Service) which supplies about 60% of all geothermal water in Iceland for district heating. It started in 1930 with the heating of 70 residential buildings (in the Laugarnes area), and now supplies water for space heating and domesting use for all houses in Reykjavík and the neighbouring communities except the one at Seltjarnarnes. The total population served by the Reykjavík heating service is about 135,000. The Seltjarnarnes community, with 4000 inhabitants, has a separate heating service from the Seltjarnarnes thermal area (Fig.1). HR uses three low-temperature areas, i.e. the Reykir area about 20 km northeast of Reykjavík, and two areas inside the town, that is the Laugarnes and Elliðaár areas. Those two areas along with the Seltjarnarnes area are called the Reykjavík geothermal areas (Fig.1).

These three areas are separated by a hydrological barrier and pumping in one area does not affect the water table in the other two. Furthermore the temperature, isotopic composition and the geochemistry of the water is different in the three areas. Shallow drillholes, less than 300 m deep, show much lower thermal gradient between the areas than is found within the system, i.e. the thermal areas show anomalous thermal highs (Tómasson et al. 1975).

These three areas have been heavily exploited during the last 20-30 years, and production is now 60 l/s of 105-110°C water from the Seltjarnarnes area; 300 l/s of 128°C water from the Laugarnes area and 200 l/s of 90°C water from the Elliðaár area. In the Reykjavík geothermal areas and neighbourhood, a total of 48 drillholes ranging between 600-3085 m in depth have been drilled since 1957 as well as about 70 shallow drillholes.

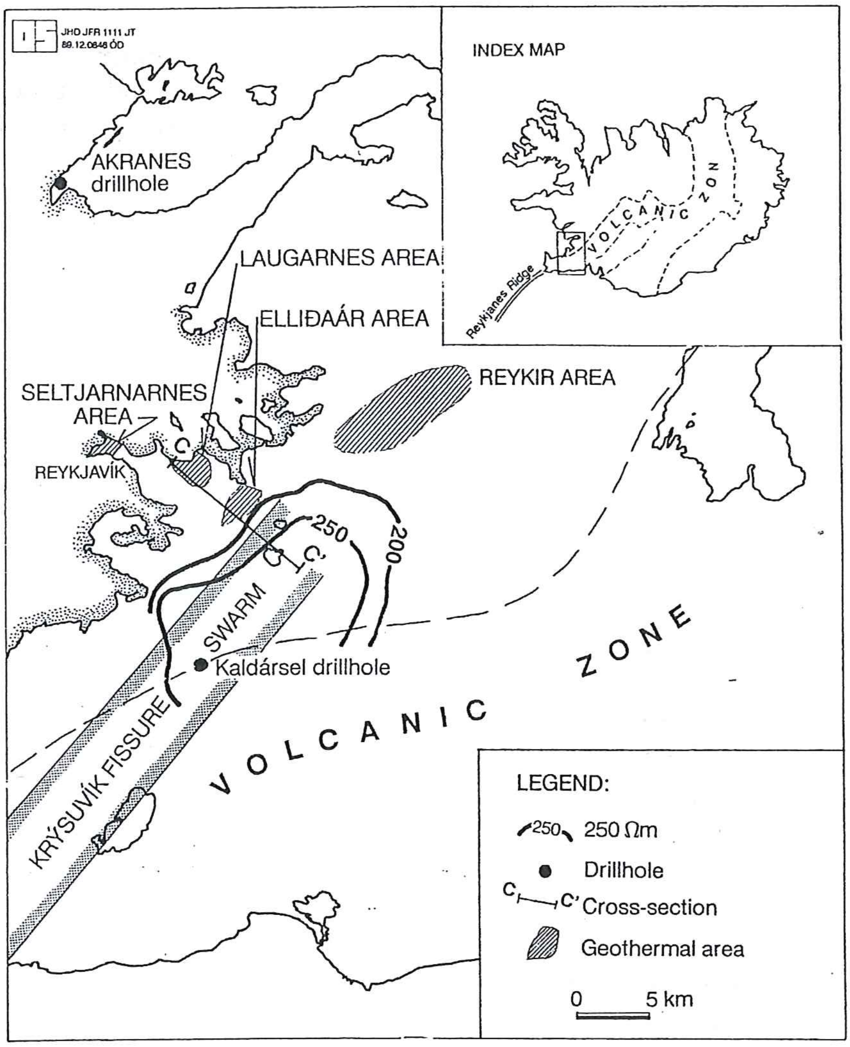

Fig. 1. Map of locations and geology. The location of the Krýsuvík fissure swarm is from Sigurðsson (1985) and the resistivity contours are from Georgsson (1985).

The Elliðaár area is nearest to the volcanic zone and only a few km from the Krýsuvík fissure swarm (Fig. 1) which extends out of the volcanic zone. In this paper the main attention is on the Elliðaár area and its connection to that fissure swarm and also to the neighbouring Laugarnes geothermal area.

It is believed that the data from these areas contribute a great deal to the understanding of the nature of lowtemperature areas in Iceland in general. The most important factors in this context are the isotopic composition of the water (Arnason 1976) and a comparison of the temperature distribution in the region from the Krýsuvík fissure swarm to the Laugarnes area, along with the conductive gradient which has been mapped in Iceland (Pálmason et al. 1979). The results of this study are compared with hypothesis presented by Einarsson (1942) and Böðvarsson (1961, 1982, 1983).

Finally, cooling of water since the beginning of utilization in the Elliðaár field is discussed. This cooling is explained in terms of the geological and thermal structure of the system.

2. THE ELLIÐAÁR GEOTHERMAL AREA

The Geology and Hydrology

Figure 1 shows the location of the Reykjavík geothermal fields, the Krýsuvík fissure swarm as well as the volcanic zone. The high resistivity area at 750 m depth in the Krýsuvík fissure swarms nearest to the Elliðaár geothermal field is also shown. The high resistivity infers that cold groundwater reaches at least down to 750 m depth or may even reach down to 1000 m depth (Georgsson 1985). There is a reasonable agreement between the surface manifestion (geological) of the Krýsuvík fissure swarm and the cold water system according to the resistivity survey.

Prior to drilling there were no warm springs in the present production field at Elliðaár. There were, however, a number of warm springs southwest of the production field (Fig. 2). The springs were bug ponds as hot as 25°C but with no measurable flow. These warm springs all disappeared when pumping started at the Elliðaár production field (western and southern fields). At Bullaugu springs, large cold springs are issued from a fissure (Fig. 2). The total flow is about 200 l/s and the temperature is 5°C. At Grafarvogur, about 7-16°C warm springs are found in an area (Fig. 2) with total outflow of 30-40 l/s.

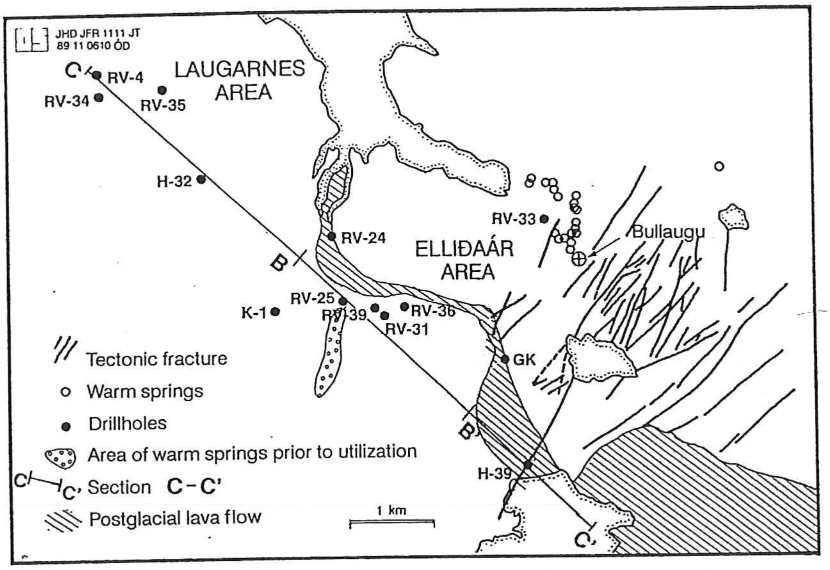

Fig. 2. Location of drillholes, cross-sections, thermal springs and geological features.

The Reykjavík geothermal areas are mostly covered by late Pleistocene olivine-tholeiites (the Reykjavík olivine tholeiite basalts) except for the Elliðaár postglacial lava flow, which flowed down the Elliðaár valley about 5600 years ago (Fig. 2). Faults and fractures associated with the Krýsuvík fissure swarm are prominent in the eastern part of the Elliðaár geothermal area (Fig. 2)

The subsurface geology

The stratigraphical sequence is divided into three units (Fig. 4 and 5) which is a simplification from Tómasson et al. (1977). These are: Unit-1) Upper Basalts, from surface down to 350-400 m depth (Fig. 4-6), previously termed B-1 and B-2. Unit-2) Hyaloclastites, from 350-400 m and down to 950-1050 m depth. This unit was previously termed M-1, B-3, M-2, B-4, and M-3. It is composed predominantly of three hyaloclastite formations (M-1, M-2 and M-3), and two basalt formations (B-3 and B-4). Unit-3) The Lower Basalts, is found below the hyaloclastites, from 950-1050 m and down to about 1800 m depth (Tómasson et al., 1977; Smárason et al., 1988).

Alteration is low in the Upper Basalts, and the rocks are almost fresh down to about 170 m depth. The Hyaloclastites and the Lower Basalts are, however, fairly altered (Smárason et al. 1989).

Faults, fractures and intrusions (dykes and inclined sheets) play an important role in the hydrology of the area. Their hydrological importance will be discussed later.

Individual fields

The Elliðaár area can be divided geographically into 7 separate fields (Fig. 3). This division, entierly based on hydrological data on relative draw-down are from Thorsteinsson (1970). These fields are: Western field, Southern field, Production field, Eastern field, Höfðabakki field, and Grafarvogur field.

