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THE COOLING OF THE SELFOSS GEOTHERMAL RESERVOIR IN SOUTHERN ICELAND

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ABSTRACT

A study of the temperature distribution in the Selfoss geothermal area is presented in this report. This geothermal area supplies the town of Selfoss with hot water and has experienced a gradual cooling during its 40 years of exploitation. By estimation of the average initial temperature, two geothermal systems were identified in this area, the upper geothermal system in the depth interval between 50 and 1000 m with a temperature range of 80-96°C, and the lower geothermal system below 1200 m depth with a temperature range between 130 to 150°C. The magnitude of cooling has been determined at several levels by comparing the initial temperature with the present temperature distribution. The direction of cold water inflow was established on the basis of constructed temperature maps at several depths, and cross-sections. It has an east - west direction from the farm Thorleifskot towards the middle part of the field. Cold water flow was specified in the upper geothermal system at two levels with the strongest influence at 150 m depth and cooling of more than 55°C. The temperature distribution in the southwest part of the field is different to the other parts of the field. These conclusions were partially confirmed through chemical analysis of water samples, mainly by differing chlorine content in the thermal water.

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1. INTRODUCTION

1.1 Scope of the work

The Selfoss geothermal area is a low temperature field located at the farms Laugardaelir and Thorleifskot in South Iceland, close to the town Selfoss (Figure 1 and 2). The water from the geothermal area has been used for domestic heating of Selfoss since 1948, i.e. 43 years, making the Selfoss District Heating Service one of the oldest in Iceland. In 1948 when the domestic heating service started, the population was 900 inhabitants, but has since then grown rapidly and is now about 4000.

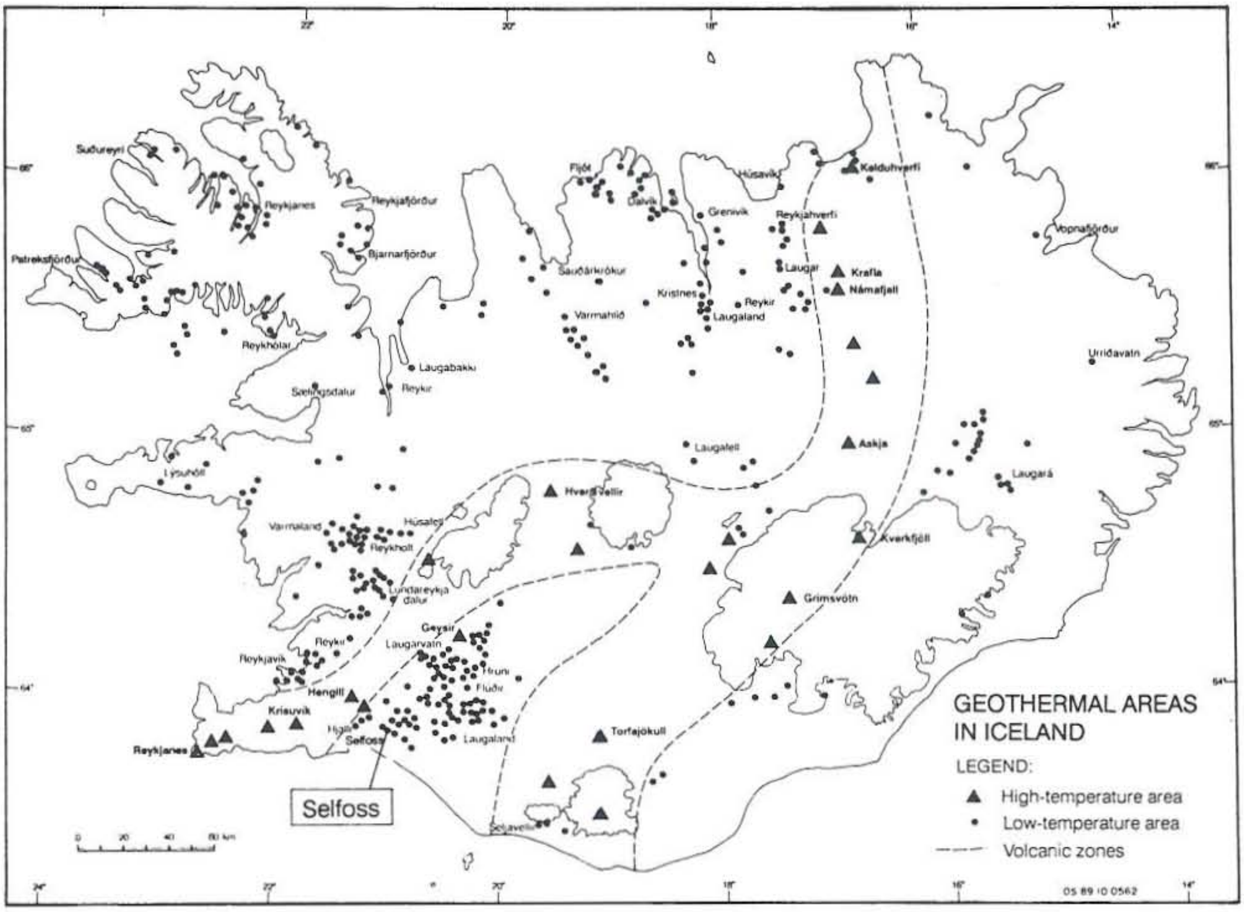


FIGURE 1: Location of the Selfoss geothermal area

The purpose of the present report is to estimate the initial and present temperature distribution in the Selfoss geothermal field, with emphasis on the considerable cooling observed in the field during the past 40 years. Gradual cooling is due to the inflow of cold groundwater into the geothermal system. This study has been carried out on the basis of temperature measurements recorded during drilling, but mostly during production.

1.2 Geology and hydrology

Iceland lies across the crest of a constructive plate boundary, the Mid-Atlantic Ridge and is composed entirely of volcanic lavas, breccias, tuffs and sediments. The zones of volcanic and

