Report 10, 1990

INTERPRETATION AND MODELLING OF THE TEMPERATURE DISTRIBUTION AT LAUGALAND IN THELAMÖRK, N-ICELAND

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ABSTRACT

In this work several possibilities as to the flowpaths of hot water were examined in a small low temperature geothermal field, Laugaland in Thelamörk, N-Iceland, after taking into consideration all available geological, geophysical and temperature data. Four possibilities were tested by calculating the temperature distribution created by a near vertical fracture on profiles perpendicular to its strike, and comparing it to measured temperatures in the wells. First, the calculations in the modelling process were made using a programme called VARMI, which numerically solves the Laplace equation in two dimensions, with no time dependency. The assumption of steady state conditions, as well as the influence of recent horizontal flow (the last 30 years) through thin horizontal layers, were then checked with a numerical simulator PT that solves both mass and energy transport equations in time; here, only the part that solves the energy transport equation was used. The possibilities that remained valid after the modelling were even more restricted after taking into consideration temperature data from well LL9, which was drilled during the completion of the report. These data made it possible to construct temperature maps at different depths, which helped to clarify some of the ambiguities that still remained.

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1. INTRODUCTION

Laugaland in Thelamörk is situated in the Hörgardalur valley about 10 km northwest of Akureyri in the Eyjafjördur area, N-Iceland (Figure 1). It is a low temperature area investigated by Akureyri District Heating in order to provide additional hot water supplies for heating the town.

Akureyri is the biggest town in N-Iceland, and since the oil crisis in 1973 the project of heating the town with geothermal water instead of using oil fired boilers started to be seriously realized. At the present time, four fields are in production: Laugaland (not to be confused with Laugaland in Thelamörk), Ytri-Tjarnir, Glerardalur and Botn. For the time being, these fields have been able to meet the town's needs, but the relatively small capacity of the reservoirs and their very low permeabilities (2 mD) lead to tremendously big drawdown in the wells (up to 330 m), which makes it necessary to look for other exploitation fields in order to cover the future needs of the town. Further research has mainly been directed towards Botn, where the wells seem to be connected to a more powerful reservoir, and to Laugaland in Thelamörk.

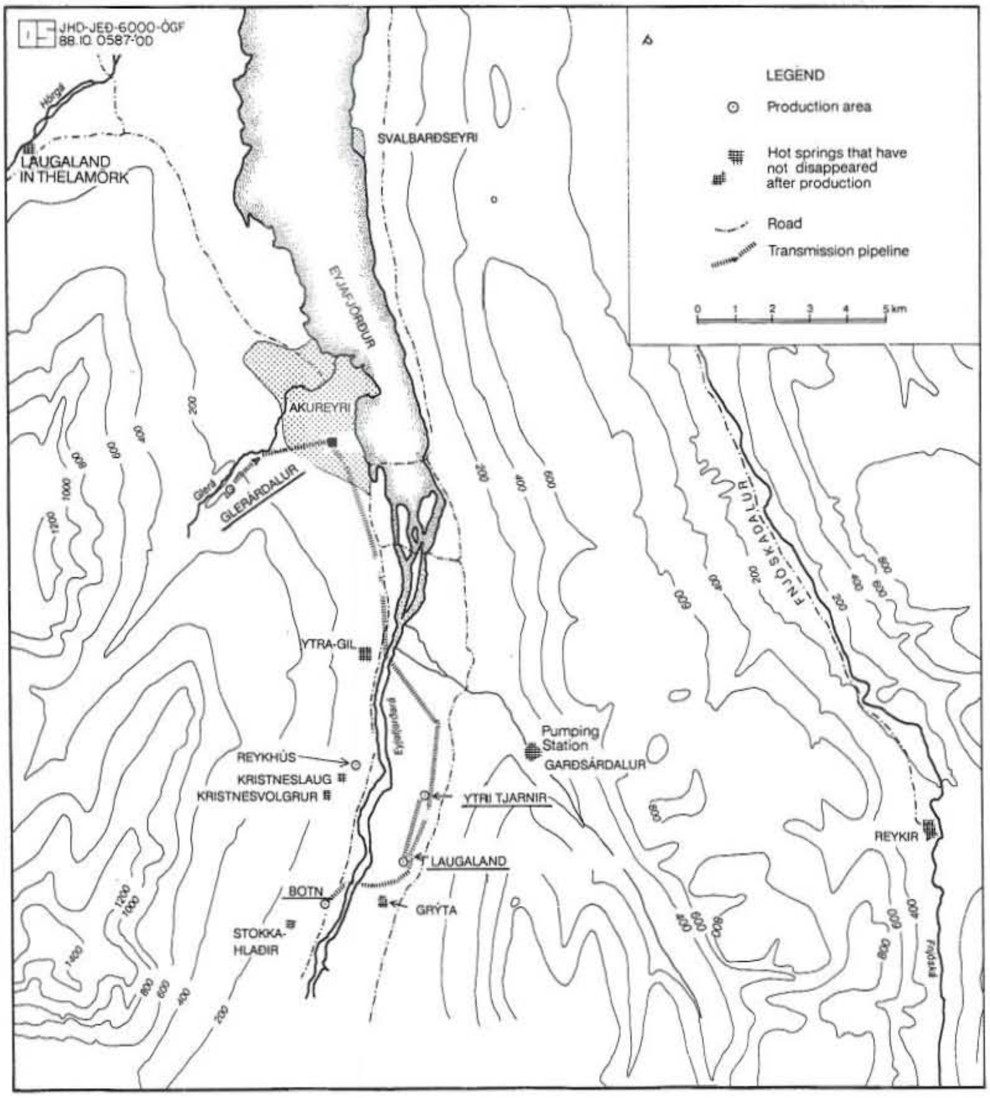

FIGURE 1: Location map of Laugaland in Thelamörk

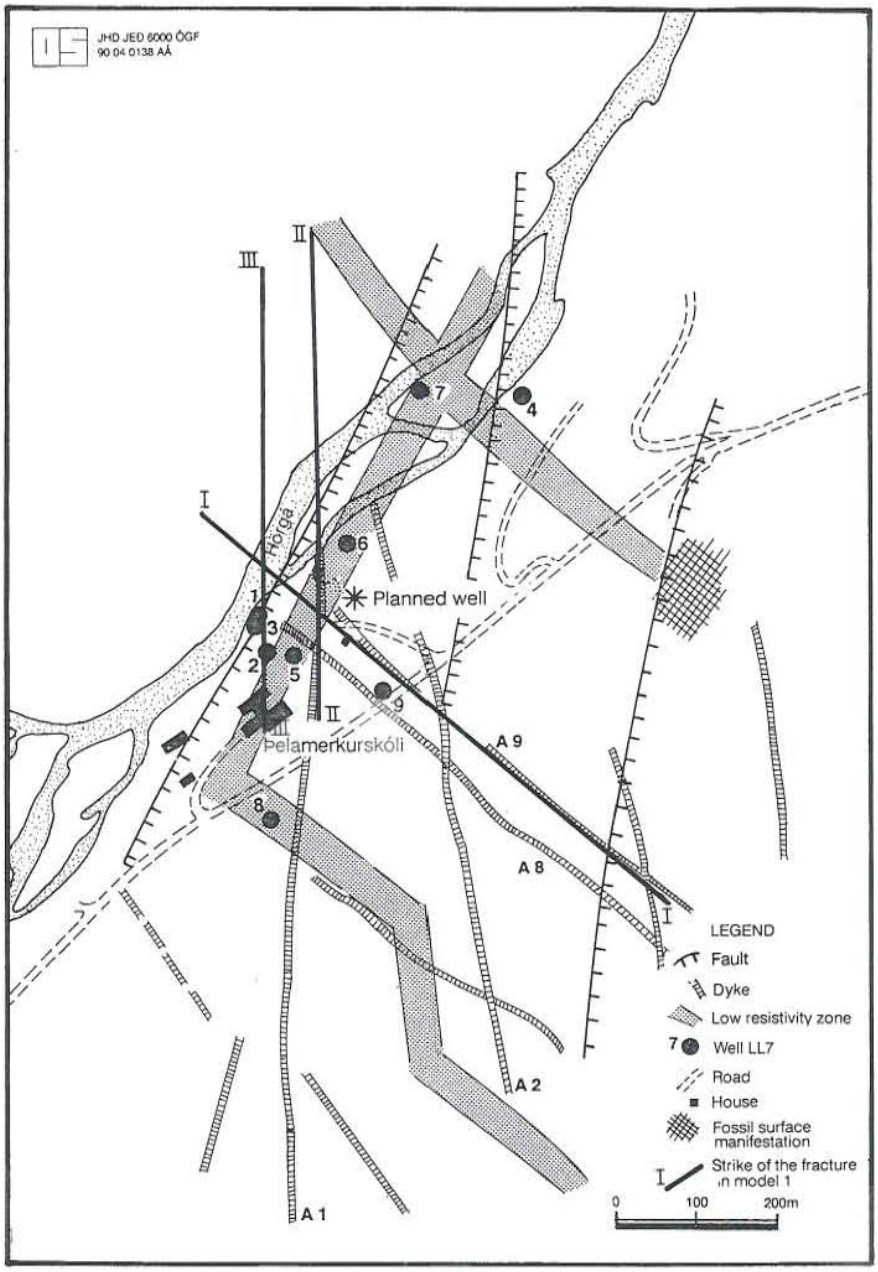

FIGURE 2: Location of the wells at Laugaland in Thelamörk

Laugaland in Thelamörk was initially investigated in 1941. In 1970, after the completion of four wells (Saemundsson et al., 1971), it was established that the amount of hot water the field could produce was not sufficient to start a district heating project. Later on, during the realisation of the project, research was carried out in the four fields mentioned above. After a later study that stated that the Laugaland in Thelamörk field could be exploited with a yield of 20-30 l/s of 90°C hot water, research resumed in 1983 (Flóvenz et al., 1984). The slight content of H_2S makes the water from Laugaland in Thelamörk suitable for storage in tanks, and mixing with the water from the other fields that are subject to oxygen content.

Surface investigations were carried out continuously in the Eyjafjördur area, especially at Laugaland in Thelamörk, including resistivity soundings, magnetic mapping of dykes and head-on profiling in order to improve the knowledge of the structure of the field. By 1990, eight wells were drilled; their locations are shown in Figure 2. Temperature and water level measurements were carried out in all the wells in order to determine the borders of the field, its capacity and the hot water flow pattern. The main concern of this work are these temperature measurements, which point out some interesting features of the temperature distribution in the field. The only deep well (LL2) indicates a temperature reversal in its lower part, with a minimum temperature of 83°C at 1050 m depth , which has to be explained. A temperature cross-section including most of the wells indicates an upflow zone situated between wells LL5 and LL6, and horizontal flow from this zone to the wells that probably started after the completion of the wells. Based mainly on these considerations, and on additional geological and geophysical data, an attempt is made in this work to define a model of the field and the upflow zone located with temperature measurements and other available data. Well LL9 (Figure 2) was drilled during the completion of this report, and in accordance with the temperature measurements in the well, some additional constraints were put on the possible flowpaths of the water.

2. SHORT HISTORY OF THE FIELD - SURFACE INVESTIGATIONS, DRILLING AND PRODUCTION

2.1 Main characteristics of the field - surface investigations

The bedrock at Laugaland in Thelamörk mainly consists of Tertiary flood basalt interbedded by thin layers of scoria and sediments. Mesolite and scolecite are the dominant alteration minerals. The lava pile is intersected by dykes and normal faults. The overall porosity of the rocks is thus considerably reduced and does not exceed 10% . The average temperature gradient in the region (based on measurements in two wells situated in N-Iceland, but out of the area in consideration) is estimated to be about 60°C/km. Surface manifestations of geothermal activity seem to be connected to near vertical fractures carrying hot water to the surface. Two surface manifestations have been mapped at Laugaland in Thelamörk, a fossil one presented in Figure 2 which is found below a 4,400 year old tephra layer, and a recent one at the approximate location of well LL1 (Figure 2) which dried out after production from well LL2 started.

In 1970, Schlumberger resistivity profiling was carried out (Saemundsson et al., 1971) in order to define areas for further investigations, as resistivity zones are usually associated with high temperature anomalies in Iceland. Two zones of relatively low resistivity were located at Laugaland in Thelamörk spreading roughly in a N-S direction. Following the resistivity profiling, detailed head-on profiling measurements were made in 1983 - 1984, in order to delineate more precisely the resistivity distribution in the field (Figure 3). The dykes in Figure 3 were placed according to the data obtained from detailed ground magnetic measurements (Flóvenz et al., 1984).