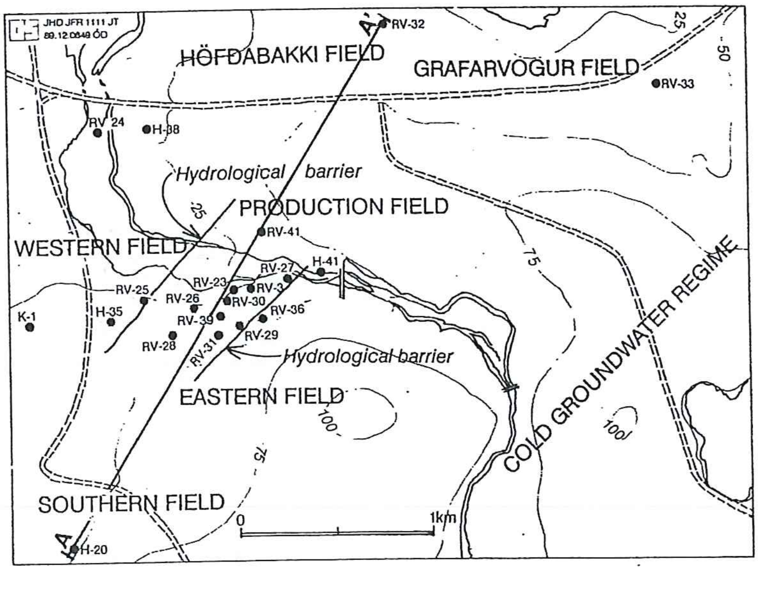

Fig. 3. Location of drillholes, geographical division of the Elliðaár area, the cross-sections A-A'. The two lines mark the production field to the west and the east (hydrological barriers).

The Western field: Drillholes RV-25, RV-24, K-1 and H-38 are located in the Western field. The draw-down is only 4-22% of the draw-down in the production field (Fig.3). The nearest drillhole in the production field is only about 200 m (Fig. 3) but draw-down decreases with increasing distance from the production field. Temperature logs indicate about 100°C (Fig. 3) hot hydrothermal system below 1000 m depth. **The Southern field:** Drillhole H-20 is located in this field. The draw-down in drillhole H-20 is only about 1% of that of the production field. The temperature above 400 m is much lower than within the producton field. **The Production field:** The producton field at Elliðaár is discussed in detail later. **The Eastern field:** Drillhole RV-36 is the only drillhole located in the Eastern field. The aquifers of this drillhole do not seem to be directly connected with the producton field. The water table is higher than in the producton field, and the hydrological tests below 1200 m depth in drillhole RV-36 showed little connection with drillholes in the production field (Tómasson 1988). **The Höfðabakki field:** This field is located north of the production field. Drillhole RV-32 is situated here. The draw-down, because of pumping in the production field, is 26%. This must be regarded as fairly good connection, considering that RV-32 is about 1000 m from the edge of the production field. The water table in drillhole RV-32 fluctuates in phase with pumping in the production field (Thorsteinsson, 1970). The highest temperature in the area (115°C) was measured in the bottom of RV-32 (1359 m). **The Grafarvogur field:** There is a fair number of warm springs in the Grafarvogur field. They have not disappeared since pumping began in the production field. Draw-down of several meters has been observed in drillhole RV-33. This occured several years after production began in the area.

Classification of aquifers

The temperature curves of the drillholes in the production field, and in the only drillhole of the eastern field (RV-36) have a temperature reversal. The temperature maxima of 100-110°C is at 500-1000 m in most drillholes (400-1380 m in drillhole RV-41). The temperature drops by 20-30°C below 1000 m depth (Fig. 4 and 6). The Western field, Höfðabakki field, and Grafarvogur field have convection cells or up-flow of 100°C, or hotter water below 1000-1200 m depth. A drillhole is needed in the Southern field to confirm which type of hydrothermal system exists there.

There are two water systems in the area, i.e. a geothermal one and a cold water system, which is some order of magnitude larger than the former. The main part of the cold water system is situated east of the geothermal area. It reaches down to 800-1000 m depth towards the northeastern part of the Krýsuvík fissure swarm (Fig. 3).

A small part of the cold water system penetrates into the geothermal system, especially in the uppermost part and the eastern part of the area (Fig. 3). Thickness of the cold water above the geothermal system is from zero to some tens of meters. The aquifers in the Elliðaár area are divided into three groups. The uppermost aquifers (A-aquifers) are found down to 300-500 m depth, and are 40-90°C. They are mostly confined to the Upper Basalts but reach down to the uppermost part of the Hyaloclastites. The middle aquifers (B-aquifers) are confined to the Hyaloclastite Unit. They form a temperature maxima of 100-110°C. The lowermost aquifers (C-aquifers) are confined to the Lower Basalts (70-115°C). The geothermal water and the cold water are side by side in the Upper Basalts, especially in the unaltered zone above 170 m depth. The geothermal water penetrates up through the cold water like a mushroom approaching the surface. The pressure in the A-aquifers was < 1 kg/cm^2 before production and 5.5 kg/cm^2 in B-aquifers (Tómasson 1988). All the fields of the Elliðaár area are hydrologically connected through the A-aquifers, especially via the uppermost aquifers.

The thermal and geological cross-section

Thermal and geological cross-sections have been described in some detail (Tómasson 1988). Two geological and thermal sections are discussed in this chapter, via section A-A' in Fig. 4 and section B-B' in Fig. 6.

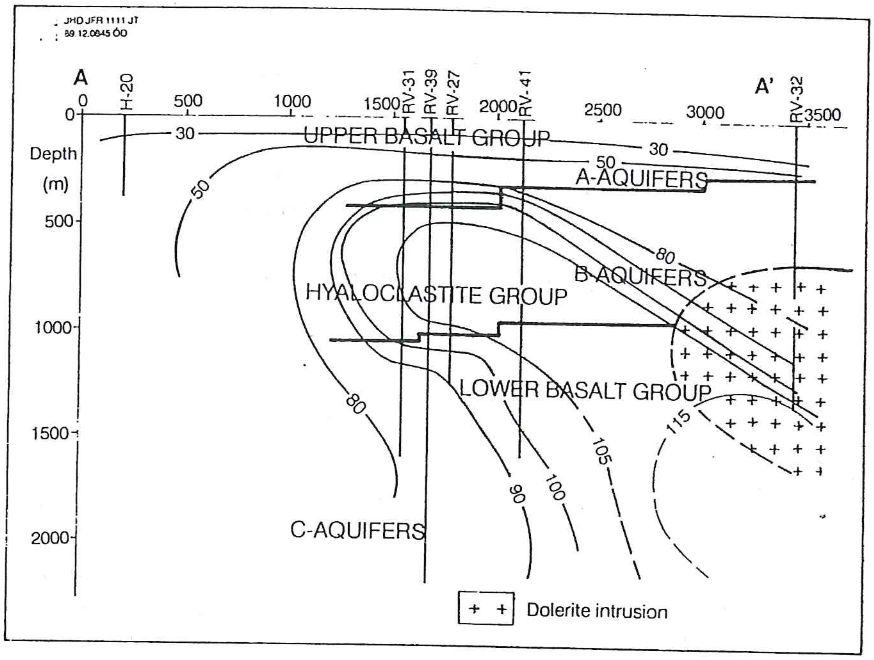

Fig. 4. Cross-section A-A' of temperature and geology.

Section A-A' is shown on Fig. 4 (Fig. 3 for location). It goes from drillhole H-20, across the hottest part of the production field and to drillhole RV-32. The section shows the geological units and the dolerite intrusion in drillhole RV-32. The temperature at the bottom 1359 m of drillhole RV-31 is 115°C. This could mean that the water in the "hot tongue" of the B-aquifers flows southwards from below the intrusion along a fault or fissure that disects the intrusion.

The "hot tongue" reaches higher and cools down towards south and is only 40°C at 400 m in drillhole H-20. The hydrological studies support this model, as there are hydrological connections between drillhole RV-32 and the production field through the A and B aquifers (Thorsteinsson, 1970).

Fig. 5 shows a hydrological barrier which separates the western field from the production field. The hot water flows up to the hyaloclastites and follows the barrier southwards to the northern part of the production field, where the water fans out toward south and creates a 100-110°C hot water tongue in the central part of the production field. A cooler system (70-75°C) is in the southwest part of the production field (Fig. 5). The origin of this system is not clear, but may possibly be the remainder of the reservoir into which the present hot water tongue intruded.

The possibility, however, that the cooler system is younger, i.e. water intrusion from the southwest, along tectoning fractures, cannot be excluded.

Cross-section B-B' (Fig.6) is nearly perpendicular to cross-section A-A' (cf. Fig. 2). The isotherms indicate clearly the "hot water tongue" especially the 105°C isotherm.

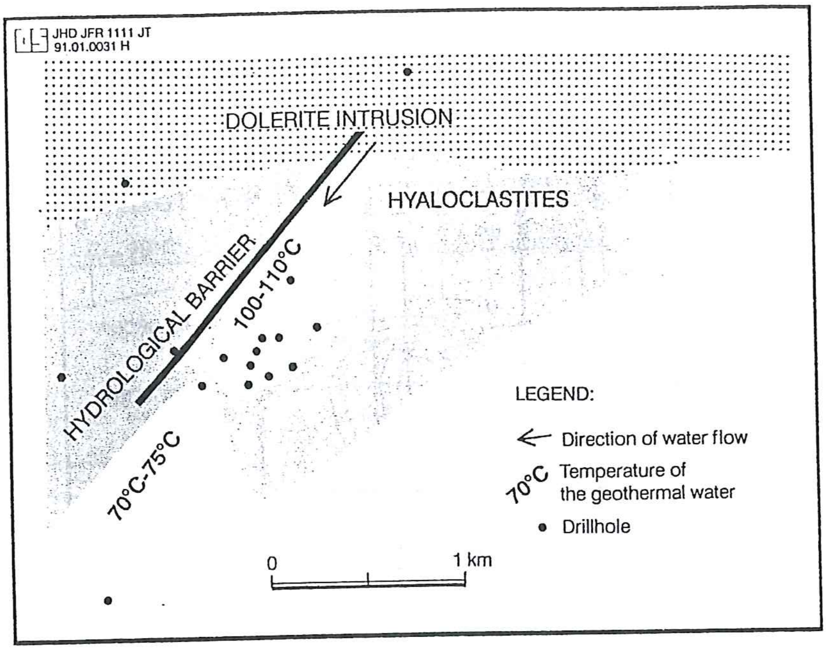

Fig. 5. The rock type, hydrological barrier and water flow at 800 m depth in the Elliðaár area.

Below the "hot water tongue" the temperature decreases and is more or less constant below 1300-1500 m depth to the bottom of the drillholes. The temperature in well RV-36 for example is 72-73°C below 1300 m depth.