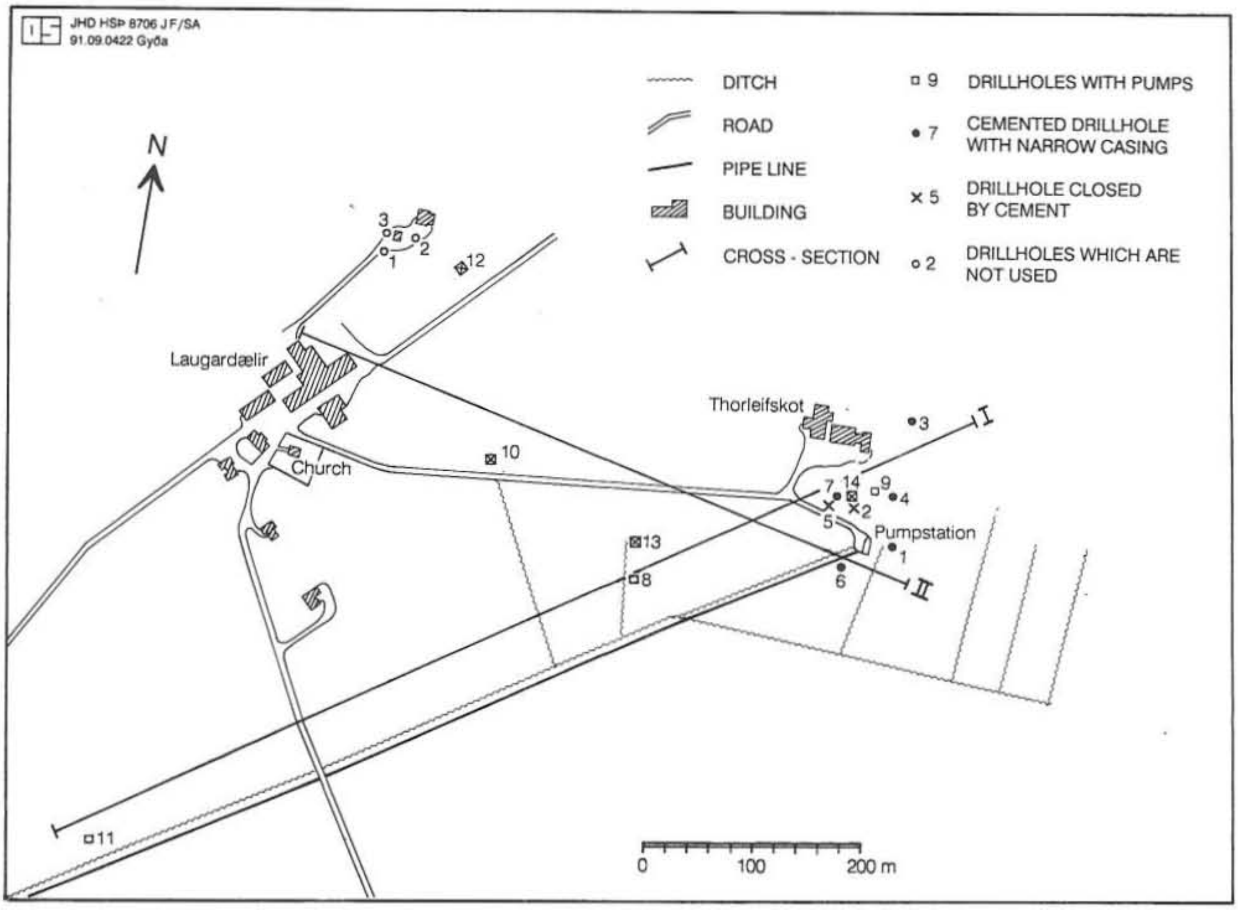
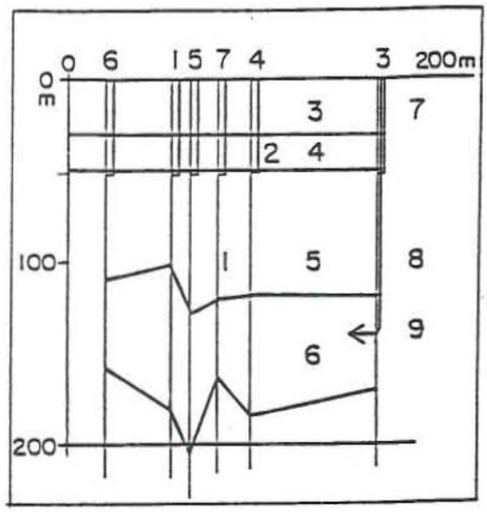


FIGURE 2: Location of wells and cross-sections in the Selfoss geothermal area

tectonic activity are flanked by Quaternary rocks, mainly sequences of subaerial lava flows intercalated by hyaloclastites and morainic horizons at intervals corresponding to glacial conditions. The Quaternary formations are bordered by Tertiary subaerial flood basalts. The low temperature areas in Iceland are located in Quaternary and Tertiary strata, mostly in lowlands and valleys.

The geological strata in the Selfoss geothermal area is of Quaternary age, and can be divided (Tomasson, 1980) into three separate formations. The uppermost formation (0-200 m) consists of the post-glacial lava flow underlain by tillite. The tillite lies unconformably on the top of Quaternary basement which consists mainly of basaltic lavas with minor sedimentary layers and dolerite intrusives (Figure 3). Simplified geological profiles in deep drillholes are presented in Figure 4.



Legend: 1. drillhole, 2. casing, 3. postglacial lava, 4. glacial sediment, 5. quarternary rock, 6. sedimentary bed within the quarternary sequence, 7. crack of casing, 8. flow of cold groundwater through the drillhole, 9. flow of cold groundwater into permeable sediment layer

FIGURE 3: The geological cross-section of the upper part of the geothermal system (Tomasson, 1980)

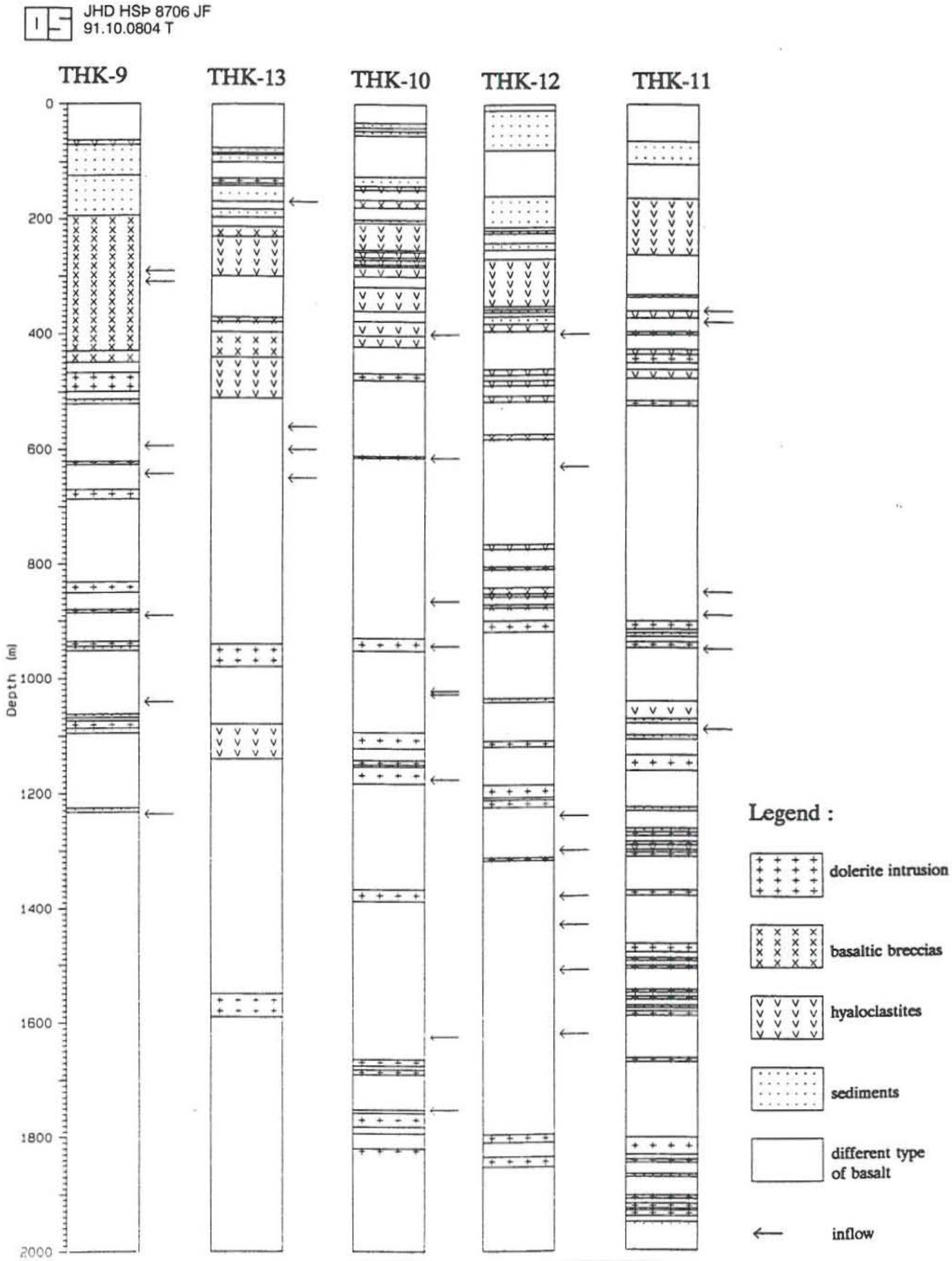


FIGURE 4: Simplified geological profiles of deep wells in the Selfoss geothermal area