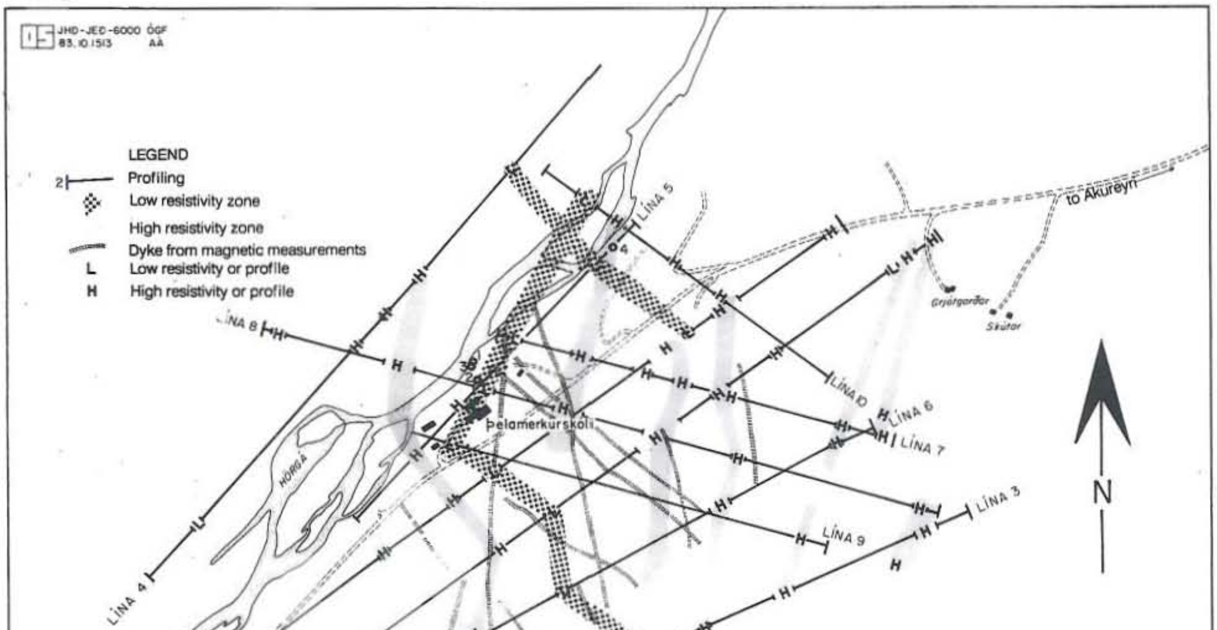

FIGURE 3: Head-on profiling map

TABLE 1: Main chacteristics of the wells at Laugaland in Thelamörk

Well no.	drilled	x (m)	y (m)	Height (m.a.s.l.)	Depth (m)	Diameter (")	Casing width (")	Casing length (m)
1	1941-44			19	375	4(?)	?	?
2	1964-65	19818.6019*	6184.7689*	29.51*	1088m	12 1/4 í 19m 8 3/4 í 446m 6 1/4 í 1088	13 3/8 9 5/8 8 1/2	1.75 19.5 20.25
3	1969-70			18	667	12 1/2 í 85m 6 1/2 í 667m	13 3/8	9
4	1970	20111.1808*	6501.6907*	21.38*	711	15 í 9m 6 1/4 í 711		
5	1989	19811.5775*	6218.6661*	33.42*	239.1	6 1/2	7 5/8	23
6	1989	19954.1335*	6302.3063*	27.62*	360.9	6 1/2	7 5/8	20
7	1889			16.52*	208.4	6 1/2	7 5/8	26
8	1989			42.84*	251.1	 10 í 12m 6 3/4	14 8 5/8	6 12
9	1990			44	367	7	7 5/8	12

* refers to the local coordinate system of Akureyri.

2.2 Drilling and production

Since 1941, eight wells have been drilled at Laugaland in Thelamörk. The locations of the wells are shown in Figure 2, and Table 1 lists their main characteristics. The first well (LL1) was drilled from 1941 to 1944, just at the location of an existing hot spring. All original documentation about the drilling history and measurements made in the well seems to be lost. Reference is made to it in a 1971 report (Saemundsson et al.,1971); there, it states that the main aquifer was at 106 m depth, at the intersection of the well and a dyke, giving 3.5 l/s of 77°C hot water. The bottomhole temperature measured with a maximum thermometer was 85°C at 375 m depth, and is not very reliable. In 1946 this well was closed, and a pressure of 3.5-4 bars was built up at the wellhead. In 1964-65 well LL2 was drilled, giving 14 l/s of 90°C hot water during drilling. In 1968 the flow was reduced to 5 l/s, and in 1982 to 2.5 l/s. Well LL2 was used as a producing well for heating the nearby school and the surrounding houses until February 1990 when it was replaced by well LL5. In 1969 and 1970, wells LL3 and LL4 were drilled. Drilling was then resumed in 1989, when four more wells were drilled, i.e. LL5, LL6, LL7 and LL8. The results of this drilling were described by Flóvenz et al. (1990).

3. BOREHOLE MEASUREMENTS

Lithological sections of all the boreholes were constructed, based on cutting analyses. They mainly consist of different kinds of basalts separated by thin fine-to-coarse grained sedimentary layers, and dykes and dolerite intrusions in some of them. Series of lithological logs (natural gamma, neutron-neutron and 16" resistivity log) were carried out in all the wells (except in LL1) showing, in correlation with the lithological sections, that the aquifers in the wells are mainly associated with the thin sedimentary layers. This correlation was missing in well LL5, due to a more complex lithology caused by the presence of dykes. Nevertheless, the aquifers in it are detected at the expected depth of these layers. The lithological logs also showed the presence of a normal fault separating well LL3 from all the other wells. Water level changes were carefully monitored during the drilling of each new well during the second phase of drilling, which gave a first estimate of the drawdown as 70 m if 10 l/s were pumped from wells LL5 and LL6, without taking into account the boundaries of the reservoir. The permeability thickness was estimated to be in the range of 3-10 Dm with 80°C hot water. The storage coefficient could not be accurately estimated (Flóvenz et al., 1990).

3.1 Temperature measurements - interpretation

The first temperature measurements were made after well LL2 was drilled, and continued systematically after the beginning of the second phase of investigations in 1989. Here follows a well by well analysis of the measured temperature curves, leading to a general conclusion about the temperature distribution in the field.

Well LL1: In 1983 an attempt was made to record the temperature profile in well LL1 (Figure 4A). The well, which was drilled a very long time ago, was plugged at 110 m depth allowing for measurements only down to that depth. The main aquifer registered during drilling cannot be detected on the curve. In the upper part of the well at about 30 m, a temperature inversion is visible on the curve probably caused by a hot inflow coming from well LL3, which was drilled only a few meters away. A very small natural discharge is registered from the well.

Well LL2: Being a producing well, several temperature profiles were measured since it was drilled. The obtained curves are presented in Figure 4B. The measurements made in 1965 were performed during drilling and just after drilling, not allowing time for the well to stabilize. Therefore, most of the following discussion will be based on subsequent measurements. The main aquifer situated at 630 m depth giving 92.5°C hot water can clearly be seen on all the curves. At about 400 m there seems to be an inflow of water colder than 90°C. Below 630 m there does not seem to be any major aquifer, and the temperature is approaching the true rock temperature. The curves in this part show a definite temperature inversion reaching a minimum value of 83°C at 1,050 m depth. The last curve from 1990 was recorded after closing the well under 1 bar pressure, and it shows a slight upflow from aquifers near 670 m and 570 m depth, which enters the formation at 140 m depth.

Well LL3: Well LL3 was drilled at the approximate location of well LL1. The recorded temperature curves are presented in Figure 4C. The curve from 1971 was still affected by drilling. Curves measured afterwards show fairly constant values through the years. From the bottom to the top, we can distinguish the main aquifer at 600 m, giving 91.4°C hot water, which corresponds to the one found in LL2. Three more aquifers can be seen at 520 m, 330 m and 250 m depths respectively. There is an upflow in the well from the deepest aquifer, and at 100 m part of the water is entering the formation (curve from 21.06.1990, well closed under 1 bar pressure).

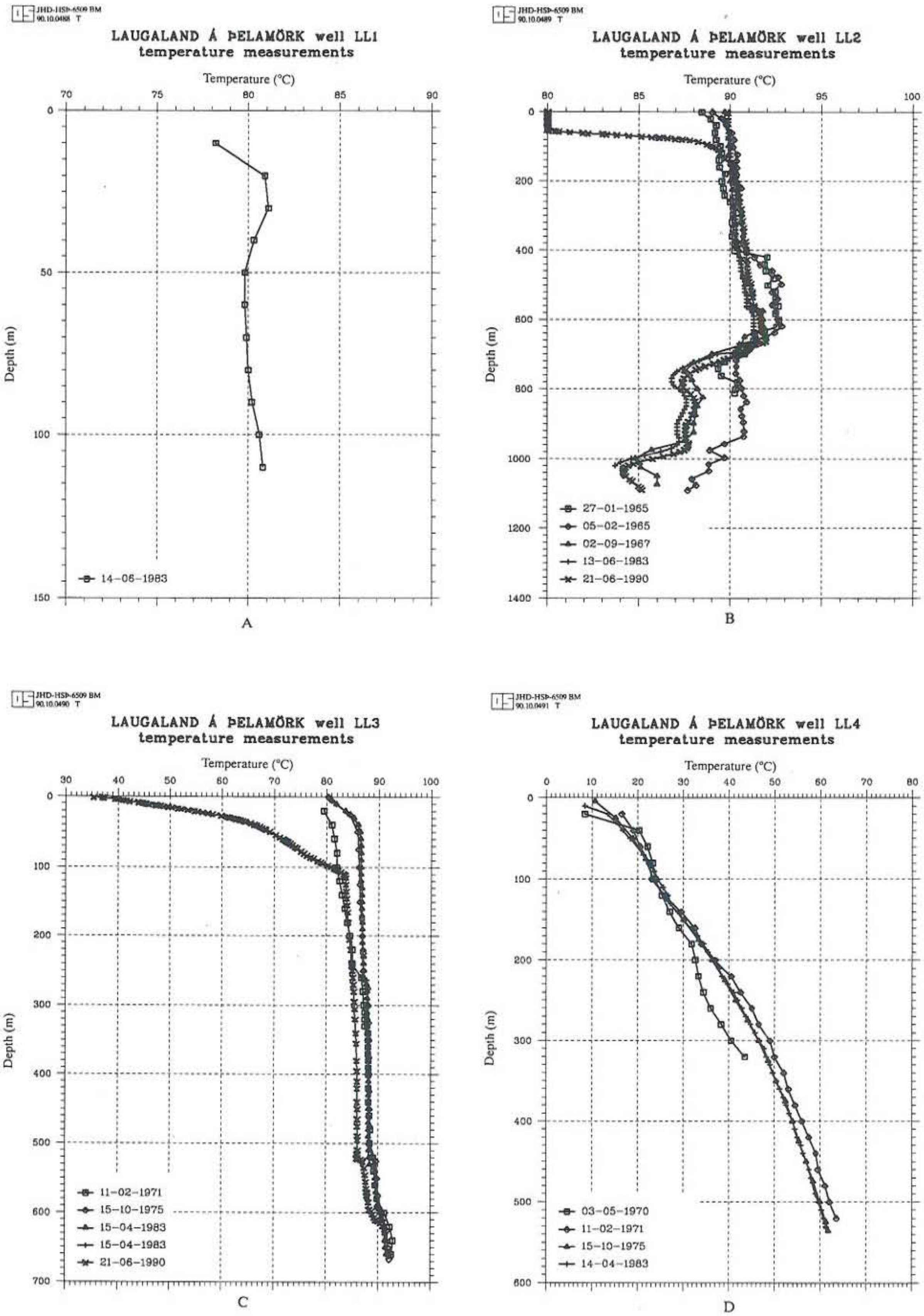

FIGURE 4: Temperature measurements in wells LL1, LL2, LL3 and LL4

Well LL4: The temperature curves presented in Figure 4D clearly indicate that this well is at the boundary of the field. It still shows anomalous values of the temperature profile compared to the regional gradient. During drilling, a small aquifer was detected at 80 m depth. The first curve from 1970 was still influenced by cooling during drilling. The curve from 1971 shows too high temperatures compared to those subsequently made. Considering that the well is not producing and that it is situated at the boundary of the field, and considering also the fact that the curves from 1975 and 1983 are practically identical, the curve from 1971 might be affected by a systematic error caused by incorrect calibration of the probe.

Well LL5: A series of records (Figure 5A) from November 1989 to January 1990 show a fairly constant behaviour of the curves, except for the first ones recorded during drilling and just after drilling which are still affected by cooling. There are two main aquifers in the well, the smaller one at 100 m depth (80°C), with downflow to the greater one at 160 m (76°C) where the water enters the formation. There is no indication of an aquifer or upflow from the bottom of the well. The curves present a clear temperature inversion.

Well LL6: The series of curves obtained in this well (Figure 5B) show an increase of the overall temperature between 30 and 150 m depth after the completion of drilling. This is due to an upflow from the main aquifer (75°C) situated at 150 m depth, up to 30 m where the water reenters the formation. A minor aquifer at 198 m depth can be seen on curves from 9. and 11. 1989. From this aquifer to the bottom, there is no flow in the well and the curves approach the true rock temperature which is 80°C at the bottom of the well. The gradient in this part of the well is 46°C/km.