There is a temperature increase of 30°C from RV-36 to RV-25 (bottom temperature 102°C) below 1500 m depth. This temperature increase occurs mainly in two jumps, i.e. between RV-36 and RV-31 (13°C), and between RV-39 and RV-25 (15°C). This means that there is a temperature jump below 1300-1500 m depth between the production field and the two fields to the west and the east of it (Fig.3). The temperature below this depth is relatively constant, 85-89°C, in the production field except in drillhole RV-28. This temperature jump between the production field and two other fields is one of the arguments for the hydrological barriers which are shown in Fig. 3 separating these fields and the production field. There are, as stated above, some hydrological evidence for hydrological barriers between the western field and the production field. Geological evidence indicates that this barrier is a fault (Tómasson 1988). The geology and special hydrological tests (inflatable packer) indicate that this fault is an effective barrier as high up as to about 450 m depth (Tómasson 1988; Tómasson and Thorsteinsson 1968). There are also geological indications for a fault between RV-36 (eastern field) and the drillholes within the production field (Tómasson 1988). Hydrological tests indicate that this fault forms a barrier up to 1200 m depth (Smárason et al. 1985) as there is no hydrological connection between RV-36 and the drillholes in the production field below that depth.

The isotope content of the water

Árnason (1976) mapped the deuterium content of rainwater in Iceland. The deutrium content is given as δD value. It varies between -50‰ to -100‰ and the deutrium value decreases away from the coast, and therefore the rainwater has an inbuilt tracer. It is possible to find where the geothermal water fell as rain or snow, by measuring the deuterium content in

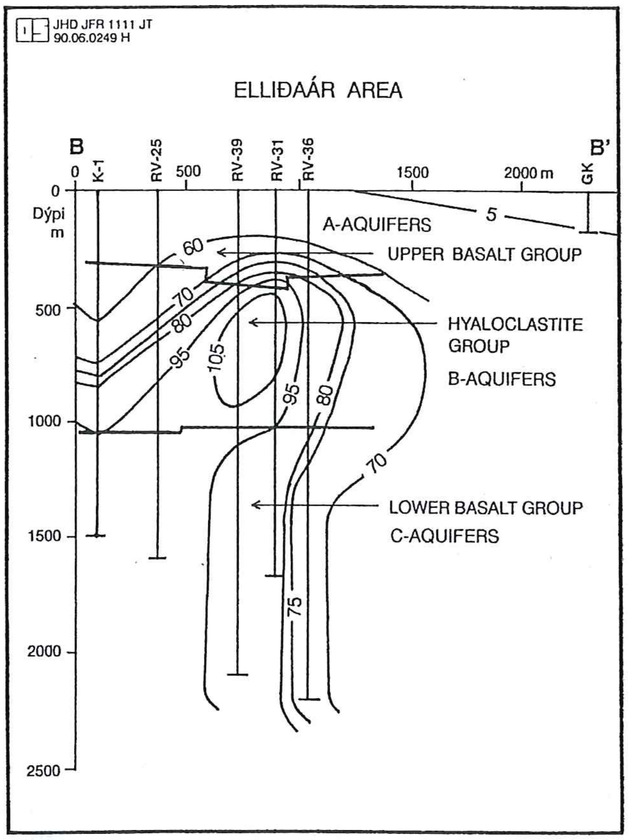

Fig. 6. Cross-section B-B' of geology and temperature.

geothermal water.

The isotope content of the water (the δD value) was measured in all drillholes of the Elliðaár area in 1968 to 1971, and in the Laugarnes area in 1960-1966. The Laugarnes area showed a slight variation and the average value was -65‰. The Elliðaár well field showed variable δD values, from -58.2‰ to -64.4‰. The first results for these isotope measurements in the Elliðaár area were reported by Árnason and Tómasson (1970), and all the measurements were made by Árnason (1976).

Árnason (1976) explained the variation in the δD values in the Elliðaár field as mixing of two groundwater systems. One was located north of the Elliðaár field and had a δD value of -65‰. The other one was located in the southern part of the field and had a δD value of -58 to 60‰. The δD values of the Elliðaár field are a mixture of the two. Tómasson et al. (1975) explained the difference in the δD values by the lighter water (δD = -64‰) being originated in the north. This water forms the hot tongue of the B-aquifers in the Elliðaár area.

Árnason's interpretation of the deutrium distribution in the Elliðaár area fits very well with the model of the geothermal system presented in this paper. The model assumes that the water in the "hot water tongue" comes from NE (has low δD value) and mixes with the colder with high δD value water in the SW as indicated in Fig. 7. However, the model of Tómasson et al. (1975) stating that the coldest water below the hot water tounge has a shorter flow path and higher δD-value than the water in the hot water tongue is still valid. Later in this paper new evidence is shown for a relationship between the temperature of the water and the length of its flow path. There is, however, a question of how much vertical mixing there is in a geothermal system with a temperature reversal.

3. NATURE AND ORIGIN OF THE LOW-TEMERATURE AREAS IN ICELAND

With special reference to Elliðaár area and its neighbourhood.

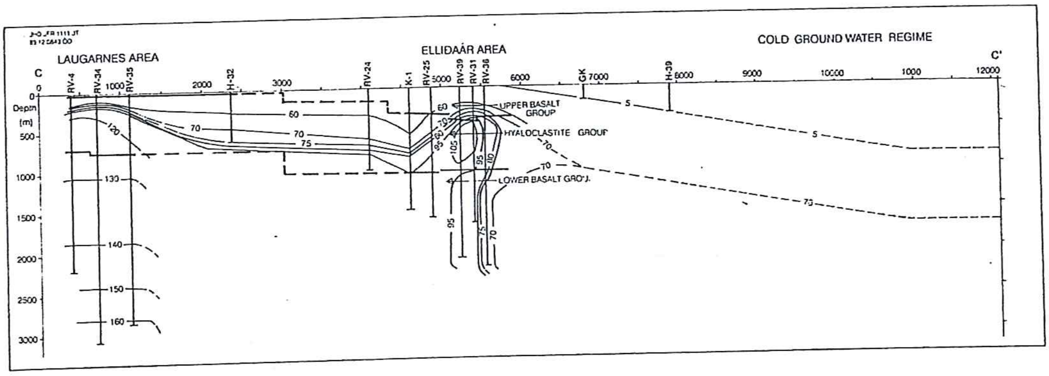

Fig. 7. Crosssection C-C' showing the geology and temperature. The location is shown in Fig. 1 and 2.

The heat condition of the Elliðaár- and Laugarnes areas is shown in Fig. 7. It shows a simplified thermal geological cross-section from drillhole RV-4 in the Laugarnes area to drillhole H-39 which lies 4 km east of the Elliðaár area (Fig. 1 and 2). From H-39 the hypothetical thermal cross-section extends some 3 km into the Krýsuvík fissure swarm. The location of the drillholes that are used in the section are shown on Fig. 2. The stratigraphy is the same as in Fig. 4 and 6. The easternmost drillholes are drillhole GK and drillhole H-39. The former is only 169 m deep, and is cold (5°C) all the way down to the bottom. Drillhole H-39 is 332 m deep and also 5°C down to the bottom. Both these drillholes therefore lie whithin the cold groundwater system.

One drillhole has been drilled through the cold groundwater layer in the Krýsuvík fissure swarm. This is the drillhole at Kaldársel that lies about 10 km south of cross-section C-C' (Fig. 1) on the boarder of the volcanic zone. The geology and temperature profile of the Kaldársel drillhole is shown on Fig. 8. The base of the cold groundwater layer is there at 750 m depth. This is in good agreement with the high resistivity in Fig. 1. The thermal gradient is 80°C/km beneath the cold groundwater system. If this thermal gradient is caused by a convective hydrothermal system deeper down, then it is possible to calculate the depth down to this system, that is to say if its reservoir temperature is known as shown in Fig. 7. There the 5°C isotherm is extended to 800 m depth. The 70° isotherm is paralell to this line. The depth of the isotherm is found by using the thermal gradient in the Kaldársel drillhole below the cold groundwater layer (80°C/km). This means that the 70°C isotherm would be about 850 m below the 5°C isotherm, which here means that when the 5°C isotherm is at 800 m, the 70°C isotherm would be at 1650 m depth. This could be the top of a convection system of a similar temperature as the convection system which is found in well RV-36 at

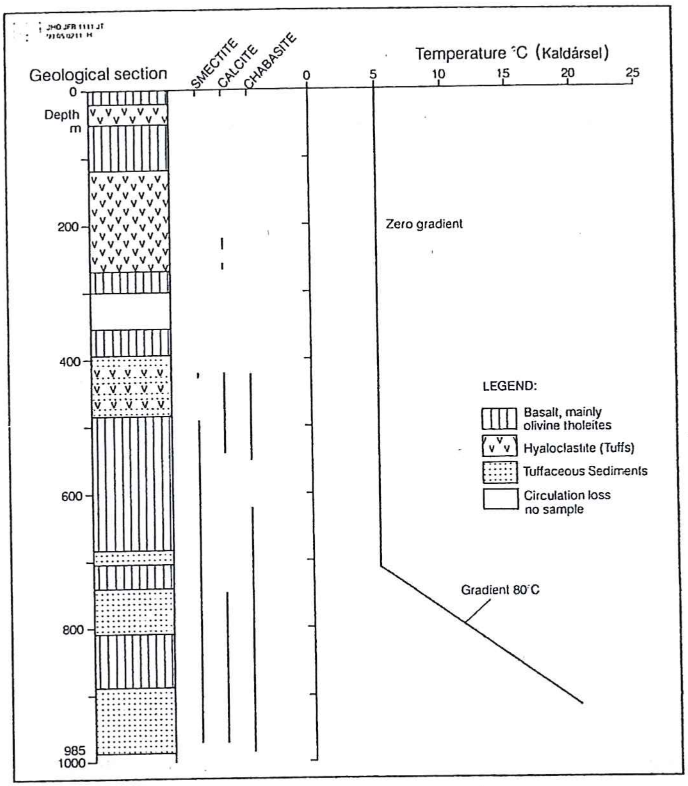

Fig. 8. A geological section showing secondary minerals and a schematic temperature curve from the Kaldársel drillhole. A small amount of smectite is present. It is badly crystallized and in most cases the structure is destroyed by heating. The calcite is in small crystals above 430 m depth but below calcite is found in bigger crystals in vein fillings. The amount of calcite is less than 1%. Chabacite is the most abundant secondary mineral with up to 10% both as regards cementing material in sediments and vein fillings.

Elliðaár, between 1300 and 2200 m depth. East of the Elliðaár area there are convection cells which are about 70°C hot. It is easy to see how the change of premises would work in this model.