The hydrological definition of the strata is different from that of the geology (Tomasson and Halldorsson, 1981) in that the succession above 300 m depth to the base of the post-glacial lava is treated as one semipermeable layer. The geothermal system is divided on the grounds of temperature into two parts. The upper part reaches down to 1000-1100 m depth and is 70-95°C hot, and the lower, with temperature up to 150°C, is below 1300 m depth. The transmissivity of the geothermal reservoir was calculated (Tomasson and Halldorsson, 1981) as $3.7 \cdot 10^{-4}$ m^2/sec and the permeability as $4 \cdot 10^{-4}$ m^2/sec. The recharge area is $2 \cdot 10^6$ m^2, as compared to the well field of $6 \cdot 10^5$ m^2.

1.3 Geochemical and geophysical survey

The geothermal water has a chlorine content of 100-500 ppm. This is a relatively high concentration compared to other low temperature fields in Iceland. The chlorine is believed to have orginated from sea water when the area was covered by the sea in early post-glacial time (Tomasson, 1967). The variation in the chlorine content is believed to be caused by the inflow of cold groundwater with a chlorine content of 5-10 ppm into the thermal system (Tomasson, 1980). Many analyses of thermal water from different drillholes in Thorleifskot were done shortly after the start of pumping. The chlorine content of these water samples was 430-520 ppm. Several water samples were also taken at a later time in the production history of each well. In these samples the chlorine content had decreased by about 100 ppm. These data were interpreted as the invasion of cold groundwater in the interval from 300 m depth up to 50 m depth, in particular between 130-150 m depth (Tomasson, 1966).

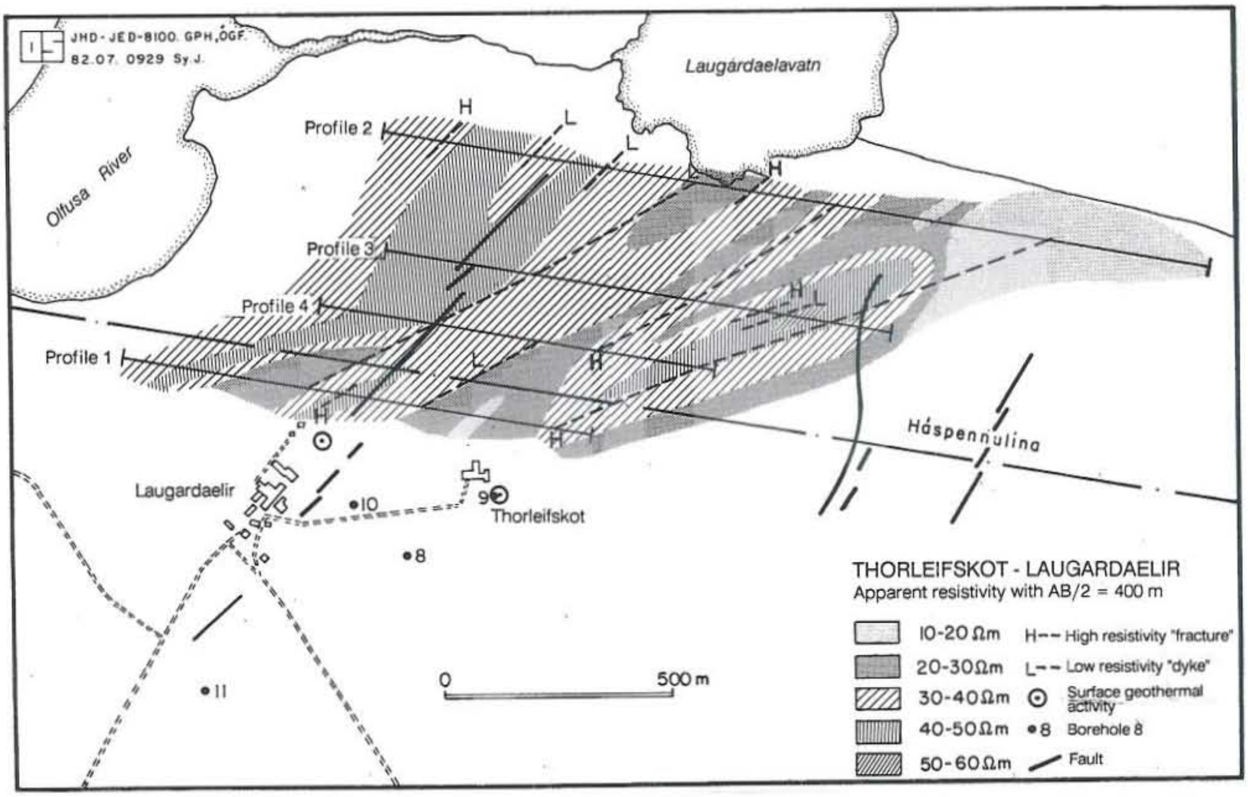


FIGURE 5: Head-on resistivity profiling in the Selfoss geothermal area

In 1982, a head-on resistivity profile was carried out close to the Selfoss geothermal area (Figure 5). The purpose of the measurements was to determine the low resistivity zones, which are usually associated with temperature anomalies in Iceland. The following results were obtained. Two low resistivity water-bearing "fractures" with NE-SW directions towards the farm Laugardaelir were found (Figure 5). Farther to the southeast these fractures can be seen on the surface where hot springs are located. Two high resistivity "dykes" with NE-SW direction were determined in the area between the farms Laugardaelir and Thorleifskot. They could be a sign of flow barrier in this area (Hersir and Flovenz, 1982).

1.4 History of field development and production

The exploitation of the area started in 1948 by utilizing the free flow of 78°C hot water from shallow drillholes near the farm Laugardaelir (Figure 2). When utilization started, the hydrostatic pressure of the geothermal water decreased, causing the inflow of cold groundwater. Each new drillhole had to be soon abandoned due to severe cooling. Based on the results from a surface geophysical survey, the drilling operations were moved to the farm Thorleifskot (Figure 2). Between 1950 and 1952 five wells were drilled in this area with depths from 150 to 300 m. The drilling was successful. From the two first wells THK-1 and 2 the flow was 15 l/s of 82°C hot water from the 130-140 m depth interval (Bodvarsson, 1951). The cold groundwater was cased off in all of these wells (Figure 3). The holes THK-6, which was 500 m deep, and THK-7, which was 490 m deep, were drilled in 1963 and 1964 and wells THK-1 and 4 were deepened. In 1964 submersible pumps were installed and with increasing pumping from the field, cooling accelerated. A new hole THK-8 was drilled in 1966 down to 450 m depth. It was located 200 m west of the older holes. In 1972 considerable cooling was observed in the well. The well was deepened down to 738 m and cemented from 250 m depth up to the casing at 50 m depth. After that the temperature of water from the drillhole increased. In 1975 and 1976 wells THK-1 to 7 were abandoned and cemented with a pipe for temperature measurements. In 1977 well THK-8 was deepened to a depth of 781 m. In 1977 well THK-9 was drilled to a depth of 1334 m and cased down to 239 m to prevent the strong inflow of cold groundwater. In 1979 well THK-10 was drilled 300 m west of well THK-9 (Figure 2). The well was 1800 m deep with casing down to 307 m. It collapsed shortly after drilling at 1100 m depth. In 1980 well THK-11 was drilled. It is located 500 m southwest of well THK-10 and is 2007 m deep with casing down to 356 m. Well THK-12 was drilled in 1983 at the farm Laugardaelir to a depth of 1936 m and cased down to 305 m. In 1985 well THK-13 was drilled close to well THK-8. The well is 1715 m deep with casing to 514 m depth. To prevent cooling in this well, well THK-8 was cemented with a pipe in 1986. In 1989 THK-14 was drilled, the last well to date in the Selfoss geothermal area. The well is located at the farm Thorleifskot and is 1430 m deep. Considerable cooling was observed in this well shortly after drilling. To prevent THK-14 from cooling, well THK-9 was cemented with a pipe in 1991, leaving THK-10, THK-12 and THK-13 as the remaining production wells in the area.