Well LL7: The temperature curves on Figure 5C show a relatively small aquifer at 150 m (42°C), while at 70 m depth there is a cold inflow coming from a very low permeable layer. The first two curves are still influenced by drilling, and they both show too low temperatures below the aquifer at 150 m depth. The last curve seems to show relatively stabilized conditions, and below 70 m depth seems to approach the true rock temperature. The bottomhole temperature value of 47°C at 200 m is much higher than expected from the regional gradient value. The well gives 0.2 l/s of free flow.

Well LL8: It was drilled for the same purpose as well LL4 in order to define the boundaries of the field. The true rock temperature seems to be somewhat inbetween the temperatures indicated by the curve obtained on 20.11.1989 (Figure 5D) just after drilling, and the curve obtained on 21.11.1989 which is affected by upflow from a small aquifer situated close to the bottom of the well. The measurements from 9.11.1990 show a cooling caused by downflow from a very small cold aquifer at 30 m depth. The bottomhole temperature of about 45°C at 240 m depth is again considerably above the value expected from the regional gradient.

As a general conclusion we may say that temperature profiles in all the wells yielded highly anomalous values for this part of the country. The main producing zone seems to be concentrated around wells LL2, LL3, LL5 and LL6 where the aquifers also had the highest temperatures. A temperature cross-section including most of the wells was constructed (Figure 6) according to an estimation of the true rock temperature from the temperature curves. Points were taken at the location of the aquifers and in the parts of the curves that were not supposed to be disturbed by internal flow in the well. The cross-section clearly shows an upflow zone situated between wells LL5 and LL6 as an area of the greatest temperature anomalies. Its lower part (below 350 m depth) is obviously unreliable, because the only data available were three points taken in well LL2. The upflow zone in the upper part of the cross-section and the extrapolated temperature gradients, as well as the necessity of explaining the reversal of the temperature in well LL2, served as a basis for subsequent modelling.

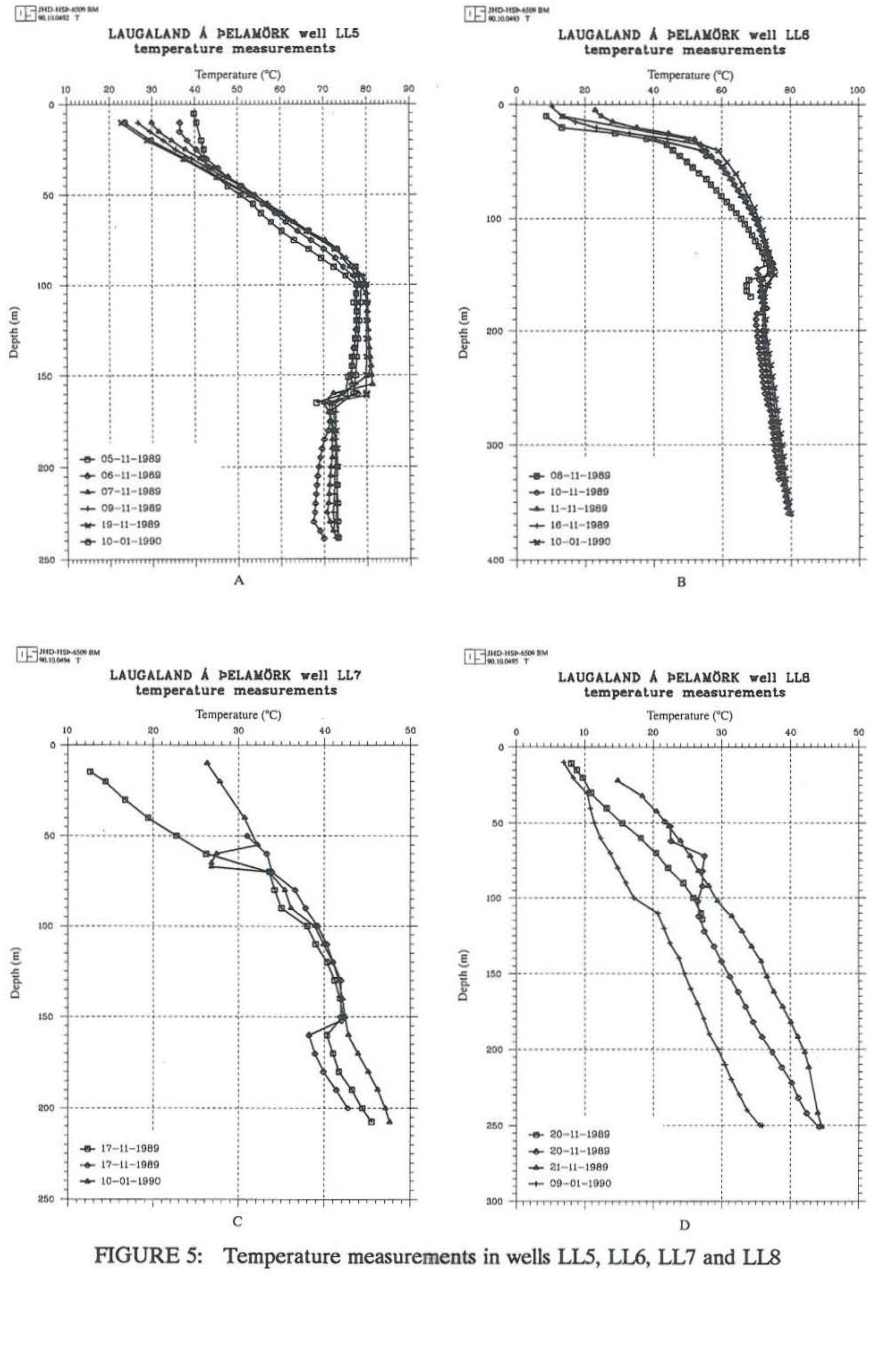

FIGURE 5: Temperature measurements in wells LL5, LL6, LL7 and LL8

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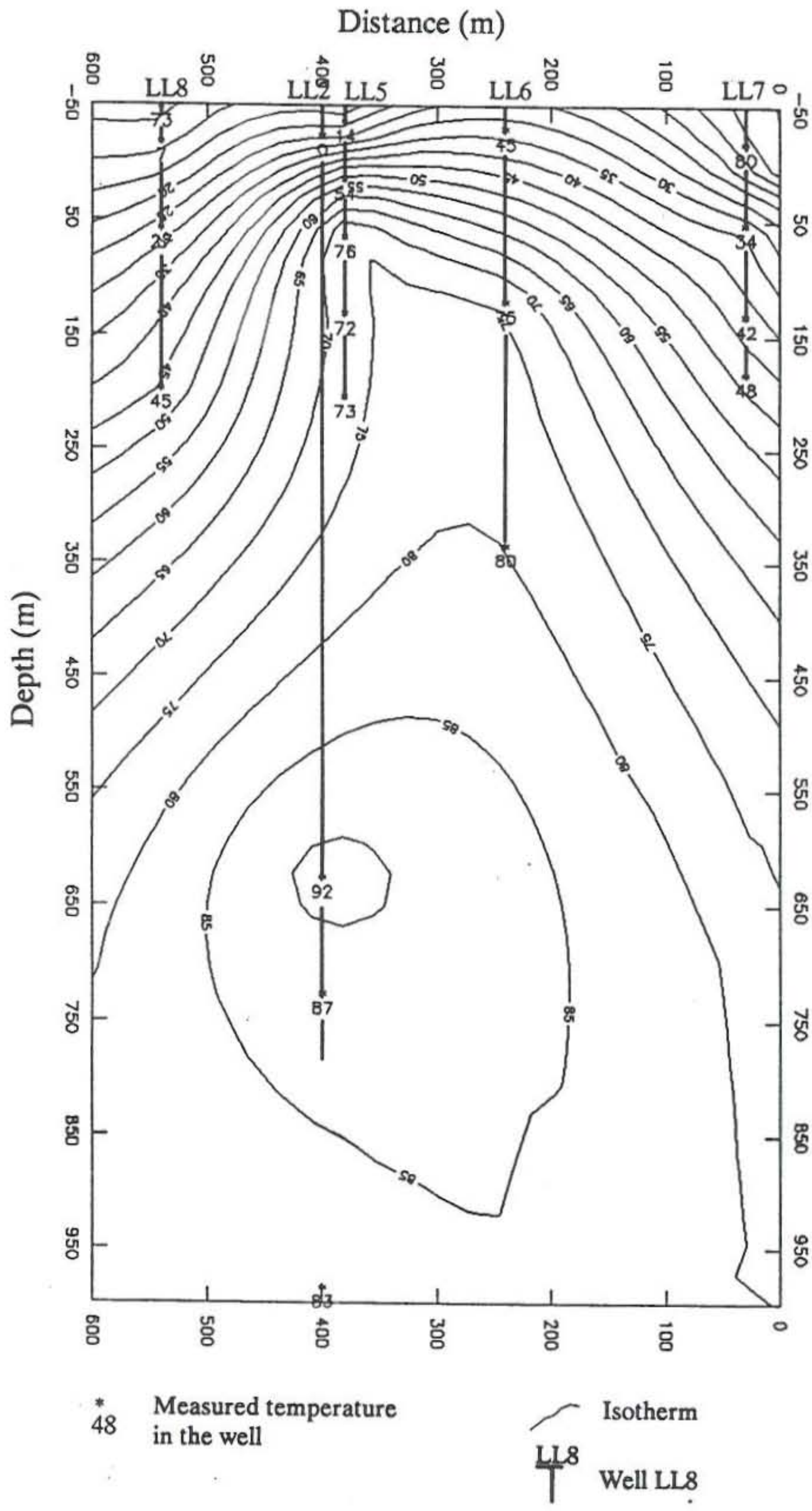

FIGURE 6: Temperature cross-section along the low resistivity zone

4. MODELLING OF THE TEMPERATURE DISTRIBUTION AT LAUGALAND IN THELAMÖRK

The low temperature areas in N-Iceland are generally associated with glacially eroded valleys where actual rivers found a natural flowpath. Surface manifestations of hot water are usually seen near the river banks, or even in the river as areas of lowest elevation. Numerous near vertical dykes that frequently intersect the formations do not usually present a permeable zone allowing the water to flow. Instead, the main flow channels carrying hot water up to the surface are considered to be fractures which sometimes coincide with the dykes and sometimes not. At Laugaland in Thelamörk, all the dykes strike between N-S and NW-SE directions.

The age of the geothermal systems in Iceland is not known, but large vertical movements at the end of deglaciation, approximately 10,000 years ago, may have initiated many of the geothermal systems in the tertiary areas of Iceland (Bödvarsson, G., 1982). A simple calculation of energy transport from deeper parts of the geothermal systems to the shallower parts also points towards some 5,000-10,000 years. Surface manifestations of geothermal activity at Laugaland in Thelamörk are found under a 4,400 years old tephra layer, indicating that geothermal activity in the area must be older.

After the head-on resistivity profiling in 1983 (Flóvenz et al., 1984), a NNE-SSW fracture crossing the hot spring was postulated (Figure 2). The drilling of wells LL5 to LL8 was aimed towards this fracture, and well LL2 is quite close to it. The results from the temperature measurements in these boreholes show, on the contrary, that the proposed fracture is not permeable except in the vicinity of wells LL5 and LL6. Thus, if the NNE-SSW fracture is the main carrier of hot water to the surface, the upflow zone is restricted to a short part of the fracture inbetween wells LL5 and LL6. The remaining part of the fracture must then already be filled with secondary minerals, which makes it almost impermeable. Well LL6 did indeed cut a fracture at 110 - 114 m depth, which was completely filled with mesolite.

Some other possibilities could explain the temperature distribution at Laugaland in Thelamörk:

1. A NW-SE striking fracture between wells LL5 and LL6 with a slight eastward dip, measured from the vertical. There is no sign of such a fracture in the resistivity profiling, but two dykes with this strike cross the area;

2. A N-S striking fracture with an eastward dip, probably coinciding at the surface with dyke A1 in Figure 2;

3. A N-S striking normal fault between wells LL2 and LL3;

4. An upflow zone at some distance from the hot spring (most likely to the south or southeast) and a horizontal flow of more than 90°C hot water at 600-700 m depth to the hot spring, where it escapes through a short fracture.

In the following text, these four different possibilities have been tested by temperature modelling, in order to put some constraints on the possible upflow zones.

4.1 General description of the methods used for modelling

The first part of the modelling process was conducted by the programme VARMI available on the HP 9000/840 computer at Orkustofnun. The programme numerically solves the Laplace equation for temperature distribution in two dimensions with no time dependence and appropriate boundary conditions.

$$\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta z^2} = 0$$

Fractures, as well as aquifers, are treated as line sources (or open boundaries). It requires a coarse triangular net, where each triangle is defined by three points and their coordinates. The programme makes it possible to refine the original net to get the desired resolution.

All four possibilities listed above were examined using this programme. As the basis for all four approaches the temperature distribution created by a two dimensional fracture slightly dipping (6°) and shifted at some depth in a plane perpendicular to its strike in the last case, has been calculated. Temperatures measured in the wells were then plotted on a profile perpendicular to the strike of the supposed fracture and compared to the calculated ones.