Definition of ΔT

The conductive gradient has been mapped in Iceland and is found to be about 50°C/km in the Tertiary basalt furthest from the active volcanic zone. It increases toward the volcanic zone and may be as high as 150°C/km near the edge of the volcanic zone (Pálmason et al. 1979).

To compare the temperatures in the Elliðaár- and Laugarnes areas to what it would be if it was only determined by the conductive gradient, we will look at three thermal patterns on Fig. 9. First we look at the temperature profile of a 1400 m deep drillhole at Akranes. The temperature rises more or less constantly with depth, which means that the drillhole is undisturbed by circulating groundwater. This drillhole is ideal for the determination of the conductive gradient. As Akranes is about 25 km north of the Reykjavík thermal areas and further from the volcanic zone than the drillholes (Fig. 1) the conductive gradient in the Reykjavík thermal areas should be somewhat higher than at Akranes. The temperature

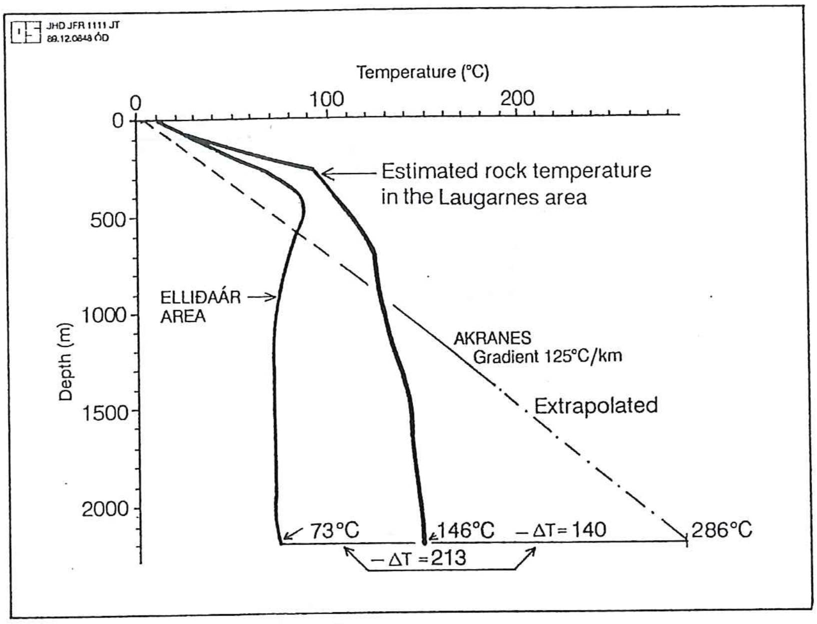

Fig. 9. Comparison of temperature curve from the Laugarnes, Elliðaár and Akranes areas. The Elliðaár area temperature curve is taken from well RV-36 which gives a reliable rock temperature. It was measured 144 days after completion of drilling. The temperature had changed little from the log measured 64 days after drilling.

profile from the Laugarnes area is combined from several drillholes. Only temperature logs which are undisturbed by cooling during drilling and of flow between aquifers in the drillholes are used (Tómasson 1988). This temperature profile should be characteristic for the rock temperature of the Laugarnes area. It characterizes an up-flow zone of a convection cell.

The third temperature profile is from well RV-36 at Elliðaár. It should give a good indication of the rock temperature around that drillhole, as the log was measured 144 days after completion of drilling and there were little changes from the previous temperature log 80 days earlier.

ΔT is here defined as the difference between the conductive temperature and the rock temperature at depth **m**. The conductive temperature on the other hand is the temperature at depth **m** as it should be according to the assumed conductive gradient. This difference is negative when the temperture is lower than it should be according to the conductive gradient and positive if it is higher. If the temperature pattern from the drillhole at Akranes is extrapolated down to 2200 m depth, the conductive temperature at that depth would be 286°C. The temperature at that depth is 146°C in drillhole RV-4. Thus, ΔT = -140°C. In well RV-36, the temperature is 73°C, and ΔT = -213°C (Fig. 9).

The ΔT-curves for different conductive gradients for the temperature curve from Laugarnes- and Elliðaár areas in Fig. 9 are calculateted in Fig. 10 and 11 and logs from drillholes RV-34 (3083 m) are used for the Laugarnes area below 2200 m. One ΔT-curve for the Kaldársel drillhole is calculated in Fig.11.

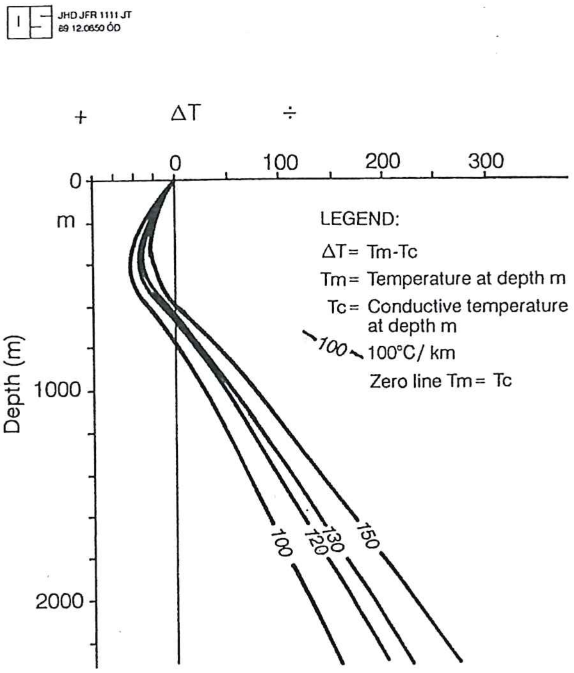

Fig. 10. Calculated ΔT-curves for different conductive gradients, from a temperature log in well RV-36. The conductive temperature is the temperature which should be at a certain depth according to the conductive gradient. The conductive temperature and the measured (rock) temperature are equal on the zero gradient line.

The use of the ΔT-curve is illustrated by using a different conductive gradient even though the conductive gradient is not exactly known as in this case. There is some uncertainity about the conductive gradient near the volcanic zone as described by Pálmason et al. (1979) and Pálmason (1981).

The ΔT-curves on Fig. 10 and 11 show some similarities. In the upper part the geothermal systems are hotter than they should be according to the conductive gradient, and ΔT is positive. Deeper in the system, ΔT is negative, i.e. the water has cooled the reservoir rocks. This cooling increases with depth in all cases, and the calculated cooling is greater if higher gradient is assumed. The maximum cooling is in the drillholes with zero gradient as in Kaldársel drillhole where the temperature is 5°C down to 750 m depth (Fig.8). The ΔT-curves are linear below a certain depth in the Laugarnes and Elliðaár areas, whereas ΔT is linear in the drillhole at Kaldáarsel from the top of the hole and the slope of the ΔT-curve and the temperature changes below 750 m depth. The ΔT-curve is therefore linear where the temperature is constant or where there is equal temperature increase with depth. The slope of the ΔT-curve is steeper where the temperature increases with depth, in the Laugarnes area, than in the Elliðaár area where there is nearly constant temperature below 1200 m depth. The ΔT-curve shows well the difference in temperature at Laugarnes and Elliðaár and the pattern of the ΔT-curve for 130°C/km conductive gradient (Fig.10) indicates 220°C cooling at 2200 m depth in well RV-36. It is necessary to go down to 3000 m depth in the Laugarnes area to reach the same degree of cooling.

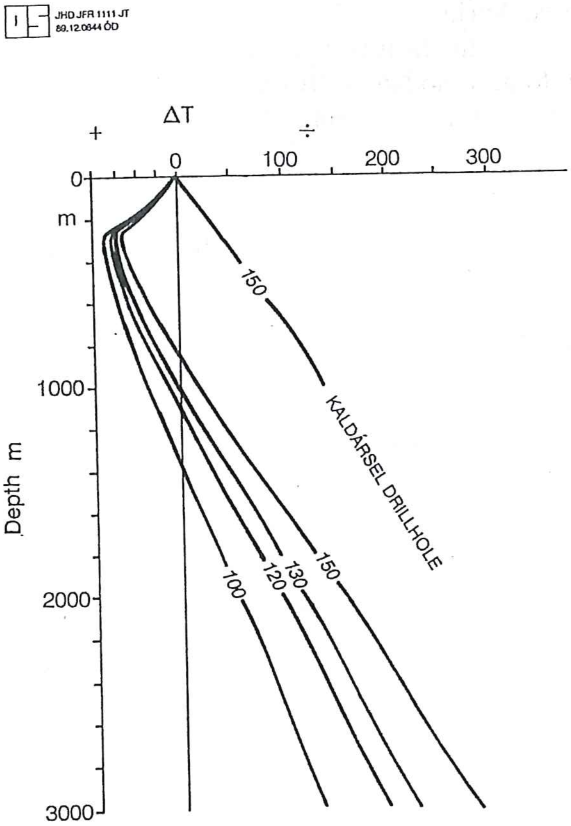

Fig. 11. Calculated ΔT-curves for the Laugarnes area, and the Kaldársel drillhole (c.f. Fig.10). Legend same as in Fig.11. The calculated temperature below 2200 m depth is taken from well RV-34.

By calculating the squareroot of the area between the zero line and the ΔT-curves (Fig. 10 and 11) we get the relative measure on cooling or heating for a certain conductive gradient. Such calculations show that the Laugarnes field has a cooling factor of 2-13, whereas the Elliðaár field has a cooling factor of 7-27.

Previous work on the nature of low-temperature areas

The low-temperature geothermal water is of meteoric origin. It is a part of the general groundwater flow, that has circulated through hot rocks at some depth in the crust (Einarsson, 1942). Deuterium isotope measurements confirm this (Árnason, 1976). According to the hypothesis the geothermal water which is found in hot springs and drillholes falls as rain at great distance (even hundreds of kilometers) away from the springs or drillholes where it is issued. The driving force of the water from one place to another is the difference in the hydrostatic pressure between the two places. The temperature of the water affects the movement of the water in addition to the gravitional force. The velocity of the flowing water is directly proportional to the pressure difference and the permeability, but inversly proportional to the distance.

Einarsson's (1942) model on the origin of the geothermal areas assumes that there is an equilibrium between the heat flow and the heated water. Some doubts have arisen about the existence of such an equlibrium. The hot springs in Borgarfjörður in western Iceland, would for example have to obtain the heat flow from such a vast area that it would be difficult to find enough rock volume to accomodate it (Bödvarsson 1961 and 1982). Bödvarsson (1961, 1982 and 1983) has suggested a transient nature of the low temperature geothermal activity.