TABLE 1: Summary of drilling operations in the Selfoss geothermal area

Borehole no.	Time (year)	Operation	Depth (m)	Casing (m)
THK-1	1950 1950 1963 1975	predrilling drilling deepening cementing pisa	45 248.8 389.6 389.6	50
THK-2	1950 1975	drilling cementing pisa	152 152	50
THK-3	1950 1959 1966 1972	drilling deepening fishing and recasing cementing pisa	213.4 446 446 446	50
THK-4	1951 1951 1963 1964 1975	predrilling drilling deepening fishing cementing pisa	20 242.7 315 315 315	50
THK-5	1951 1951 1975	predrilling drilling cementing pisa	30.8 372 372	50
THK-6	1963 1963 1975	predrilling drilling cementing pisa	17.8 502.5 502.5	50
THK-7	1963 1976	drilling cementing pisa	430 430	50
THK-8	1966 1972 1977 1986	predrilling drilling deepening cementing pisa	489 738.5 781.4 781.4	250
THK-9	1976 1977 1991	predrilling drilling cementing pisa	25.3 1335 1335	239.4
THK-10	1978 1979	predrilling drilling	36.2 1859	306.8
THK-11	1980 1980	predrilling drilling	34 2007	356.4
THK-12	1982 1985	predrilling drilling	83.2 1936	305
THK-13	1985 1985	predrilling drilling	49 1715	514
THK-14	1988	drilling	1433.5	476.5

2. INTERPRETATION OF TEMPERATURE MEASUREMENTS

Nearly 200 temperature measurements from 14 boreholes drilled in the Selfoss geothermal area were studied in order to understand better the temperature distribution there. Temperature in the wells was measured during drilling, but mainly after drilling and during production. This data has been recorded for the past 42 years in nonproductive and productive wells.

2.1 Analysis of temperature measurements

From the existing temperature measurements were selected those which provide information about initial temperature, temperature changes with time and the present temperature state in the geothermal field. The chosen graphs from each well are presented in Figures 6, 7 and 8. Measurements which did not reach the bottom or were strongly disturbed were not considered, e.g. wells THK-2 and THK-5 (Figure 2). Temperature graphs which represent the natural status of the Selfoss geothermal system were recorded in wells THK-1 (Figure 6a), THK-6 (Figure 6d), THK-7 (Figure 7a), THK-8 (Figure 7b), THK-9 (Figure 7c) and THK-14 (Figure 8d). The disturbed temperatures are observed in wells THK-10 (Figure 7d), THK-12 (Figure 8b) and THK-13 (Figure 8c). These wells are productive, so the disturbances are due to the production.

Generally, the temperature measurements are considerably disturbed by cooling in the depth interval 100-400 m, with the strongest influence at 150 m depth. Cooling is also observed below 500 m due to internal flow down to 900-1000 m in wells THK-9 (Figure 7c) and THK-14 (Figure 8d). Temperature distribution in well THK-11 (Figure 8a) is different from the other wells.

2.2 Estimation of the initial temperature

In order to study the cooling effects, the initial temperature distribution of the geothermal field must be known. All temperature measurements during drilling and the warm-up period have been studied to gain information on the initial temperatures in the Selfoss geothermal system.

To estimate the initial temperature it is necessary to use the temperature measurements which are undisturbed and are quite constant during a period of time. The least disturbed temperature value in the well measured during drilling is the bottom hole temperature as well as temperatures measured a long time after drilling, if they are not influenced by internal flow in the well. The bottom hole temperatures from wells which were drilled deeper than previous wells were taken into consideration in the Selfoss geothermal area. These bottom hole temperatures are not disturbed by the cooling caused by downflow in surrounding shallower wells. Temperatures showing no changes over time were also included in the interpretation. The average initial temperature graph T_{in} which represents the initial temperature distribution in the Selfoss geothermal area, excluding the southwest part of the field around the well THK-11, is shown in Figure 9a. This curve can also be approximated by the polynomial expression with the equation:

$$T = -3.2 \cdot 10^4 + 0.9 \cdot 10^3 \cdot H - 7.6 \cdot H^2 + 0.02 \cdot H^3$$

where T is the temperature in (°C) and H is the depth in (m). The graph representing the initial temperature distribution in the southwest part of the Selfoss geothermal area is shown in Figure 9b.