The dip of the fracture away from well LL2 had to be assumed, in order to fit the temperature reversal observed in the well. For the horizontal flow from the fracture to the aquifers, two possibilities have been examined: the case of steady state flow in the aquifers, and the hypothesis that the flow started just after drilling of the wells. In the second case it was assumed that the effect of such a flow would be confined to the immediate vicinity of the aquifers, and thus could be neglected as to its influence on the global behaviour of the field.

As the hydrothermal system in consideration is estimated to date from the last glaciation period 10,000 years ago (older than 4,400 years), the second part of the modelling job consisted of examining its evolution with time, determining its actual state, and the time it takes to stabilize. In this part, the assumption that flow which started after drilling the wells could be neglected as to its global influence on the temperature distribution, was also checked.

Modelling of the behaviour of such a system in time was accomplished by using a numerical simulator, PT (Bödvarsson, G. S., 1982) which numerically solves mass and energy transport for a liquid saturated medium, using the Integrated Finite Difference Method (Edwards, 1972; Narasimhan and Witherspoon, 1976) for discretizing the saturated medium and formulating the governing equations. The equations are solved by direct means, using an efficient sparse solver (Duff, 1977). Only part of the programme solving the energy transport equation was used:

$$\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2} = \frac{\rho c}{k}\frac{\delta T}{\delta t}$$

where:
T - *temperature*
k - *thermal conductivity*
ρ - *density*
c - *specific heat*

For the sake of simplicity, and to be able to compare the results obtained by both approaches, a two dimensional model was assumed here. After the definition of each element that was included in the grid, and its connections with neighbouring elements, initial temperature conditions for each element had to be specified, as well as the rock and fluid properties. The initial conditions were set at time 0, when the temperature of each element was set according to the regional gradient, except along the fracture. For the rock and fluid properties, average values for the area were assumed. All other conditions were similar to the previous modelling. The boundary elements were defined as constant temperature elements by assigning them a big enough volume.

In both cases, the boundaries of the model were set at 2,000 m depth from the fracture where its influence is supposed to be negligible, and a regional gradient distribution of temperature could be assumed. The mean annual temperature was assumed at the surface (4°C), and the value at 1,500 m depth was calculated from the regional gradient. At other depths along the fracture the temperatures were set slightly above the temperatures recorded at the aquifers at corresponding depths. In the modelling process the heat equation alone was used and the temperature distribution along the fracture was assumed to be constant in time.

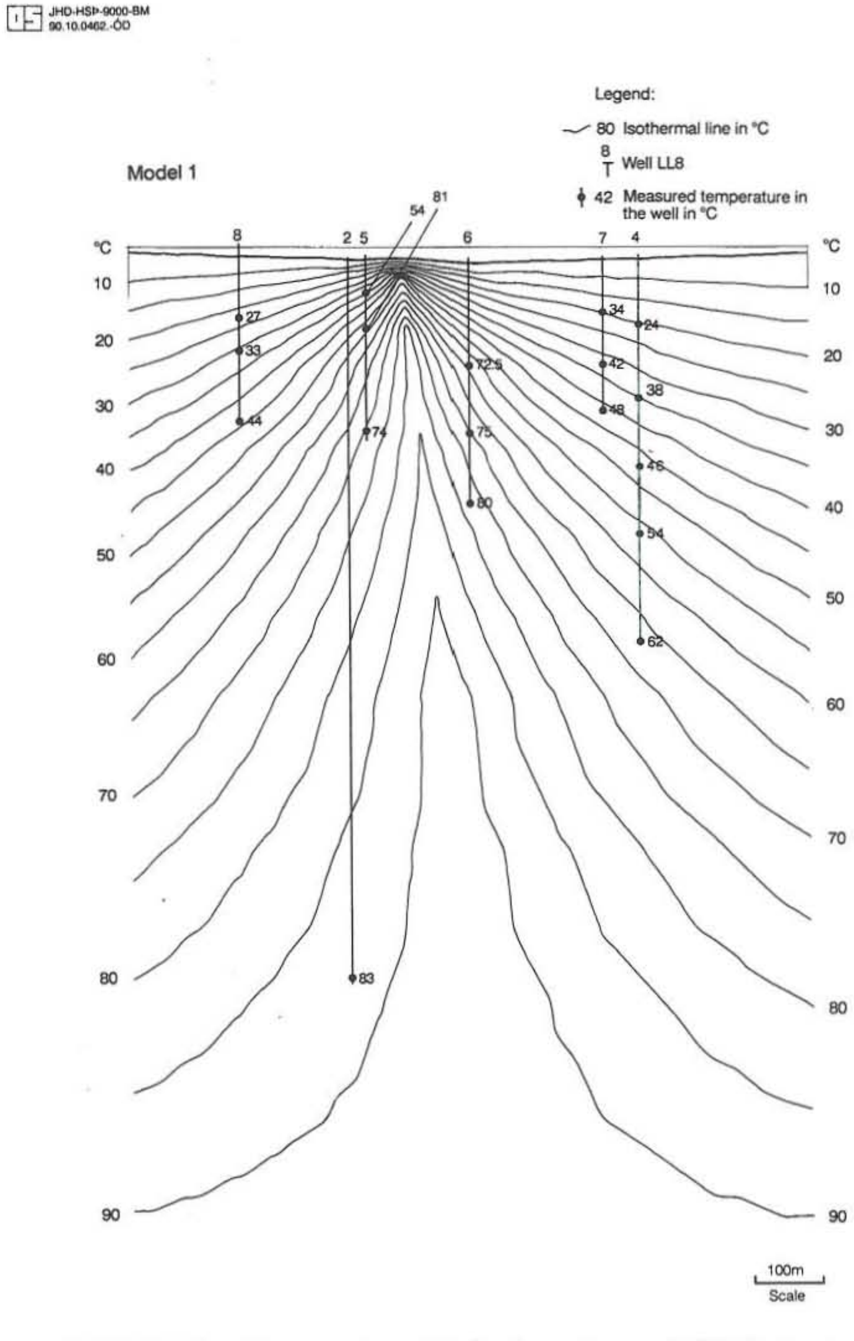

FIGURE 7: Temperature distribution along a NW-SE fracture

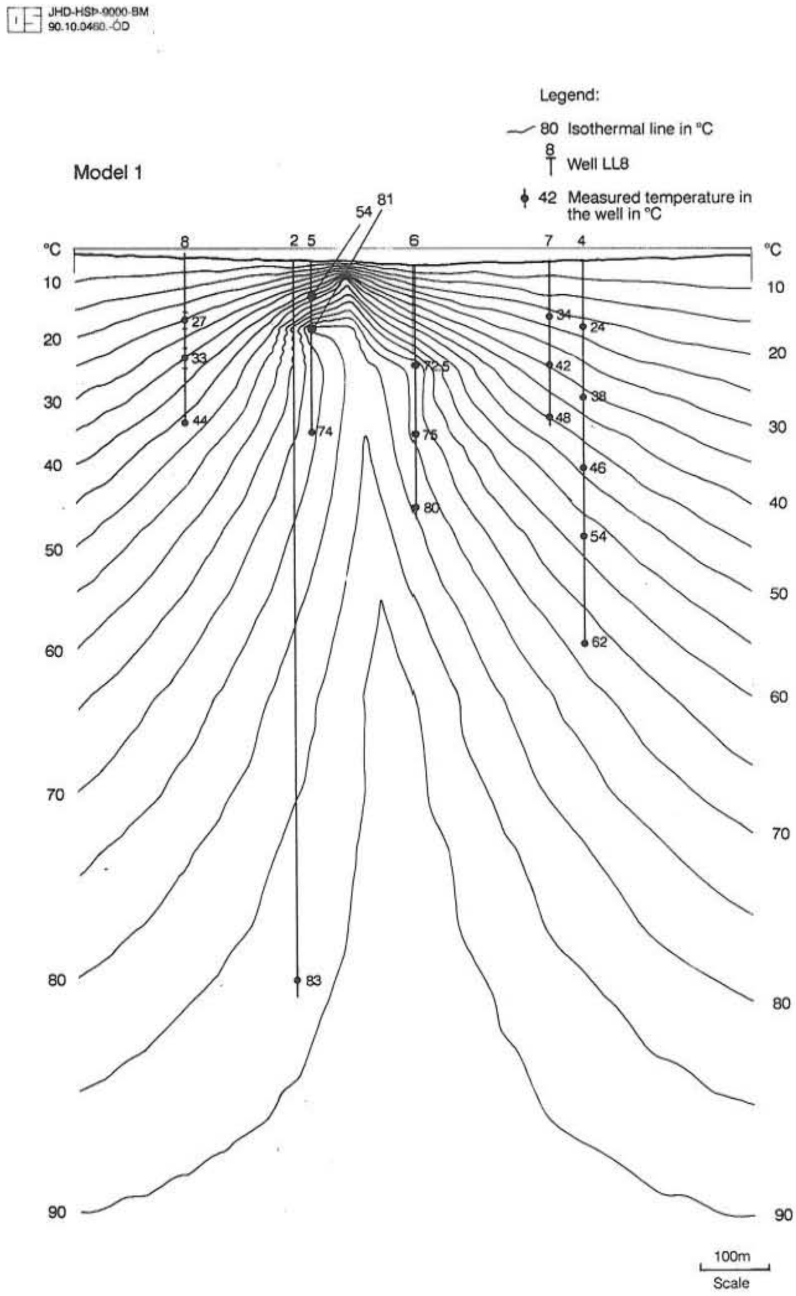

FIGURE 8: Temperature distribution a NW-SE fracture, horizontal flow in LL5, LL6 and LL7

4.2 Model 1: the NW-SE fracture

The results of the modelling are presented in Figures 7 - 9.

Figure 7 shows the calculated temperature distribution, assuming a simple vertical fracture, compared to the observed temperatures in the boreholes. Recorded temperatures in wells LL5, LL6 and LL7 are higher than the calculated ones, but no flow was assumed from the fracture to the wells along thin near horizontal scoria layers in the model.

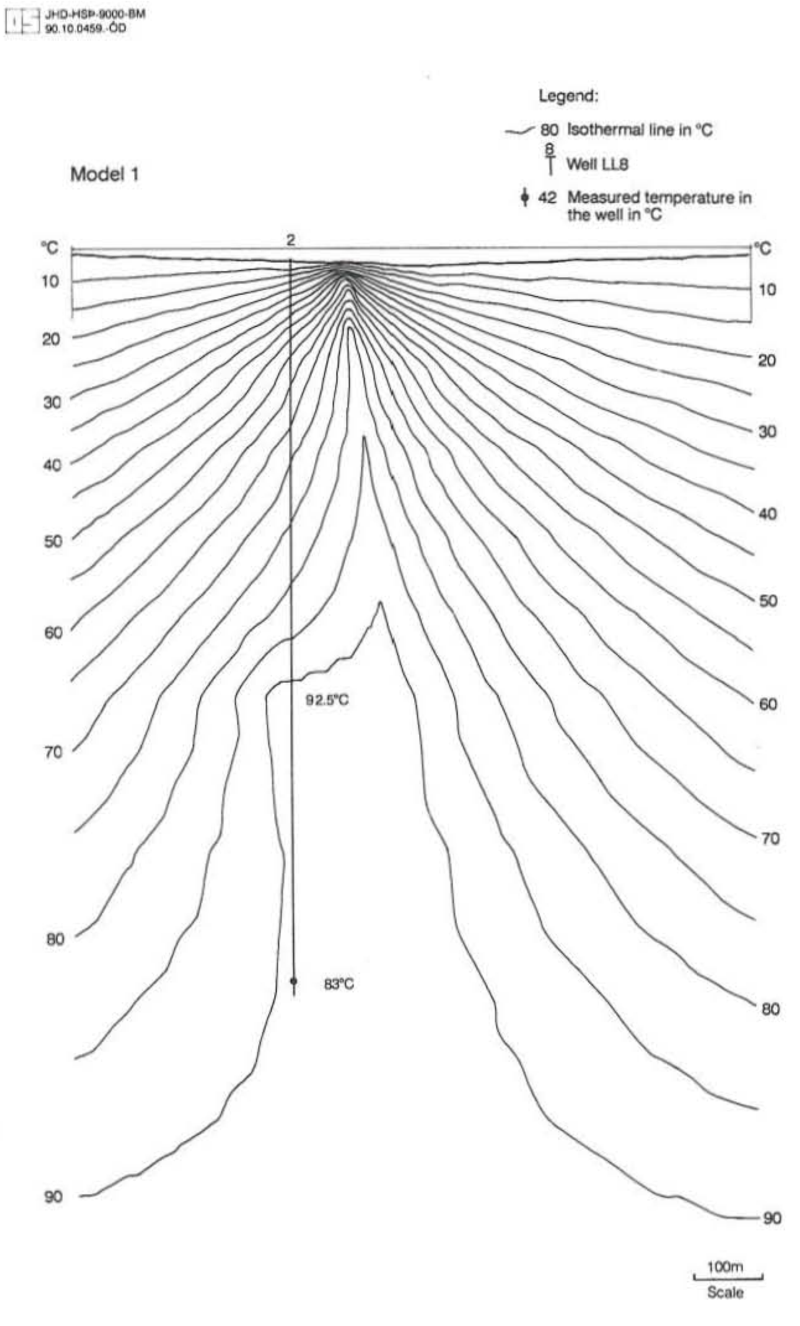

FIGURE 9: Temperature distribution along a NW-SE fracture, steady state horizontal flow towards LL2 at 650 m depth

In the upper part of well LL4, the measured values show a good correlation with the calculated ones. On the other hand, the gradient in the lower part of the well is smaller and the bottom hole temperature is about 5°C lower than calculated.