Thermal mining

The state of knowledge and the nature and origin of the low-temperature activity in Iceland has been discussed above. There are two main theories about the nature of the energy in the low-temperature activity, i.e. the steady state theory (Einarsson 1942) and the transient nature of the geothermal activity (Bodvarsson 1961, 1982 and 1983). The transient nature of the low temperature activity means that circulating water is equivalent to mining heat from the rock it passes through. This process will in the following text be called thermal mining. This discussion of the nature of the geothermal energy has focused on the energy of the outflowing water, i.e. temperature and yield.

It has already been proven that the thermal mining is going on inside the geothermal systems at Laugarnes and Elliðaár, by using ΔT-calculation, which shows that the upper part of the systems have been heated up, but the lower part has been cooled, compared to the conductive gradient. The cooling is greater than heating and might be up to 27-times. This meens that it is going on thermal mining inside the geothermal systems. But there are many questions unanswered conserning this thermal such as age of the thermal mining and is the thermal mining going on outside the thermal areas? In this purpose we shall now focus on the temperature of the rock in the geological and thermal section C-C' in Fig. 7. The temperature in the NE-Krýsuvík fissure swarm which extends out of the volcanic zone (Fig. 1) is about 5°C down to 800-1000 m depth which means that all the heat has been mined from the rock at this depth interval. The temperature in the coldest wells (RV-36) in the Elliðaár field is 73°C at 2200 m depth. Fig.10 shows a 213°C cooling at 2200 m depth in RV-36, whereas the cooling at the same depth in Laugarnes area is 140°C.

The water at 2200 m depth in well RV-36 has only flowed 5-6 km from the downflow zone according to the hydrological model in Fig.7. The water in Laugarnes area has, on the other hand, flowed 40-50 km as indicated by the isotopic composition of the water (Árnason 1976). The thermal mining is therefore greatest in the down-flow zone as the water is coldest there and the difference between the rock temperature and the water is greatest.

In order to have thermal mining, the rock permeability must be so high that the water absorbs more heat from the rock than the heatflow adds to it. The thermal mining increases with increasing permeability and reaches a maximum when the flowing water absorbs all the heat from rock as is e.g. occuring in the northernmost part Krýsuvík fissure swarm down to 800-1000 m depth. It is therefore the permeability and the distance of the geothermal field from the down-flow zone that controls the magnitude of rock cooling. Good permeability is needed for high degree of cooling, but the permeability does not have to be uniformly distributed. The deeper the permeable aquifers reach, the greater the cooling becomes. The low temperature at 2000 m depth in the eastern part of the Elliðaár area could be caused by aquifers below present drillholes.

Pálmason (1981) suggested that according to sea-floor spreading models, fissures above 2000 m would get compressed. Below 2000 m they would on the other hand expand (open up) because of spreading in areas close to the volcanic zones. This supports the hypothesis that we might expect greater permeability at greater depths in the Elliðaár field.

ΔT informs us about the amount of cooling. It only tells us about the volume of the rock cooling inside the geothermal systems but nothing about the rate of the cooling. The hydrological model shown in Fig. 7, indicates that the thermal mining is going on east of the Elliðaár area into the Krýsuvíkur fissure swarm. The model also indicates that the thermal mining is going on in the NE-part of the Krýsuvíkur swarm within an area of about 100 km^2 which is greater than the thermal mining measured in RV-36. We know from drilling that the thermal mining reaches down to 3 km which infers that there could be some 100 km^3 of rocks being thermally mined east of Elliðaár area, but only a fraction of the water which has been heated by these rocks will come to the Elliðaár area. It is not unreasonable to assume that the rock volume outside the Elliðaár area which participates in the heating up of the geothermal fluid is an order of magnitude greater than inside the reservoir. The rock volume which has been cooled is sufficient to allow the hypothesis that the thermal mining is one of the main energy sources for the low-temperature system in question if the time scale is in the order of 10.000 years (cf. Bödvarsson 1983). The alteration of the rocks informs us on the relickt rocks temperatures. The alteration in the Kaldársel drillhole indicates (Fig. 8) that the temperature of the rock which the hole disects has always been lower than the conductive gradient. The bottom of the hole may always have been 90°C colder than the conductive gradient shown in Fig. 8 and 12. But the alteration indicates also that the temperature in the rock has been a little higher than is now measured in the drillhole, or 40-50°C at 412 m depth (cf. Fig.8).

If the alteration in the drillhole at Kaldársel (Fig. 8) is typical for the rocks of the northern part of the Krýsuvík fissure swarm, then the temperature in the uppermost 1000 m must always have been lower than the conductive gradient. This means that a part of the thermal mining is of a similar age as the rocks, or dating back at least a few hundred thousand years. But the present rock temperature is still lower than the alteration temperature. This could mean that the thermal mining may be different from one time to another and may be at its maximum now.

The geothermal areas at Laugarnes and Elliðaár are both within a fossil high temperature field with temperatures up to about 300°C according to alteration mineralogy (Tómasson et al. 1977; Smárason et al. 1989). It is likely that the area was a high temperature field when it was located within the active volcanic zone about 1-2 million years ago, and that it drifted out of the active zone and cooled down. The thermal mining could therefore be a process which is operating as a part of crustal rifting. Even though the thermal mining is a continuous process, there is no reason to assume that it is always gradual, because many geological processes are discontinuous, e.g. tectonism and climatic changes (ice ages).

The Ice Age was a major geological change affecting all groundwater flow by hindering water recharge and thus lowering of the water table, especially in the case of an arctic glacier where there is no water under the ice cap. The lowering of the watertable would furthermore cause the groundwater flow to slow down or even come to a hald. The water table would rise again at the end of each glaciation, and the permeability may have increased because of lowered pressure in the crust that followed deglaciation. Böðvarsson (1983) suggests that thermal mining may have started at the end of the last glaciation.

Resistivity surveys show that most of the volcanic zone is relatively cold down to several hundred meters depth (Björnsson 1971). The situation may have been similar along the whole of the volcanic zone. Therefore we can assume that the thermal mining is important for the energy balance of the low-temperature areas in general, but if the down-flow zones in the volcanic zones are similar to what we observed in the Kaldársel drillhole then this down-flow is a permanent feature from the time the rocks were put in place (upper most 1000 m) and the rock has never been heated up to the conductive gradient. The alteration in the Laugarnes-and Elliðaár areas indicates a much higher temperature than is presently observed there, so a real cooling has occured there. This cooling is, however, old as stated above and probably related to curstal rifting.

The following hypothesis could further illustrate the mechanism of thermal mining. The thermal mining is probably of the same age and a consequence of crustal rifting. It is at each time greatest within and at the margin of each fissure swarm in the active volcanic zone. It is reduced as the rocks get older and rock fracturing (permeability) decreases. Although thermal mining is considered to be a gradual process, extending over geological time intervals it most probably divides into distinct shorter-lived episodes connected e.g. to fracture anomaly and climatic changes. Thermal mining is presently likely to be high, since only 10,000 years have passed since the last glaciation ended succeeding a glacial period of about 70,000 years. It is likely that precently mining of the heat that was stored and collected in the rock during the last glaciation is taking place. It is possible to see indications of somewhat higher temperatures in the alteration of the rock, as in the drillhole at Kaldársel. This has, however, not heated the rock up to the value that could be expected from the conductive gradient.

4. RESPONSE TO PRODUCTION

Production in Elliðaár area began in 1968. The maximal pumping rate has been about 200 l/s and the maximal draw-down is about 140 m. The amount of water pumped from the area up to the end of 1987 was 74 Gl (Fig. 14). In the beginning the average temperature of the water pumped from the area was 104°C. The water was and still is low in chloride, about 16 mg/l, which is the same as in the rain water in the area. Silica is in accordance to the temperature (Gunnlaugsson 1982). Silica and fluoride have decreased since utilization began as a result of the cooling of the water.

Considerable cooling has taken place in the Elliðaár field, or about 0.5°C/year on average during the last 12 years (Vatnaskil Consulting Engineers, 1982). The cooling seems to have continued at a similar rate. The cooling is shown in table 1. It has been variable from one drillhole to another, and about 6-21°C in drillholes that were drilled in 1967-1969 (Table 1).

In table 1 the cooling varies from one drillholes to another and appears to be greatest in the wells in which the B-aquifers give the highest proportin of the water, whereas the A-aquifers are always small (the size of A-aquifers may, however, be underestimated). Both these columns and the temperature measurements in the drillholes (Tómasson, 1988) indicate that the cooling is mostly confined to A- and B-aquifers. The temperature curve which indicates cooling is of two types, i.e. general cooling as a result of downflow in the drillhole, and cooling of individual aquifers.

Cooling of the A-aquifers and down-flow in the drillholes.

The cooling of the A-aquifers is easily explained by the hydrology of the area where geothermal water projects like a mushroom into the cold groundwater system.

When the pressure decreases in the A-aquifers due to pumping, the cold water migrates into the A-aquifers.

An example of (a measurement of) cooling caused by down-flow in a drillhole is shown by three temperature measurements in well RV-25 (Fig.12). There are two aquifers in this drillhole; at 300 m in the A-aquifers and at 1470 m depth in the C-aquifers. Just after drilling was completed in 1968 there was free flow from the drillhole, and 100°C water flowed up the hole from 1470 m. The 100°C water was mixed with water from the aquifers at 300 m depth and the mixture was 74°C at the well head. By 1972 the pattern of flow in the drillhole had

TABLE 1. Cooling of water from the production wells

Well No	Drilling completed year	Proportional yield at A, B and C aquifers during drilling 1) and after 2)	Initial temperature °C	Temperature 01.02.87 °C	Cooling °C
RV-23	1967	A 6%, B 42%, C 52%	100	94	6
RV-26	1968	A 1%, B 99%	110	98	12
RV-29	1969	B 100%	111	90	21
RV-30	1969	B 70%, C 30%	105	91,8	13,2
RV-31	1969	B 10%, C 90%	94	87,8	6,2
RV-36	1980	B 7%, C 93%(B 30%, C 70%)	80 3)	78,6	1,4
RV-37	1981	B 20%, C 80%(B 50%, C 50%)	92	89,4	2,6
RV-39	1984	B 64%, C 26%(B 80%, C 20%)	103	103,5	

1) The ratio of circulation losses or circulation gains during drilling.

2) The permeability of the B-aquifers increases more in the stimulation tests than that of the other aquifers. The numbers in brackets indicate likely ratios after stimulation.