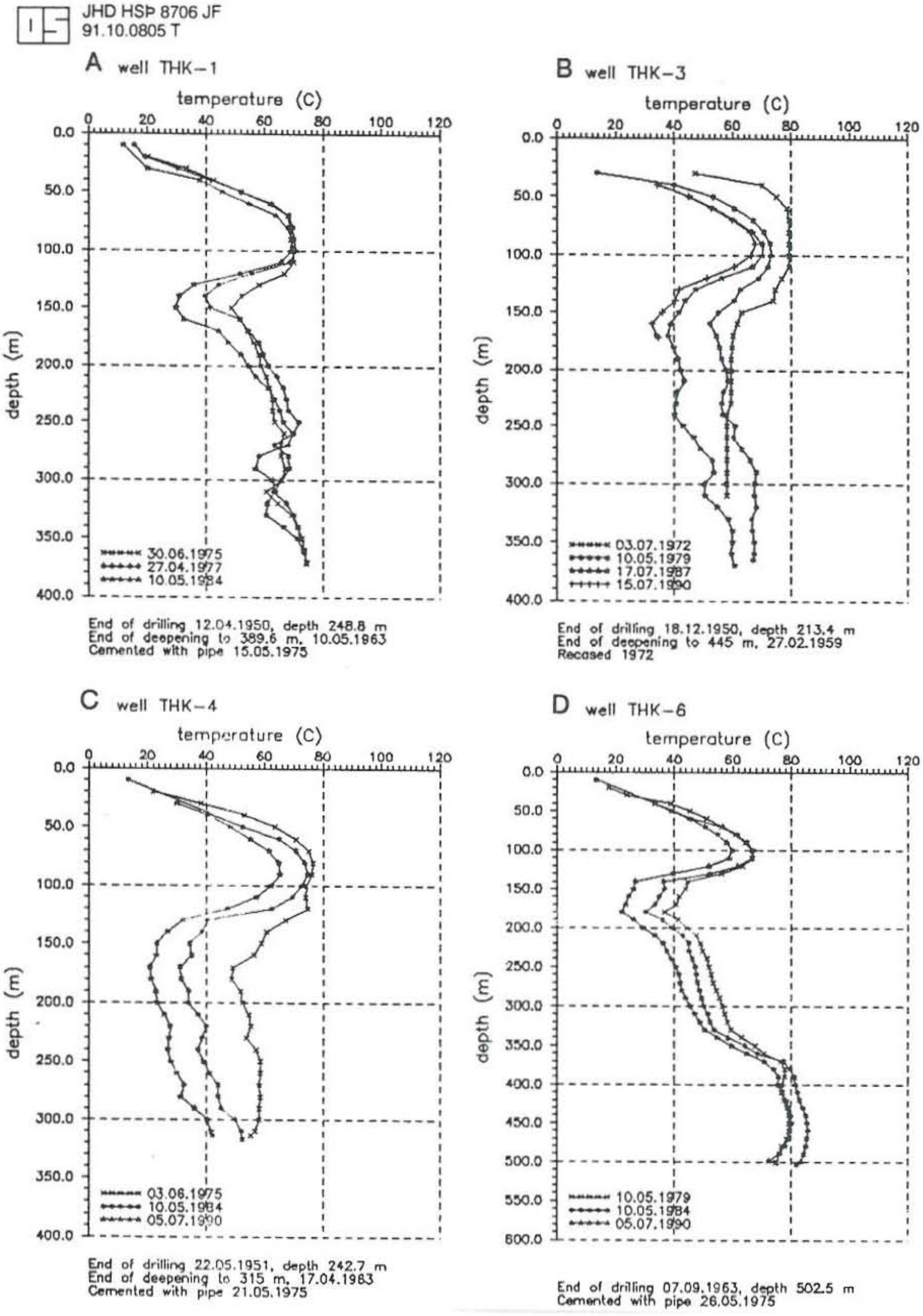


FIGURE 6: Selected temperature graphs for wells THK-1, 3, 4, and 6

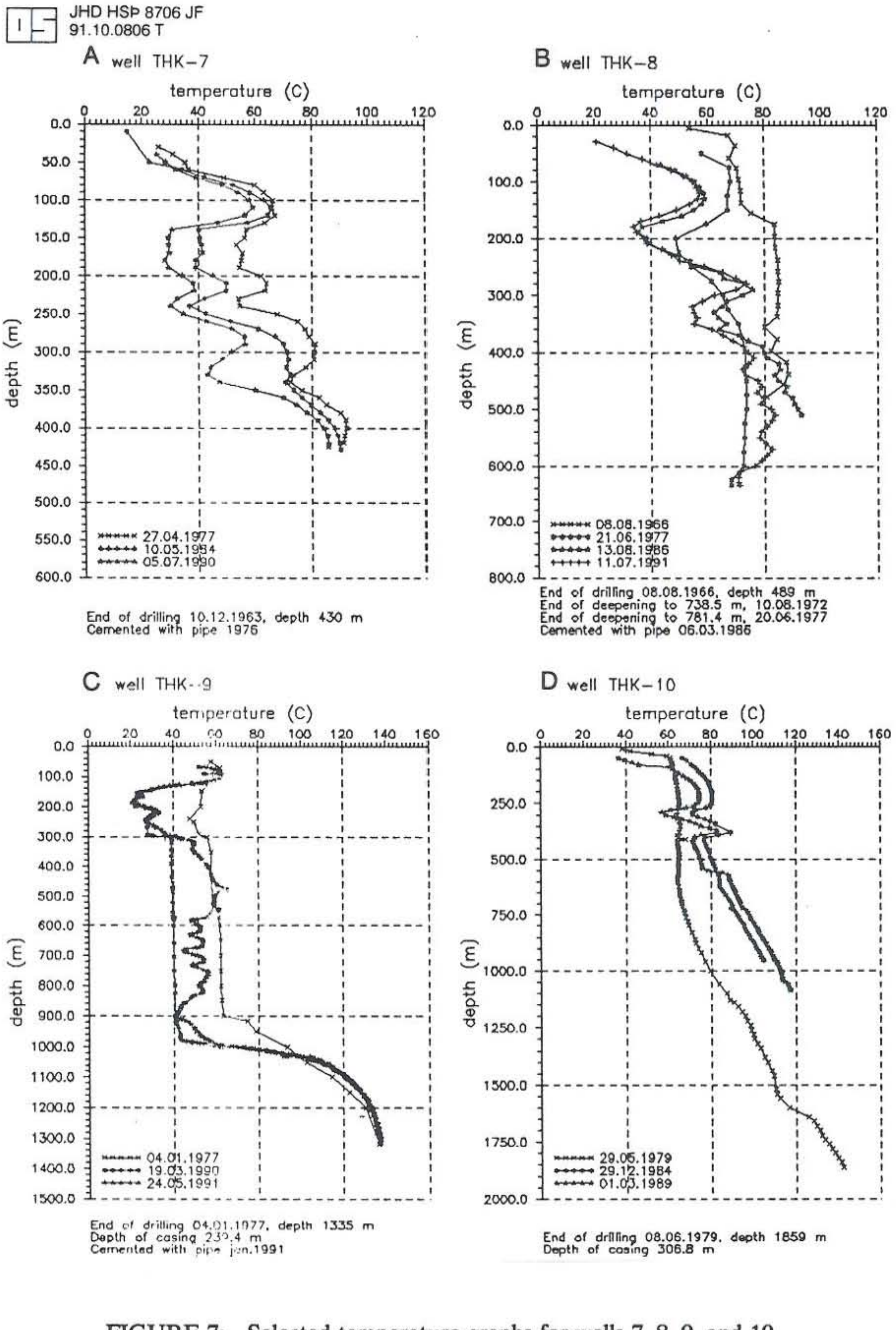


FIGURE 7: Selected temperature graphs for wells 7, 8, 9, and 10

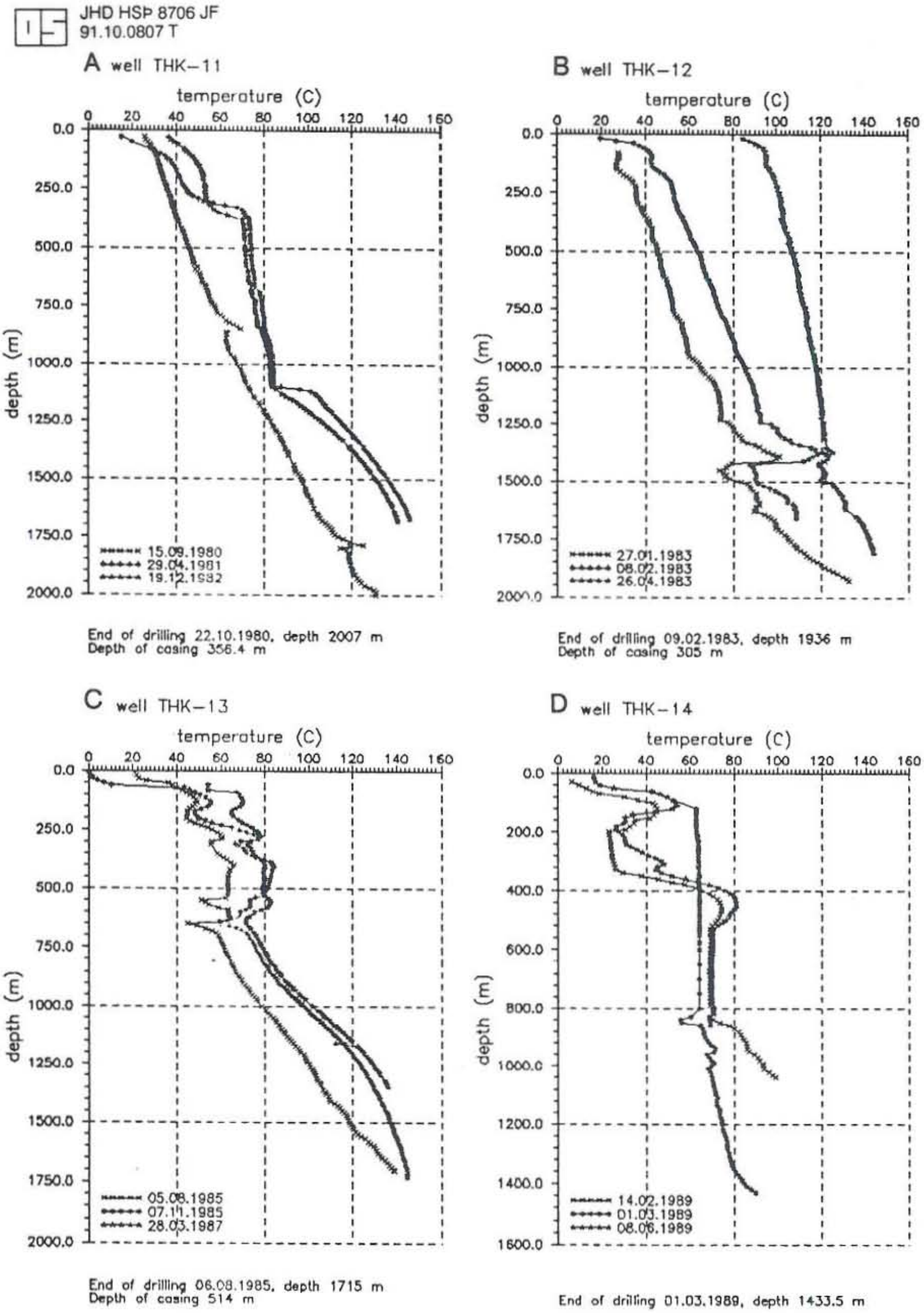


FIGURE 8: Selected temperature graphs for wells THK-11, 12, 13, and 14

The temperature distribution in the southwest part of the geothermal field is different, as is noticeable in the comparison of the initial temperature graphs (Figure 9). For the other parts of the field, the following conclusions can be made. This geothermal field is characterized by two geothermal systems. The upper geothermal system is in the interval between 50 and 1000 m depth with a temperature range 80-96°C and the lower geothermal system is below 1200 m depth with temperatures between 130 and 150°C. Between these two geothermal systems is a nonpermeable barrier. Connection between these two hot systems is unlikely.

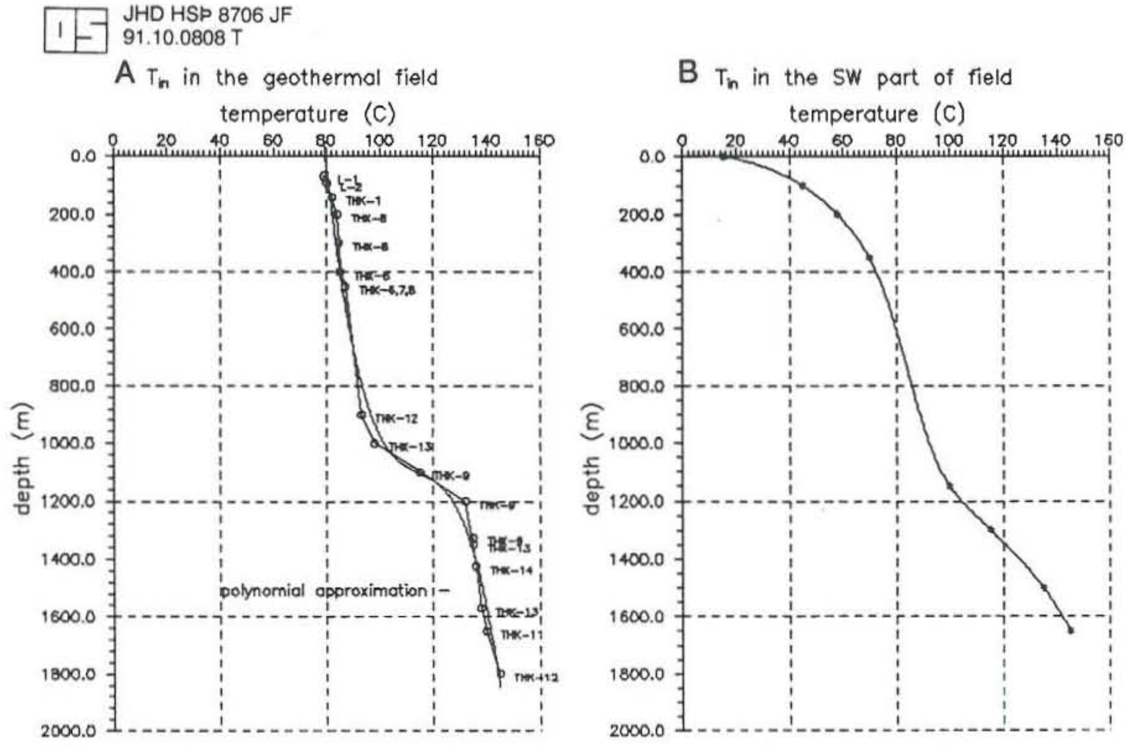


FIGURE 9: Average initial temperatures T_{in} in the Selfoss geothermal area

2.3 Comparison of present and initial temperatures

In order to estimate the cooling in each well, as well as in the whole geothermal field after more than 40 years production, a comparison was made between the average initial temperature and the present or latest temperature measurements. Both temperature curves are plotted in Figures 10, 11 and 12. The cooling is caused by a gradual influx of cold water at the depth interval between 100 and 400 m with the strongest influence at 150 m depth, and by cold water intrusion below 500 m depth and downflow in the wells to 1000 m depth. The greatest cooling, more than 55°C at 150 m depth, is observed in the nonproductive wells THK-1 (Figure 10a), THK-4 (Figure 10c), THK-6 (Figure 10d), THK-7 (Figure 11a), THK-9 (Figure 11c) and THK-14 (Figure 12d). Cooling below 500 m depth is observed in well THK-9 (Figure 11c), 50-60°C, and in well THK-14 (Figure 12d), about 20°C.

Cooling in productive wells is observed in wells THK-10 (Figure 11d) and THK-13 (Figure 12c) both in the upper interval as well as below 500 m depth. The temperature changes are not observed in the southwest part of the geothermal area, which is evident from a comparison of the initial temperature distribution in this part of field with the present temperature distribution in well THK-11 (Figure 12a). This subject will also be discussed later.