In well LL2, the calculated value is 4-5°C higher at the depth of the recorded minimum temperature of the reversal. A temperature reversal can be obtained by using such a model if we assume recent horizontal flow from the fracture to well LL2 at 650 m depth, with 92.5°C temperature at the aquifer.

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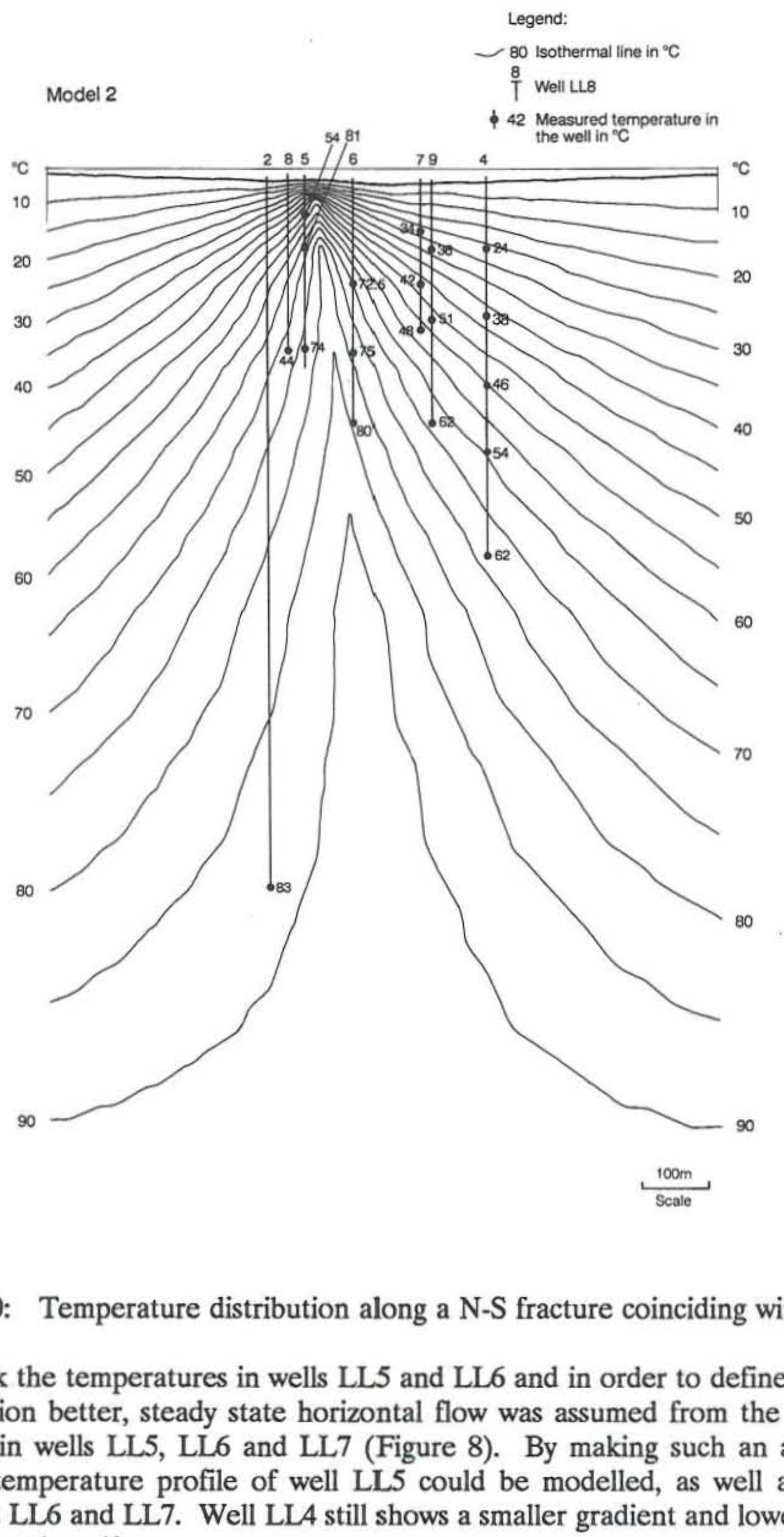

FIGURE 10: Temperature distribution along a N-S fracture coinciding with dyke A1

In order to check the temperatures in wells LL5 and LL6 and in order to define the upper part of the cross-section better, steady state horizontal flow was assumed from the fracture to the upper aquifers in wells LL5, LL6 and LL7 (Figure 8). By making such an assumption, the reversal in the temperature profile of well LL5 could be modelled, as well as temperatures recorded in wells LL6 and LL7. Well LL4 still shows a smaller gradient and lower temperatures below the horizontal aquifers.

In Figure 9, steady state horizontal flow from the proposed fracture at 650 m depth towards well LL2 was assumed. The obtained results show clearly that such a model could not be used to create the inversion recorded by temperature measurements made in the well. Thus, this seems to support the hypothesis that the flow started after completion of the well. From the above considerations, it might be concluded that the modelling would have shown a real possibility of the existence of such a fracture, if it was not for the great difficulty in explaining the temperature distributions in wells LL7 and LL4 with such a model.

4.3 Model 2: N-S fracture coinciding with dyke A1

This possibility has been examined in Figure 10 on a profile perpendicular to the strike of the fracture. For wells LL2, LL5 and LL6 we may draw the same conclusions as for the previous model. Wells LL8, LL7 and LL4 show too low measured temperatures compared to the

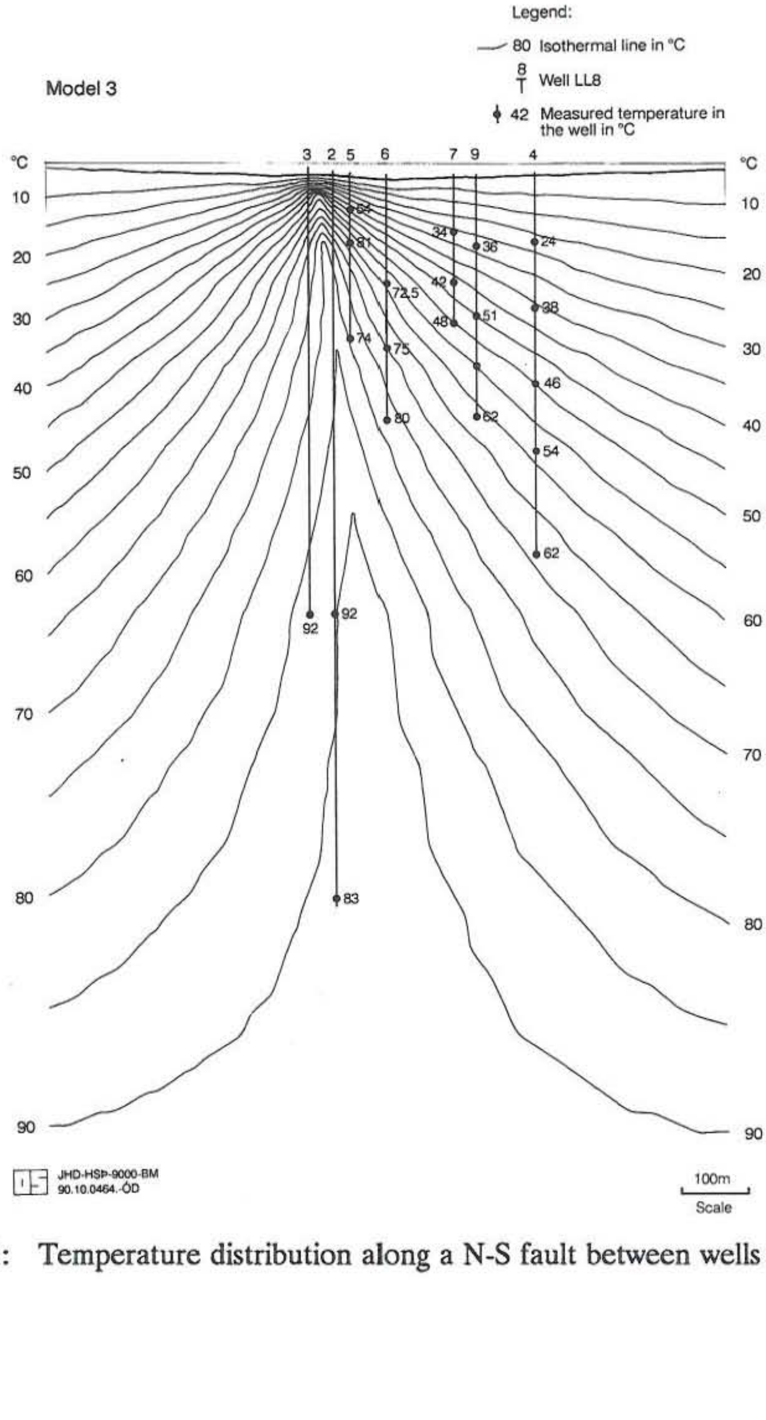

FIGURE 11: Temperature distribution along a N-S fault between wells LL2 and LL3

calculated ones, but still much higher than the regional gradient. As they are situated further away from the supposed upflow zone than the other wells, we may conclude that, in this case, a two dimensional model could be assumed only in the vicinity of wells LL2, LL5 and LL6, i.e. a short near vertical fracture close to these wells, coinciding with dyke A1 could explain the observed temperature distribution. It should be noted here that dyke A1 has a dip towards the west, while the fracture in the model must have a dip towards the east.

4.4 Model 3: the N-S fault between wells LL2 and LL3

The results are presented in Figure 11. Better than in the previous case, the temperature profiles in wells LL5, LL6, LL7 and LL4 seem to be in accordance with the calculations, keeping always