3) The highest temperature was 82.8°C in 1984.

changed, and 63°C hot water flows down the hole and cools the drillhole by 30-40°C from 300 m down to 1500 m depth.

The reason for down-flow in drillholes is explained by pressure drop in the lower aquifers to below the pressure of the upper one. The fact that the down-flow is always from the A-aquifers must indicate that the pressure of that aquifers has decreased less.

The explanation of this is that the hot water in the A-aquifers is surrounded by a cold groundwater system. There are no geological barriers between these two systems, so when pressure drops occurs in the A-aquifers (because of production) the cold groundwater flows into the A-aquifers which maintains a relatively high pressure after cooling begins. The reason for this is that the cold groundwater system is enormous in size compared to the hydrothermal system. The pressure drop in the hydrothermal system therefore does not influence the pressure in the cold water system.

The down-flow of water in the drillholes depends on several factors:

1) There must be at least two aquifers in the drillhole and one of these is in contact with the cold water system.

2) The flow between the aquifers is directly proportional to the permeability of the aquifers.

3) The flow between aquifers is directly proportional to the pressure difference between the aquifers.

The pressure difference between aquifers is not directly proportional to the total draw down (pressure drop) in the drillholes, i.e. during pumping from a drillhole the pressure in all aquifers is equal and the same as the total draw-down in the well. Pumping from the A-aquifers decreases the danger of a down-flow in well.

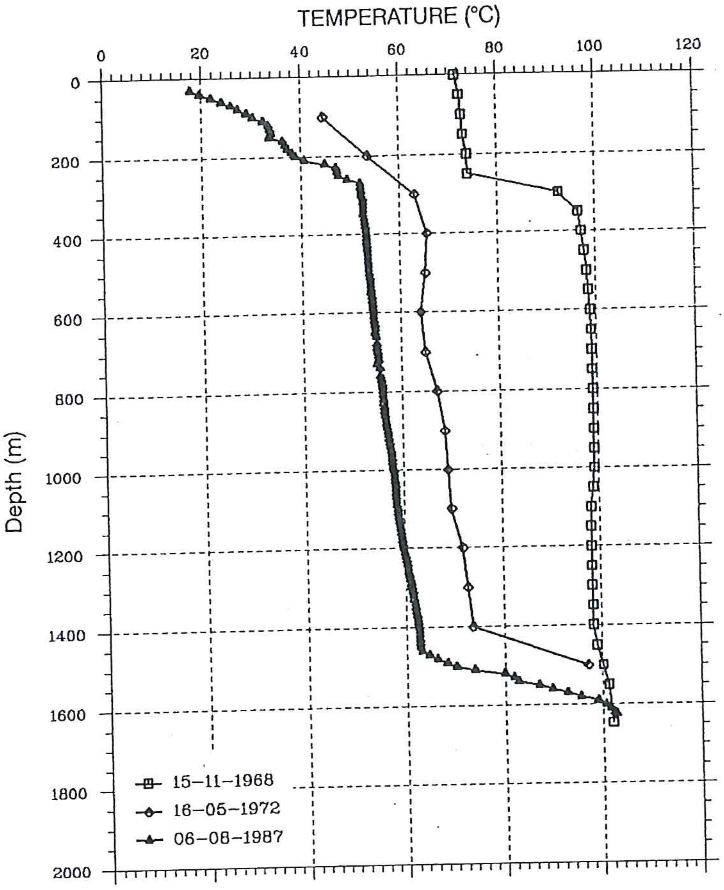

Fig. 12. Temperature curve from drillhole RV-25.

Down-flow is present in all drillholes outside the Elliðaár production field and the down-flow seemed to some extent greatest in the drillholes which have highest draw-down. The total pressure decrease the pressure difference between aquifers (3).

The A-aquifers has cooled most in the production field (20-50°C) because the hot water which is pumped from the aquifers is replaced by cold groundwater. The cooling affects individual aquifers, but the bulk rock seems less affected by the cooling as best illustrated in well RV-27 where no cooling has occurred because it cuts no A-aquifers. The cooling of A-aquifers in the drillholes outside the production field is small and is in most cases less than 10°C. In one case (well RV-32), no cooling is observed even though there is down-flow in the well. This means that there has been a pressure increase in the A-aquifers, caused by the cold groundwater system, even though the cold water has not yet reached the drillhole.

The A-aquifers in well RV-33 has cooled by about 40°C. This drillhole is farthest from the production field and least affected by pressure decrease (<5 m) from the production (pumping). There are the big cold water springs (Bullaugu) some hundred meters east of the drillhole. There is also indication that this cold water system reaches the drillhole in the uppermost 50 m (Tómasson 1988). Because of the strong water system near the drillhole only a small pressure decrease in the hot water system is needed for the cold water to invade the A-aquifers.

The cooling from the side

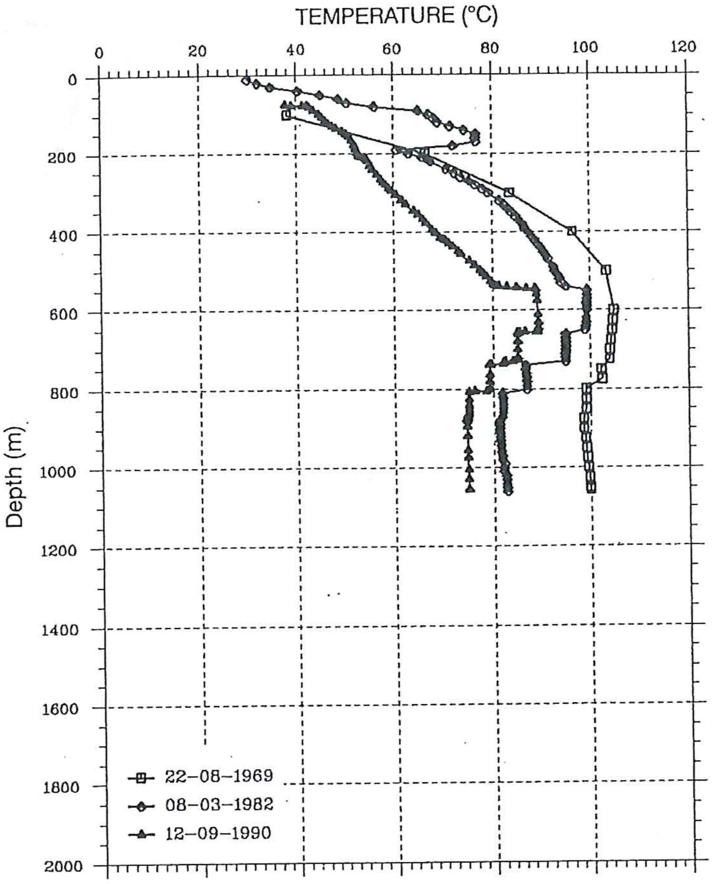

Fig. 13. Temperature curve from drillhole RV-29.

Temperature curve from drillholes RV-29 and RV-30 are shown in Fig. 13 and 14. In both these drillholes cooling has occurred in the deeper parts of the drillholes. In RV-29 beneath 800 m and in RV-30 between 700 and 800 m depth. The coldwater intrusion comes from the sides, probably from the southeast. The cooling of drillhole RV-29 could be explained by temperature levelling in the geothermal system, which fits with the location of the drillhole in the southeastern edge of the hot water tongue as illustrated in Fig. 6 and 7. When pumping begins from the well, the water in the permeable zones which the drillhole cuts is replaced by colder water from the southeast. The cooling will decrease with time as there will be larger amounts of rock which contain water with the same temperature. This is reflected in Fig. 15 where the cooling rate of the water from RV-29 has decreased as the water temperature approaches 90°C, which is similar temperature as indicated by the chemistry of the water responsible for the cooling (Gunnlaugsson 1982) and also similar to the temperature of the B-aquifers in drillhole RV-36.

This temperature levelling is only a temporary prosess, which is replaced by direct inflow of cold groundwater. The pressure increases in the cooling aquifers in RV-29 which supports this statement. The downflow in the hole indicates this pressure increase. The downflow is observed from from the temperature curve and the flowmeter and is greatest from 800 m to the bottom. The downflow was only detectable from 630 m depth by the flowmeter. There is therefore a downflow into the bottom aquifers which have cooled much less than the 800 m aquifers and the temperature curve shows only temperature of the inflowing water which cools the rock around the aquifers, for a relatively small distance from the hole bottom.

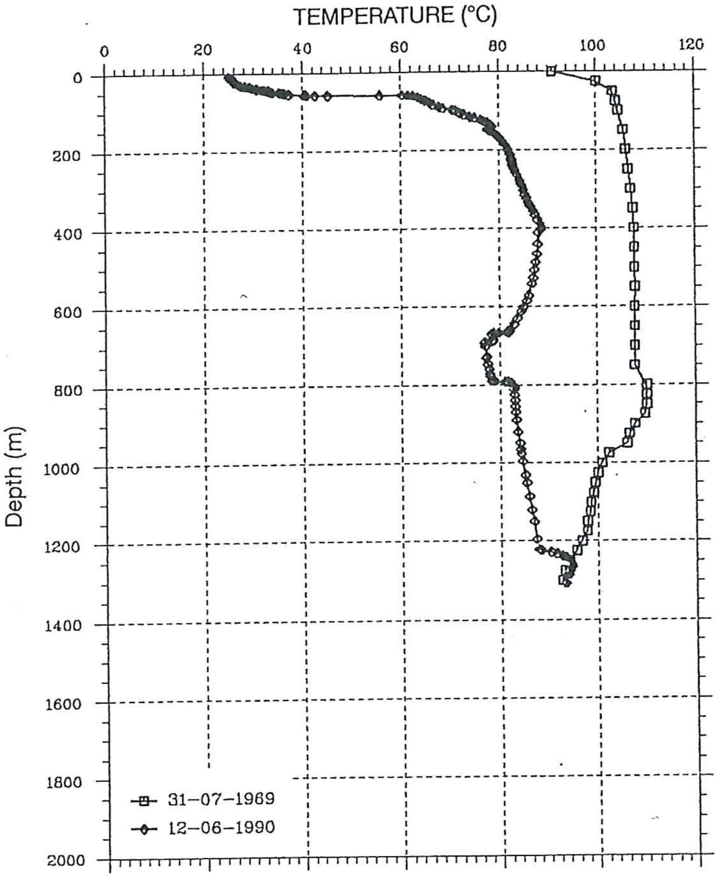

Fig. 14. Temperature curve from drillhole RV-30.