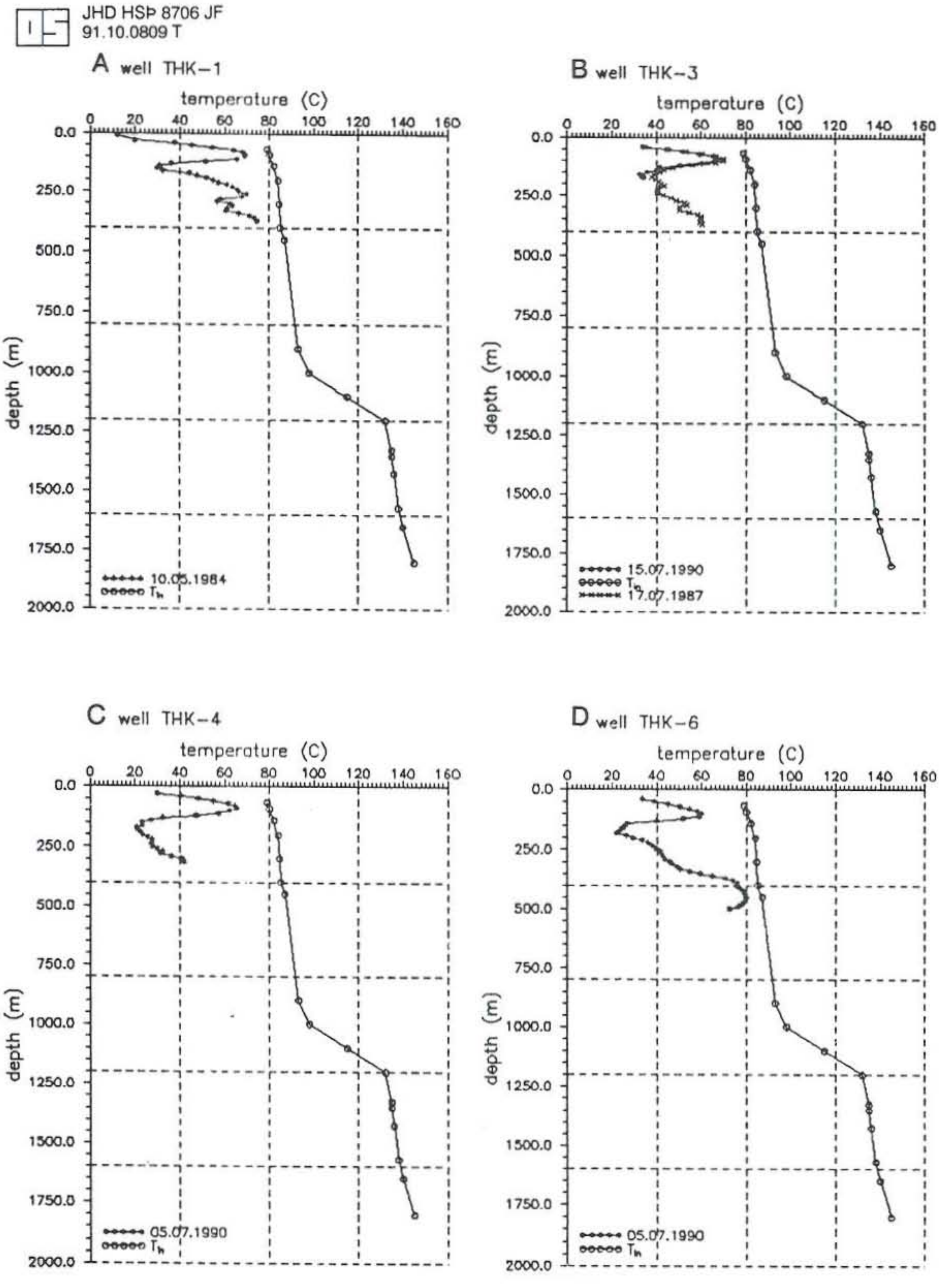


FIGURE 10: Comparison of the present and/or the latest temperature measurements with the initial temperature graph T_{in}

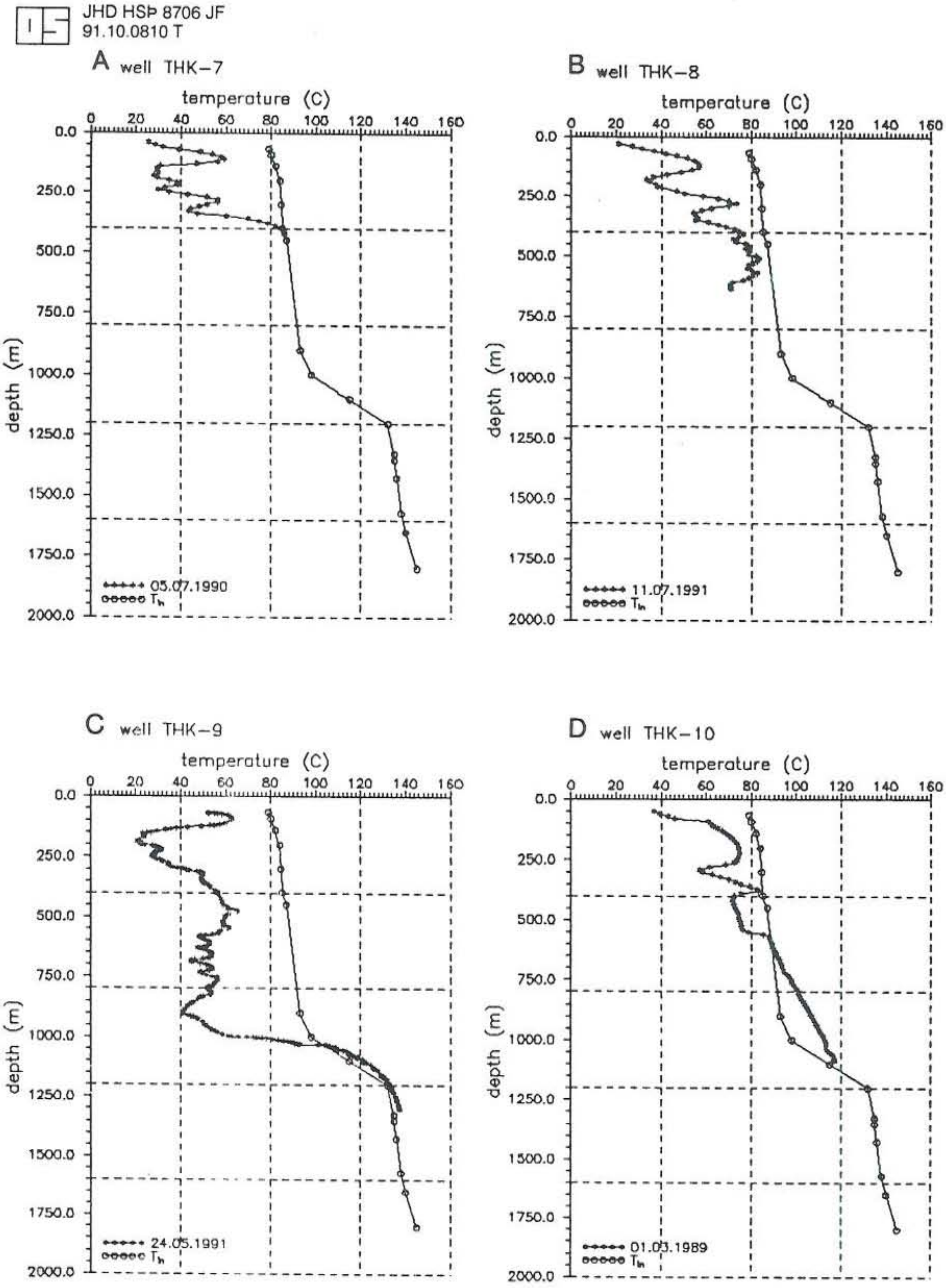


FIGURE 11: Comparison of the present and/or the latest temperature measurements with the initial temperature curve T_{in}