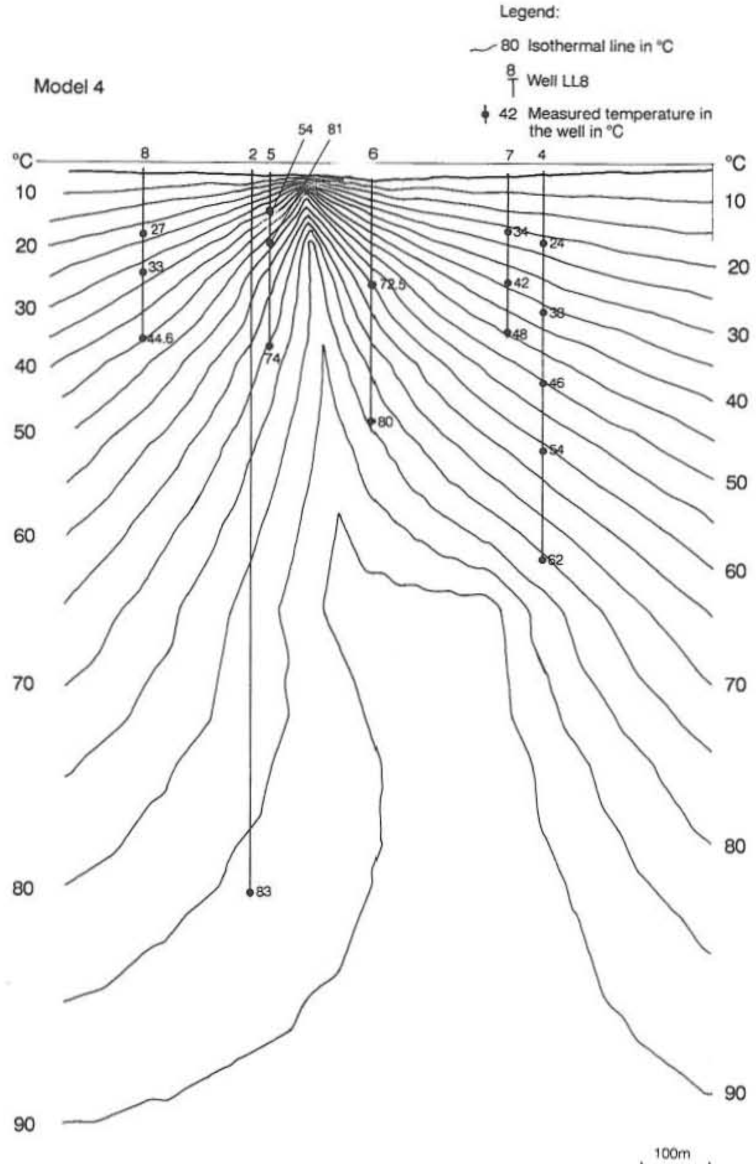

FIGURE 12: Temperature distribution along shifted NW-SE fracture, 200 m

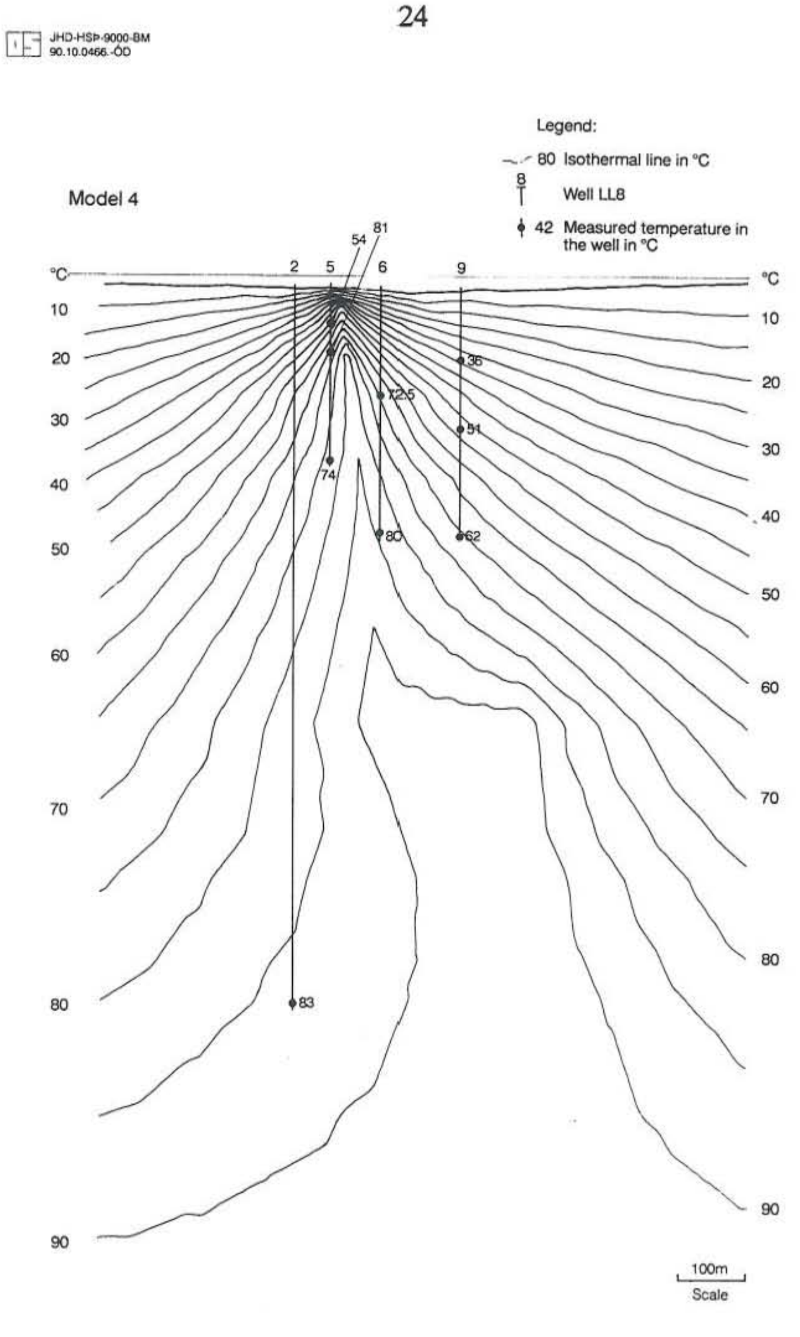

FIGURE 13: Temperature distribution along a shifted N-S fracture, 200 m

in mind the assumed horizontal flow from the fracture towards wells LL5, LL6 and eventually LL7 (Figure 8). As previously, the low temperatures in wells LL4, and especially LL8 could be explained by the fact that they are close to the borders of the field, but the reversal in well LL2 cannot be obtained by such a model as the fracture would be too close to the well, unless we assume that the fractures are not permeable south of the river Hörgá.

4.5 Model 4: a fracture with a horizontal shift

This model has been checked by moving the fracture horizontally at 650 m depth from well LL2 for Model 1 and Model 2, first 200 m (Figures 12 and 13), and then 600 m for Model 2 only (Figure 14).

If we consider Model 1, the shift would be towards well LL4 and, thus, induce too high temperatures compared to the measured ones as shown in Figure 12, so we may exclude such a possibility. This conclusion is made for a shift of 200 m; a greater shift has not been taken into consideration.

For Model 2 we have already shown that the fracture must be short and that wells LL4, LL7 and LL8 were out of the area. Thus, they are not plotted on the cross-section. The shift of 200 m (Figure 13) does not seem to affect the temperature distribution in the wells in the upper part very much, and a shift of 600 m has only a minor effect, reducing the temperature by only about 2°C at 1,050 m depth in well LL2 (Figure 14). Nevertheless, such a possibility is not excluded by these results and should be checked in future investigations.

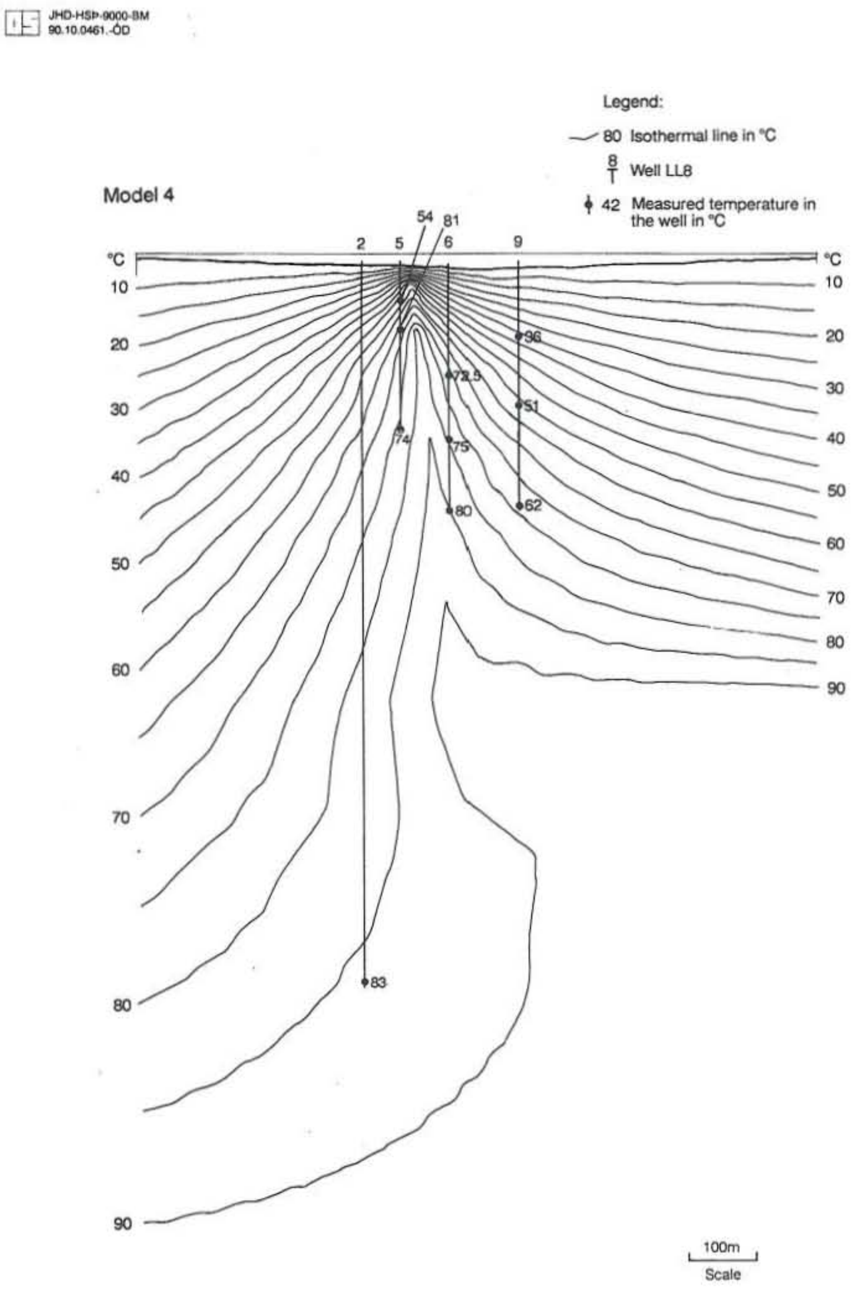

FIGURE 14: Temperature distribution along a shifted N-S fracture, 600 m

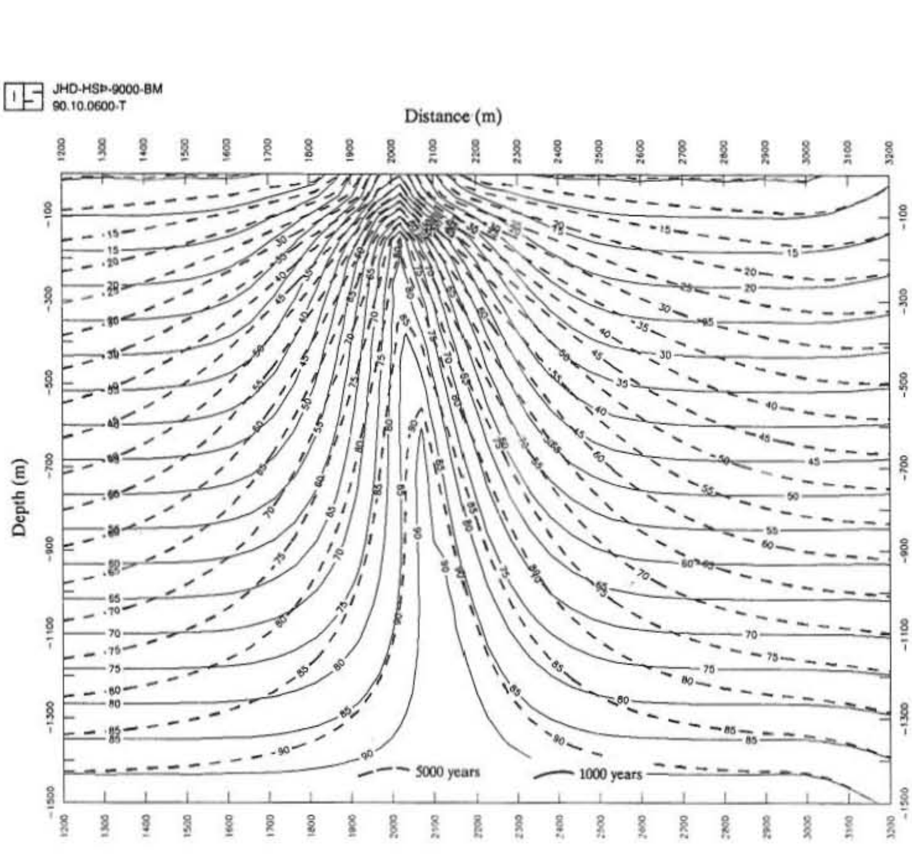

FIGURE 15: Temperature cross-section (in °C) calculated for 1,000 and 5,000 years

4.6 Modelling in time

As was stated before, the fossil surface manifestation indicates that the age of this hydrothermal system ranges from some 5,000 years to about 10,000 years. The following part of the modelling job was made in order to determine if and when the assumption of steady state conditions is valid, and to check the influence of relatively recent flow (30 years in well LL2) on the global behaviour of the temperature field.

The temperature distributions created by a near vertical fracture are presented in Figures 15 to 18, for different times.

The temperature distributions after 1,000 and 5,000 years are plotted on Figure 15. We can see significant differences between these distributions, especially in the vicinity of the fracture. Figure 16 shows the temperatures after 5,000 and 10,000 years. They seem to have stabilized around the fracture and close to the surface, but there are now differences (about 2.5°C) in the deeper parts and further away from the fracture.

In Figure 17 we can compare near to steady state conditions (50,000 years) and the conditions of the previous 10,000 years. The differences are small, reaching a maximum value again of about 2.5°C. But if we now compare the cross-sections after 5,000 and 50,000 years (Figure 18), we see that differences in temperatures are significant, in the range of 5°C in most parts of the cross-section.