There are two other hydrological observations which support the statement above. The geothermal water will be replaced by cold groundwater, i.e. the draw-down with time stops after two months (Vatnaskil 1982). On the other hand the water table rises by about 100 m in one week after pumping is stopped. The stop of draw-down with time means that the total inflow of water into the system is equal to the water pumped from the system (probably mostly cold groundwater). The time lapse between the beginning of pumping and the detection of the inflowing water by the draw-down curve indicats that the main inflow of cold water is either at some distance from the production field or there is low permeability between the cold groundwater system and the geothermal system. However, the rapid rise of the watertable after pumping is stopped indicates good permeability between the cold water system and the geothermal system. Therefore the inflow must be at some distance from the production field which could well be the fissure swarm east of the area (Fig. 2). Thus, the main reason for the cooling is inflow of cold groundwater replacing the geothermal water pumped from the system. The main part of this inflow occurs outside the geothermal system and therefore a part of the rock which is cooled by cold groundwater lies outside the geothermal system.

The cold water inflow from the southeast is most likely along fissures which have nearly NW-SE direction or a fissure which is perpenticular to the main fissure direction. This must be so because the greatest cooling is in RV-29 and RV-30 and these drillholes form a line (a little more N-S) as shown on Fig. 16, and RV-30 is in the midle of the production field. The inflow of cold water into the geothermal system results in pressure increase of the aquifers into which the cold water flows. Therefore the cooling of B-aquifers is not only horizontal but also vertical, that is downflow in the system is similar to that which has been described for the A-

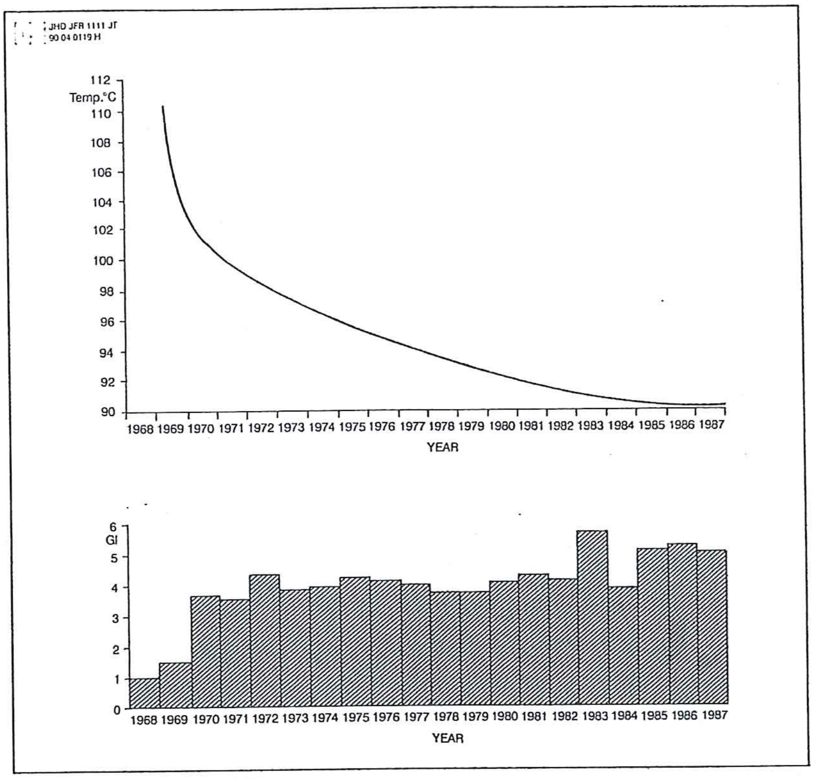

Fig. 15. Cooling in well RV-29 with time, along with the amount of water pumped from the Elliðaár geothermal system from beginning of utilation up to 1987.

aquifers.

The discussion above has dealt with the cooling of the A and B aquifers. There is, however, no indication of cooling (from the temperature curve) of the C-aquifers except through production wells from the down-flow from the A-aquifers in drillholes to the C-aquifers. The cooling of the water (Table 1) indicates that there is little cooling in wells where the C-aquifers are dominant.

Reaction to cooling

What can be done to slow down the cooling? We discussed earlier how the cooling is controlled by cooler water that flows into the field after production begins. Let us look at the four factors that chiefly control the pattern of cooling, and see if they can be measured and if it is possible to influence them and change the cooling pattern. These four factors are:

1. The temperature of the water that flows into the geothermal system.
2. The amount of water that flows into the geothermal system.
3. The original temperature of the rock that the water is cooling.
4. Volume of hot rock that is being cooled.

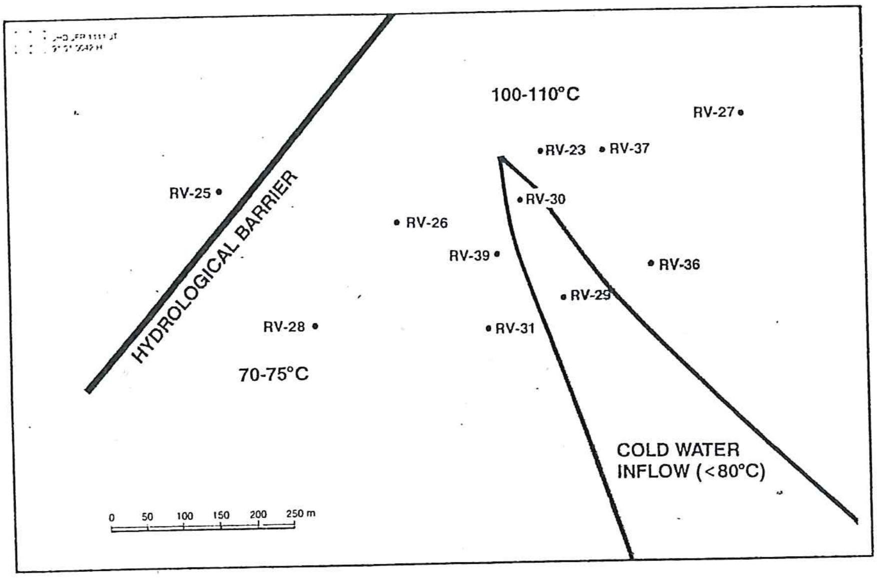

Fig. 16. The cold water inflow and the original water flow at 800 m depth in the production field (see also Fig. 5).

The answer to the first point is known: The water cooling the A-aquifers is cold groundwater, 5°C.

The second point: The volume of cold water that flows into the geothermal system can never exceed the amount that is pumped out. Chemical analysis and/or isotope measurements could reveal the ratio of cold water that has mixed into the geothermal water, and therefore the amount of cold water that has flowed into the system. This could, however, be difficult if there are two types of water of different temperatures but similar isotope ratios.

The third point: The initial temperature of the rock that is being cooled is fairly well known, especially in the B-aquifers. The initial rock temperatures in the A-aquifers is more uncertain. It should be possible to observe the changes in rock temperatures through observation drillholes.

The fourth point: Cooling is taking place in aquifers A and B. It does not seem to penetrate below 1200 m depth. The volume of the rocks which contain A- and B-aquifers can be estimated. The rocks which contain the A-aquifers are 2-3 km^3 and the rocks which contain B-aquifers are likely to be less than 1 km^3 but the water which is cooling the B-aquifers is cooling rock outside the geothermal area and the volume of that rock is unknown (Tómasson 1988). The heat energy of the rock mass which contains the A-aquifers will most likely not be fully utilized, since the down-flow from this aquifers is confined to narrow channels. It will also be cased off in future and the water will not be used directly for production. The water from this aquifers will on the other hand eventually flow down into deeper aquifers through confined fractures and channels.

Most of the thermal energy in the rockmass which contains the B-aquifers can be used down to the minimum temperature of the water which is useable for domestic heating. This is due to the fact that many of the aquifers are sub-horizontal and effectively withdraw the thermal energy from the rock. However, the volume of the rock which the water is cooling and is intruded into the B-aquifers is bigger than the rock which confines the B-aquifers, as the water is likely to have come from some distances, as described above.

Only a small fraction of the rocks which contain the B-aquifers have been cooled, and the greatest cooling is along a permeable structure NE-SW abovee 800 depth. Aquifers in drillholes that were drilled after 1980 show no indication of cooled aquifers, except perhaps for slight cooling in well RV-37. This could be explained by cooling of aquifers during drilling. This drillhole lies in the eastern part of the well field and it is therefore likely that some cooling has taken place.

What can be done to stop or reduce the rate of cooling? The cooling resulting from the down-flow from the A-aquifers and the aquifers in B-aquifers which have got pressure increase by cold water inflow. This flow from cooling aquifers to lower aquifers through drillholes can be stopped by recasing the sections of the drillholes which contain the cooling aquifers. The down-flow from the cooling aquifers would, however, continue through vertical structure in the rocks, i.e. through the same flow path (fissure and fault) which earlier brought the hot water to the A-aquifers. This down-flow will increase if the pumping from the cooling aquifers were to be stopped, because there would be a pressure increase in the cooling aquifers. By letting all waterflow from the cooling aquifers penetrate through the rock, the down-flow would be heated by the rock and the cooling effect of the water would be delayed perhaps for some years. The down-flow can, however, begin again in the recased drillholes and other drillholes with deeper casings because the pressure effect from the cold water system will gradually penetrate deeper into the geothermal system with time. This has been experienced in the Selfoss geothermal area which has been utilized for 40 years (Tómasson and Halldórsson 1981). The pressure effect from the cold water system at Selfoss now reaches down to 650 m depth, where all the cooling comes from cold water system above the geothermal system. The cooling in B-aquifers (from aside) can also be answered by drilling new wells, in that part of the system, where little or no cooling has occured.

5. CONCLUSIONS

1. The rocks in the Elliðaár and Laugarnes areas are of Quaternary age. The Krísuvík fissure swarm which extends NW from the volcanic zone lies only a few km to the east of the Elliðaár area. There are two groundwater systems present in the Elliðaár area, i.e. the geothermal system and the cold groundwater system which can be from zero to some tens of meters thick inside the Elliðaár area, but deepens to the east and extends down to about 1000 m depth in the Krýsuvík fissure swarm.
2. The subsurface geology formation is divided into three groups, i.e. the upper basalt group; the hyaloclastite group; and the lower basalt group. The aquifers are grouped in a similar way; the A-aquifers which reaches down to 300-400 m depth and is mostly confined to the upper basalt group; the B-aquifers which is confined to the hyaloclastic group (down to 1100-1200 m); and the C-aquifers which is confined to the lower basalt group.
3. The Elliðaár area is divided into several sub-fields, one of which is the production field. In the production field there is a temperature reversal. It has a 100-110°C hot water tongue flowing in from the north between 400-1200 m depth which cools and mixes with more local water toward the south. The aquifers below the hot water tongue contain 72-85°C water.