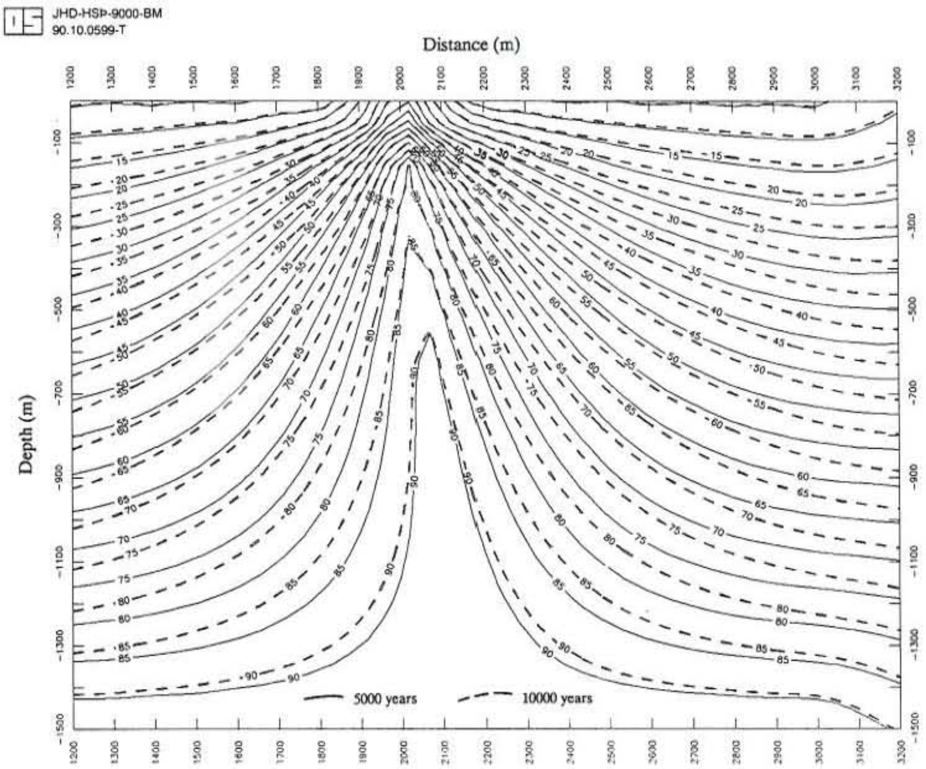

FIGURE 16: Temperature cross-section calculated for 5,000 and 10,000 years

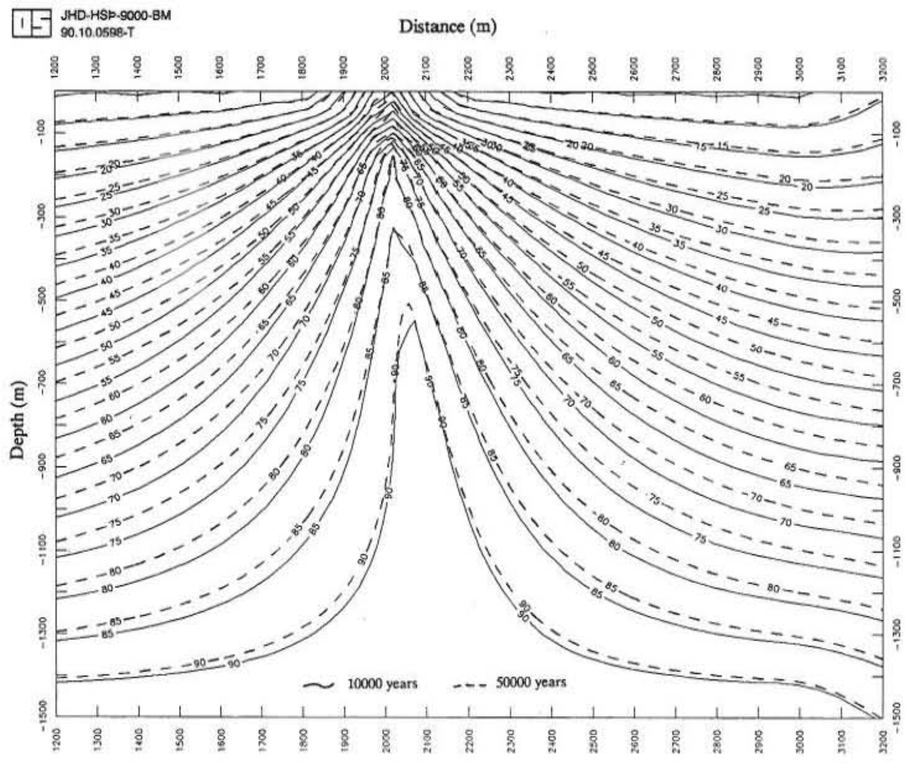

FIGURE 17: Temperature cross-section calculated for 10,000 and 50,000 years

In Figure 19, the temperature distribution after 5,030 years is superimposed on the distribution after 5,000 years, assuming that after 5,000 years of flow through a simple near vertical fracture, flow started horizontally at 650 m towards well LL2. The picture clearly shows that the flow has only a slight local influence, and that it could be neglected during the analysis of the field, except within a few meters of the horizontal layers.

We may, thus, conclude that for systems older than 10,000 years, the assumption of steady state conditions is reasonable and does not introduce severe errors, but for systems that are younger than 10,000 years, the fact that they have not yet reached steady state conditions must be taken into account during the analysis of their temperature distribution. As to the influence of recent flow, it can be considered negligable.

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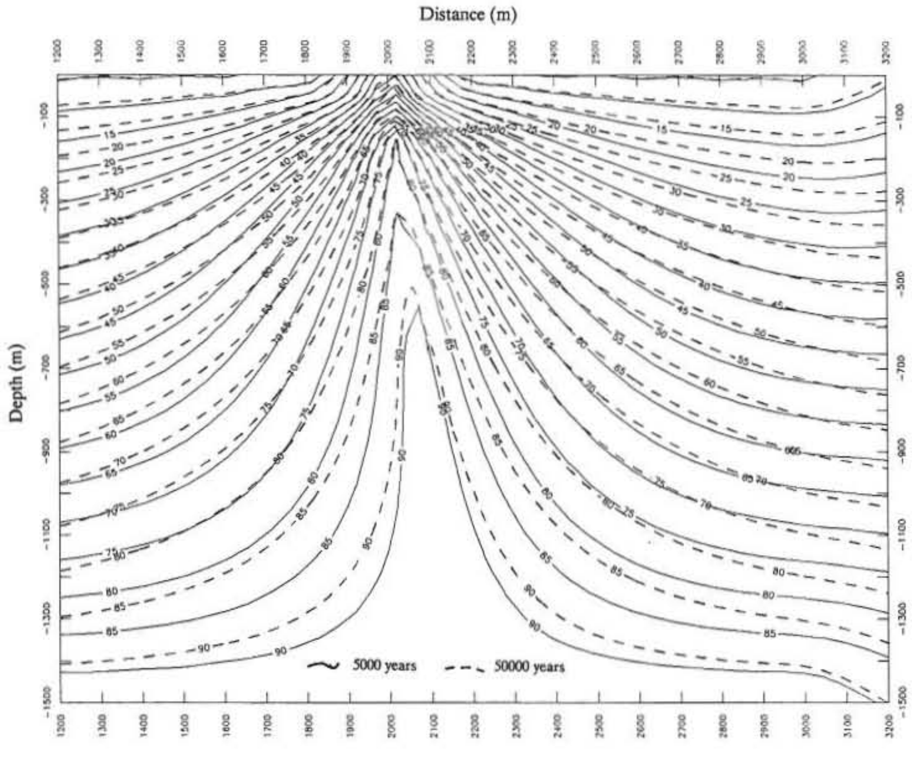

FIGURE 18: Temperature cross-section calculated for 5,000 and 50,000 years

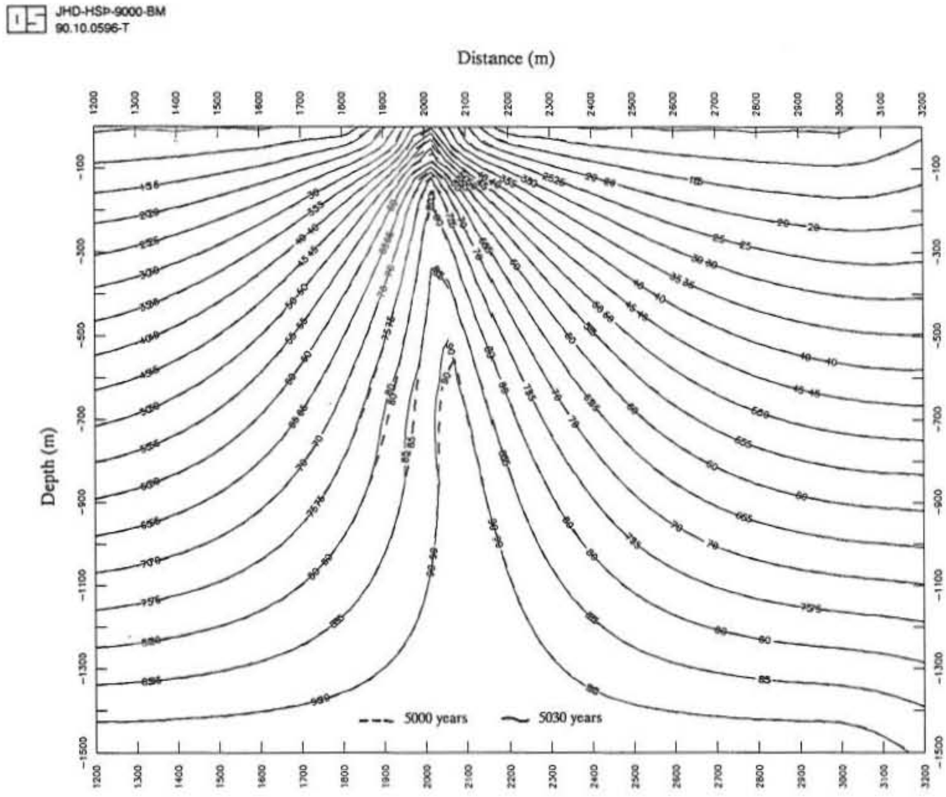

FIGURE 19: Temperature cross-section calculated for 5,000 years and 30 years of horizontal flow from the fracture to well LL2 at 650 m depth

5. WELL LL9

5.1 Purpose of drilling

Well LL9 was drilled as a research well in order to check the different possibilities that have been discussed, and especially the hypothesis discussed under section 4.5 of horizontal flow from a structure shifted away from the wells at 650 m depth. The conception of this model was induced by the existence of the fossil surface manifestation (Figure 2), and the idea that some movements in the crust circa 5,000 years ago closed the previous flow channel and opened another one at the location of the recent hot spring. Furthermore, an observed slight southward dip of the permeable horizontal layers in the boreholes could make an easy pass for such a flow from a shifted upflow zone towards wells LL2, LL3, LL5 and LL6. The location of well LL9 was carefully chosen to put as many constraints as possible on the considered models, and to clarify the situation for the location of a deep producing well that is planned for the next step. Drilling of well LL9 was completed during the modelling process, and the results of the temperature measurements in the well are used to achieve the formerly defined task.

5.2 Temperature logs

Presented in Figure 20 are four temperature logs made in well LL9, three of them during drilling, and the last one just after drilling. The well is practically dry with two really minor aquifers at 190 m and 215 m depths, with a total flow during air drilling of 0.26 l/s. The lower part of the curve measured just after drilling has not yet reached equilibrium and is still possibly 5°C too cool.

5.3 Temperature maps

After drilling well LL9, temperature maps were constructed at different depths between 100 m and 400 m (Figures 21A-D). This was impossible to achieve before, because the wells were all nearly linearly distributed along the low resistivity fracture, delineated by the head-on profiling. In wells too shallow for the depths of the isothermal maps, temperatures were extrapolated from the curves to the maximum possible temperature.

The temperature map (Figure 21A) at 100 m depth clearly shows a N-S trend of the isolines, with temperatures increasing from LL4, LL9 and LL8 towards LL5, LL6 and LL2. On the other hand, this feature cannot be seen on the maps at 200 m, 300 m and 400 m depth (Figures 21B, 21C and 21D) where the isolines are parallel to the low resistivity NNE-SSW fracture, with a tendency to close around wells LL1, LL2, LL3, LL5 and LL6.

This indicates that in the shallower parts (above 200 m) the upflow zone coincides with a N-S structure reaching south from well LL2, and probably extends towards the north above well LL7. In the deeper parts (below 200 m) the upflow zone coincides with the low resistivity fracture, and seems to be confined to the vicinity of wells LL1, LL2, LL3, LL5 and LL6.

5.4 Conclusions drawn from temperature data in well LL9

Temperatures measured in well LL9 were plotted on all the previously considered models. Going again through the pictures we may conclude that:

- In the model of a NW-SE fracture (Model 1, Figure 7), well LL9 would be situated very close to the modelled fracture, and the recorded temperatures are far too low for such an assumption. Having this in mind, and after considering data from LL4 and LL7, this model can be excluded.

- In the case of a N-S fracture (Model 2, Figure 10) temperatures recorded in well LL9 are quite close to the expected ones from the model, if we keep in mind that the latest temperature profile has not yet reached thermal equilibrium after drilling.

- In the case of a fault in the vicinity of well LL3 (Model 3, Figure 11), the temperature profile in the well could be explained by such a model.

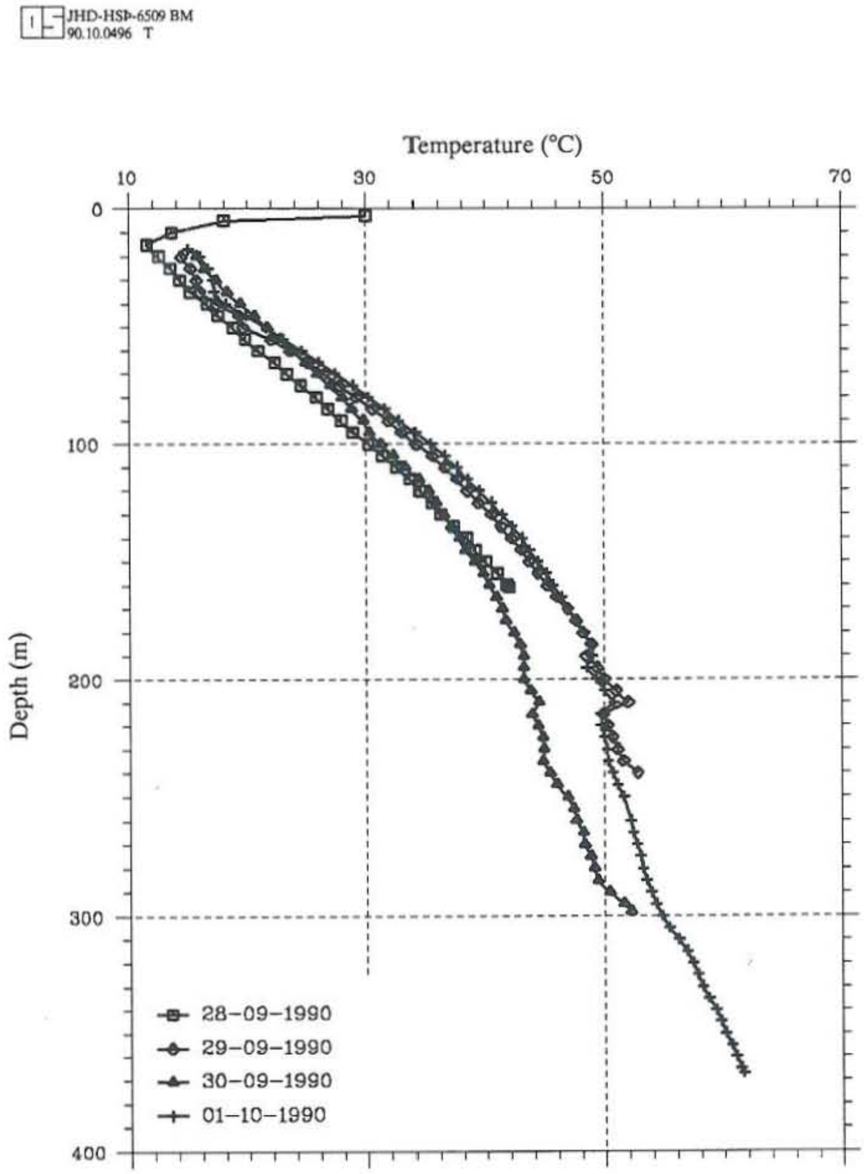

FIGURE 20: Temperature measurements in well LL9

- In the case of Model 4 where a shifted fracture towards the fossil geothermal surface manifestation is assumed, Figure 14 clearly shows that the measured temperatures are too low compared to the model, so this possibility can be excluded.

From the analysis of the data obtained from well LL9, we may conclude that only the hypotheses under Models 2 and 3 remain valid to some extent, keeping in mind the already considered limitations. Theses conclusions are supported by the isothermal maps which indicate that the upflow zone follows a N-S structure above 200 m depth, but a NNE-SSW structure at 200-400 m depth.

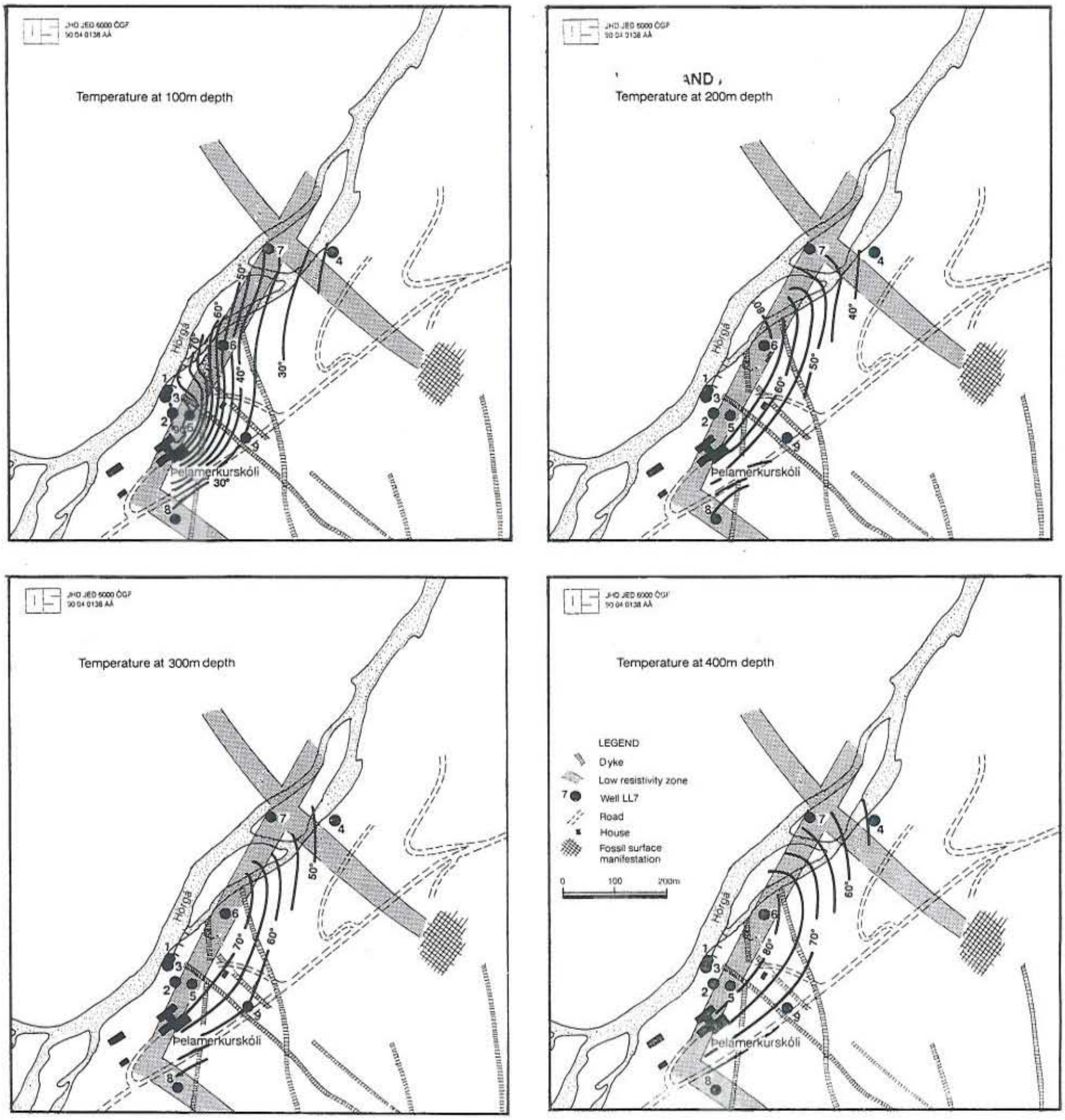

FIGURE 21: Temperature maps at 100, 200, 300 and 400 m depths

6. GENERAL CONCLUSIONS AND RECOMMENDATIONS

The main task of this work was to model and explain the temperature distribution at Laugaland in Thelamörk in order to put some constraints on the flowpaths of the hot water.

The analysis of the temperature curves pointed out several guidelines for subsequent modelling, for example, the existence of an upflow zone situated between wells LL5 and LL6, and the necessity to explain, in particular, the temperature reversal recorded in well LL2.

Four different models have been taken into account during the modelling process, based on temperature data and previous knowledge of the area. After a careful analysis of the modelling data, two of them remain provisionally valid.

The hypothesis of a NW-SE fracture has been excluded because it cannot explain the temperature behaviour of wells LL7, LL4 and LL9.

The hypothesis of an upflow zone coinciding with a fault registered between wells LL2 and LL3 is not able to give an inversion in well LL2, due to its proximity to the upflow zone. The same applies to the hypothesis of an upflow zone limited to the low resistivity fracture postulated after the head-on profiling surveys (Flóvenz et al., 1984). Thus, if the upflow is connected to a N-S fault between LL2 and LL3, the fault cannot be permeable south of LL3, and if it coincides with a fracture according to the head-on profiling, it must be limited to a very short part of this structure between wells LL5 and LL6, almost like a pipe. It can be no closer to LL2 and LL5 than 50 m in order to create a temperature inversion in these wells. Horizontal flow along thin scoria layers is assumed from the upflow zone towards the wells, and this flow is recent in the case of well LL2, with possibly steady state conditions in the other wells.

The modelling process has shown that, in order to have a temperature inversion in well LL2 in combination with horizontal flow, a dip of the fracture away from this well has to be assumed which, according to the previous considerations, would restrict it towards the east or slightly southeast, at least in its deeper part where the inversion is recorded. A western dip could be possible only in the case where the whole upflow zone is situated north of well LL2.

Some constraints have been put on the direction to which the upflow zone can be shifted in the horizontal flow model (Model 4). It was restricted to the southeast direction from the supposed fracture in the case of a N-S fracture coinciding with dyke A1 (Figure 2).

Drilling of well LL9 and the comparison of the measured temperatures in this well to the modelled temperature distributions restricted the remaining possibilities, leaving only the N-S fracture coinciding with dyke A1, or the N-S fault and the pipe as possible upflow zones.

The temperature maps at 100 m - 400 m depth indicate that the hot water flow takes place along the N-S fracture in the uppermost 100 m - 200 m, but below these depths it seems to be associated with the postulated low resistivity fracture.

Modelling of the evolution of the temperature distribution in time created by a near vertical fracture carrying hot water, has pointed out the necessity to take into account the fact that the system has not yet reached steady state conditions, if it is younger than 10,000 years. As the presumed age of the system at Laugaland in Thelamörk is 5,000 - 10,000 years, steady state modelling shows somewhat too high temperatures. It has also confirmed that horizontal flow, which seems to have started after drilling well LL2, could be disregarded as to its influence on the overall behaviour of the temperature field.

The drilling of LL9 and the modelling processes have definitely restricted the possibilities as to how to locate the next well, which should be a production well. It is recommended to drill this well in the vicinity of the upflow zone (Figure 2).

In order to delineate the northern extent of the field, another shallow research well could be drilled west of dyke A1 on the other side of the river, at the same latitude as wells LL7 and LL4.

ACKNOWLEDGEMENTS

If I start in chronological order, the first person to whom I owe thanks is my colleague, Mirjana Georgijeva, who broke the ice and opened the door for other Yougoslavian students to attend the UNU Training programme at the National Energy Authority (Orkustofnun), Reykjavik. Then come Dr. Mihajlo Milivojevic who arranged an interview for me and recommended me to Dr. Ingvar B. Fridleifsson, my Professor Dr. Dragi Stefanovic and all my colleagues who allowed me leave in order to attend the course. But most of all, thanks to Ingvar B. Fridleifsson for selecting me, organizing our training, and making my stay here -almost- perfect.

My thanks go to my advisor Helga Tulinius first for our mountain hikes that took me some 15 years back, then for choosing this theme for my report and for guiding me through it. But for most of the work on the report, I was very happy to collaborate with Ólafur (Óli) Flovenz, who knows this field by heart and always kept my enthusiasm for my work at a high level. Thanks also to Valgardur Stefansson for listening to me, especially at the beginning; to Gudni Axelsson for his advice on PT and for just being there to answer my questions; to Grímur Björnsson, who gave me the opportunity in our field trip to do measurements in a well on "my" field, and to listen for hours and hours to his conversations in Icelandic; and to my son Ilija who kept on asking me questions about my work by phone, and for whom I really did my best.

Further thanks to Marcia Kjartansson, who was here to listen to our problems, cheer us up and did a great job in reading our reports and correcting our English; to Ludvik (Lúlli) S. Georgsson for making our lives enjoyable, and who did not stint his time in finding ways to surprise us, always agreeably; to all our teachers, especially Benedikt (Benni) Steingrimsson for being the most charming and Gudni Axelsson for being the best; to Jósef Hólmjárn (Jobbi) for my thermometer and to Hilmar Sigvaldason for his good memory; to all the fellows who became a kind of big family during our stay here; to all the staff at Orkustofnun who were with us and helped us; to the drawing room office, the kitchen ladies for my favourite cake, and to Johanna, who cheered us up in the afternoons; and lastly, to Iceland for giving me such nice memories of my stay here.

Special thanks to my "wife" Klara, first because she was first to be selected, and needed someone with whom to share the apartment, and then for becoming such a good friend.

And, as I am returning to Yugoslavia, I want to thank my parents and brother who were taking care of my son most of the time, and my son's father, Rade, who was there the rest of the time. I had nothing to worry about, and this made my stay here fruitful and enjoyable.

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