4. The temperature increases at 2000 m depth by 74°C (72-146°C) from the easternmost drillhole in the Elliðaár area to the Laugarnes area. The 72°C hot water is assumed to come from the Krýsuvík fissure swarm and the circulation path of this water is less than 10 km, whereas the hottest water in the Elliðaár area and the water in Laugarnes have a circulation path of some 40 km or more judging from isotopic composition of the water.

5. We can find the relative heating or cooling in the geothermal system by comparing the temperature in the drillholes with the conductive gradient. The upper part of the system has been heated up in the Laugarnes and Elliðaár areas compared to the conductive gradient whereas the lower part has been cooled. The cooling is 2-27 times greater than the heating. Thermal mining therefore takes place in these areas. The cooling is linear with depth in both areas. The thermal mining can therefore be expected to reach below the depth of the present drillholes. The actual thermal mining is therefore much greater than has been calculated so far. The cooling of the Elliðaár area is much greater than in the Laugarnes area, although the cooling increases with depth in both areas.

6. The thermal mining takes place along the whole percolation path of the water, from the down-flow zone to the up-flow zone. It is greatest in the down-flow zone, and decreases away from it, because the water gets gradually hotter the longer it flows through relatively hot rocks. The temperature of the water approaches the temperature of the rock that it flows through, and its cooling effect is reduced. The volume of the rocks which have cooled because of thermal mining could therefore be many cubic km or even tens of cubic km.

7. The alteration of the rocks in the Kaldársel drillhole indicates that the rocks have always been considerably colder than the temperature of the conductive gradient. The thermal mining there began as the rocks were formed about 200,000 years ago. The alteration mineralogy in the Laugarnes and Elliðaár areas indicates that these areas were originally high-temperature areas, 200-300°C hot. It is likely that the high-temperature activity occured when the area was a part of the active volcanic zone, about 1-2 million years ago. The area cooled down as it drifted out of the active rift zone.

   The thermal mining is a part of the geological process which created the country through sea floor spreading (continental drift). However, not all geological processes are continuous, and the most important discontinuous process for Iceland is the Ice Age, because during the Ice Age the groundwater circulation was retarded by the arctic glacier. Increased fracture formation may have occured due to isostatic uplift after the glaciation. This leads to increased groundwater circulation and thermal mining. The thermal mining is therefore likely to be relatively high at present as only ten thousand years have passed since the end of the last glaciation.

8. Since the production began in the Elliðaár area in 1969, the water pumped from the area has cooled considerably, or between 6-21°C upto 1987 (the thermal mining being induced by the production).

   The cooling is because cold groundwater is replacing the geothermal water which is pumped out of the system. The cold water inflow comes both from the cold water above the geothermal system and from the side from the cold water system southeast of the geothermal system. The greatest cooling is from the top of the geothermal system (100-800 m) and no cooling has been traced below 1200 m depth.

9. The cold water system is orders of magnitude bigger than the geothermal system. Therefore the pressure drop in the geothermal system does not influence the pressure in the cold groundwater system. Because of this there will be a relative pressure

increase in the aquifers which are mixed with cold water which in turn will cause down-flow in the holes and the cold groundwater will penetrade deeper into the system with time through vertical structures (cracks and tectonic fissures).

10. There are two types of thermal mining which have been described in this paper i.e. thermal mining by natural causes and thermal mining induced through utilitation of the geothermal system. The latter type of thermal mining is many orders of magnitute faster than the former.

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REFERENCES

Arnason, B. (1976). Groundwater systems in Iceland, traced by deuterium. *Soc. Sci. Islandica, 42,* 236 pp.

Arnason, B. and Tómasson, J. (1970). Deuterium and chlorides in geothermal studies in Iceland. *Geothermics, 2, Special Issue.* 1405-1415.

Boðvarsson, G. (1961). Physical characteristic of natural heat resources in Iceland. *Jökull 11.* 29-38.

Boðvarsson, G. (1982). Glaciation and geothermal process in Iceland. *Jökull 32.* 21-27.

Boðvarsson, G. (1983). Temperature/flow statistics and thermomechanics of low-temperature geothermal systems in Iceland. *J. Volcanol. Geothermal Res., 19.* 255-280.

Einarsson, T. (1942). Über das Wesen der heissen Quellen Islands. *Societs Scentiarum Islandica V. Reykjavík,* 91 pp.

Georgsson, L.S. (1985). Höfuðborgarsvæði - Borgarfjörður. The results of resistivity measurements (in Icelandic). *Orkustofnun, report OS-85111/JHD-14.* 42 pp.

Gunnlaugsson, E. (1982). The chemical analysis of water from the Elliðaár area. Addition to the report of Consulting engineer, Vatnaskil. 22 pp.

Jakobsson, S. (1979). Petrology of recent basalts of the eastern volcanic zone of Iceland. *Icelandic Museum of Natural History, Reykjavík 26.* 103 pp.

Palmason, G. (1981). Crustal rifting and related thermo-mechanical processes in the lithosphere beneath Iceland. *Sonderdruck aus der Geologishen Rungclan 70.* 245-259.

Palmason, G., Arnorsson, S., Kristjánsson, L., Fridleifsson, I.B., Kristmannsdottir, H., Saemundsson, K., Stefansson, V., Steingrímsson, B. and Tomasson, J. (1979). The Iceland Crust: Evidence from drillhole data on structure and processes. In: *Deep drilling Result in the Atlantic Ocean:* Ocean Crust (Ed. Talwani, M., Harrison, C.G. and Hayes, D.E.), *Maurice Ewing Series, 2,* Am. Geophys. Union, 43-65.

Saemundsson, K. (1978). Fissure swarms and central volcanoes of the neovolcanic zones of Iceland. *Geol. I. Spec. Issue 10.* 415-432.

Sigurdsson, F. (1986). Hydrogeology and groundwater on the Reykjanes peninsula. *Jökull 36.* 11-29.

Smárason, O.B., Tómasson, J. and Ganda, S. (1989). Alteration mineralogy of the Elliðaár geothermal field, Reykjavík, Iceland. *Water-Rock Interaction WRI-6 Proceedings the 6th interaction Symposium, Malvern U.K.* 643-646.

Smárason, O.B. Tulinius, H., Tómason, J., Thorsteinsson, Th., Hermannsson, G. and Ágústsson, H. (1985). Drillhole RV-36. Drilling and research (in Icelandic). *Orkustofnun, report OS-85113/JHD-66 B.* 63 pp.

Thorsteinsson, Th. (1970). Waterlevel measurements in drillholes in the Elliðaár Area 1969-1970 (in Icelandic). *Orkustofnun report,* 19 pp.

Tómasson, J. (1988). Elliðaár Area. The origin and the nature of the geothermal activity (in Icelandic). *Orkustofnun, report OS-88027/JHD-B.* 67 pp.

Tómasson, J. and Thorsteinsson, Th. (1968). The injection tests in drillholes at Elliðaár Area (RV-24 and RV-28) (in Icelandic). Orkustofnun, report, 18 pp.

Tómasson, J., Friðleifsson, I.B. and Stefánsson, V. (1975). A hydrological model of the flow of thermal water SW-Iceland with special reference to to the Reykir and Reykjavík thermal areas. *Second UN Symp. on the developement and use of geothermal resources, San Francisco.* 643-648.

Tómasson, J., Thorsteinsson, Th., Kristmannsdóttir, H. and Friðleifsson, I.B. (1977). Geothermal research in Reykjavík and neigbourhood (in Icelandic). *Orkustofnun, report OSJHD/7703,* 109 pp.

Tómasson, J. and Halldórsson, G.K. (1981). The cooling of Selfoss geothermal area, S-Iceland. *Geothermal Resource Council, Transactions 5,* 209-211.

Vatnaskil Consulting Engineers (1982). Elliðaár area. *The influence of the production on the geothermal resource energy surplus* (in Icelandic). 58 pp.

FIGURES CAPTIONS

Fig. 1.	Map of locations and geology. The location of the Krýsuvík fissure swarm is from Sigurðsson (1985) and the resistivity contours are from Georgsson (1985).
Fig. 2.	Location of drillholes, cross-sections, thermal springs and geological features.
Fig. 3.	Location of drillholes, geographical division of the Elliðaár area, the cross-sections A-A'. The two lines mark the production field to the west and the east (hydrological barriers).
Fig. 4.	Cross-section A-A' of temperature and geology.
Fig. 5.	The rock type, hydrological barrier and water flow at 800 m depth in the Elliðaár area.
Fig. 6.	Cross-section B-B' of geology and temperature.
Fig. 7.	Crosssection C-C' showing the geology and temperature. The location is shown in Fig. 1 and 2.
Fig. 8.	A geological section showing secondary minerals and a schematic temperature curve from the Kaldársel drillhole. A small amount of smectite is present. It is badly crystallized and in most cases the structure is destroyed by heating. The calcite is in small crystals above 430 m depth but below calcite is found in bigger crystals in vein fillings. The amount of calcite is less than 1%. Chabacite is the most abundant secondary mineral with up to 10% both as regards cementing material in sediments and vein fillings.
Fig. 9.	Comparison of temperature curve from the Laugarnes, Elliðaár and Akranes areas. The Elliðaár area temperature curve is taken from well RV-36 which gives a reliable rock temperature. It was measured 144 days after completion of drilling. The temperature had changed little from the log measured 64 days after drilling.
Fig. 10.	Calculated ΔT-curves for different conductive gradients, from a temperature log in well RV-36. The conductive temperature is the temperature which should be at a certain depth according to the conductive gradient. The conductive temperature and the measured (rock) temperature are equal on the zero gradient line.
Fig. 11.	Calculated ΔT-curves for the Laugarnes area, and the Kaldársel drillhole (c.f. Fig.10). Legend same as in Fig.11. The calculated temperature below 2200 m depth is taken from well RV-34.
Fig. 12.	Temperature curve from drillhole RV-25.
Fig. 13.	Temperature curve from drillhole RV-29.
Fig. 14.	Temperature curve from drillhole RV-30.
Fig. 15.	Cooling in well RV-29 with time, along with the amount of water pumped from the Elliðaár geothermal system from beginning of utilation up to 1987.
Fig. 16.	The cold water inflow and the original water flow at 800 m depth in the production field (see also Fig. 5).