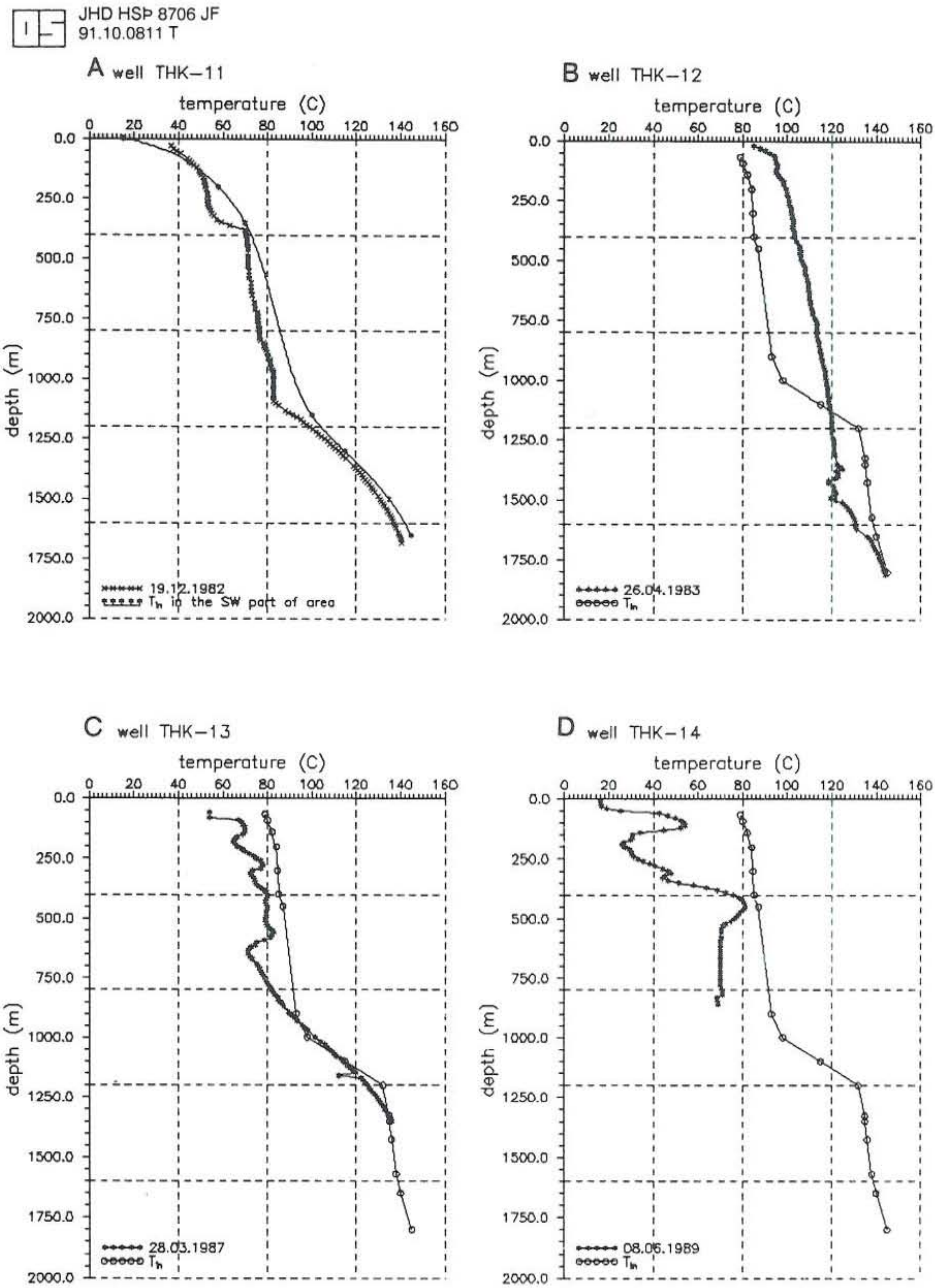


FIGURE 12: Comparison of the present and/or the latest temperature measurements with the initial temperature curve T_{in}

Cooling is also observed at 100 m depth. We believe that the reason for this cooling is not due to cold water inflow at this level, but rather to conductive cooling from the level below. Temperatures close to the initial temperatures are observed at the depth interval between 400 and 500 m in wells THK-6 (Figure 10d), THK-7 (Figure 11a), THK-8 (Figure 11b), THK-13 (Figure 12c) and THK-14 (Figure 12d). The fact that the temperatures at this level are close to the initial temperatures confirms that the cooling in the upper geothermal system is due to the inflow of cold groundwater at the two levels or intervals previously mentioned.

No cooling is observed in well THK-12 (Figure 12b) in the upper geothermal system. The temperature is, in fact, higher than the initial value. Cooling in the lower aquifer, below 1200 m depth, is caused by the production from this well, mainly from the feedzone at 1325 m depth. So it is possible to say that well THK-12 is, at present, the main production well in the Selfoss geothermal area.

3. THE TEMPERATURE DISTRIBUTION IN THE FIELD

Temperature maps at 100, 150, 400, 600, 800 and 1200 m depths (Figures 13a and c, 14a and c, 15a and c) were constructed to represent the temperature distribution in the Selfoss geothermal area. The present or latest temperature measurements were considered. Similarly, the maps of cooling effects were constructed for the same levels to enhance the rate of cooling with time (Figures 13b and d, 14b and d, 15b and d). These maps show the differences between present and initial temperatures T_{in}.

The lowest temperatures are measured in the eastern part of field at the farm Thorleifskot. At 100 m depth the temperatures are between 60 and 70°C (Figure 13a), at 150 m depth between 25 and 30°C (Figure 13c), at 600 m depth from 55 to 65°C (Figure 14c) and at 800 m depth from 50 to 70°C (Figure 15a). The highest temperature is observed in the northwestern part of the field at Laugardaelir at 100 m, 150 m, 400 m, 600 m and 800 m depth where the temperature rises from 95 to 113°C (Figure 13a and c, 14a and c, 15a). At 1200 m depth the highest temperature, 133°C, was measured in well THK-9 at Thorleifskot (Figure 15c).

A small cooling effect, between 10 and 20°C, is observed at 100 m depth (Figure 13b) in the whole geothermal field, except in the northwestern and southwestern corners. The strongest cooling of more than 50°C is observed in the eastern part of the field at 150 m depth. The direction of cold water flow is from east to west and the cold front has reached well THK-10 in the central part of the field (Figure 13d), where the cooling effect has decreased to 10°C. The smallest cooling, within 10°C, is observed at 400 m depth (Figure 14b). Cooling of more than 30°C at 600 m depth is observed in wells THK-9 and 14, decreasing to 10°C toward wells THK-8 and 13 (Figure 14d). The direction of cold water flow is from east to west. Similar temperature distribution is seen at 800 m depth (Figure 15b). At 1200 m depth small cooling is only observed in the northwestern part of the field (Figure 15d).

The results of the analysis of the maps can be summarized as follows. A gradual cooling is observed in the eastern part of the geothermal field in the upper geothermal system in the 100-1000 m depth interval. This takes place at two levels, above 400 m depth and below 500 m. The strongest intrusion of cold groundwater is at 150 m depth at Thorleifskot where cooling is in excess of 50°C. The direction of the cold water flow is from east to west and the cold water front has reached the production wells THK-13 and THK-10 in the central part of the field. There cooling is now around 10°C. The cold water flows through the sedimentary layers (Figures 3 and 4) which have higher permeability than adjacent lava flow units.

The small cooling at 100 m depth is believed to be caused by conductive cooling from the level below, rather than intrusion of cold water. In order to check this assumption the conductive cooling in a 100 m thick slab with the same temperature (40°C) at the top and bottom was calculated (Carslaw and Jaeger, 1950, p. 75-77). Assuming the thermal diffusivity, $\kappa = 6\ 10^{-7}\ m^2/s$, we see that cooling by conduction alone is expected to be about 10°C over a 40 year period (Figure 16). However, the observed cooling over this period is 16°C. As the applied model for conductive cooling assumes that the entire cooling at the lower level takes place instantaneously, the model will overestimate the conductive cooling actually taking place. It is, therefore, concluded that the cooling at 100 m depth is not only due to conduction, but there must also be a cooling effect due to advection. The ratio between the total cooling and the cooling by conduction only (Nussel number) is 16/10 or 1.6. As the model used for calculation of the conductive cooling overestimated the conductive component, it is concluded that about half of the cooling at 100 m depth is due to conduction, and the other half to advection.

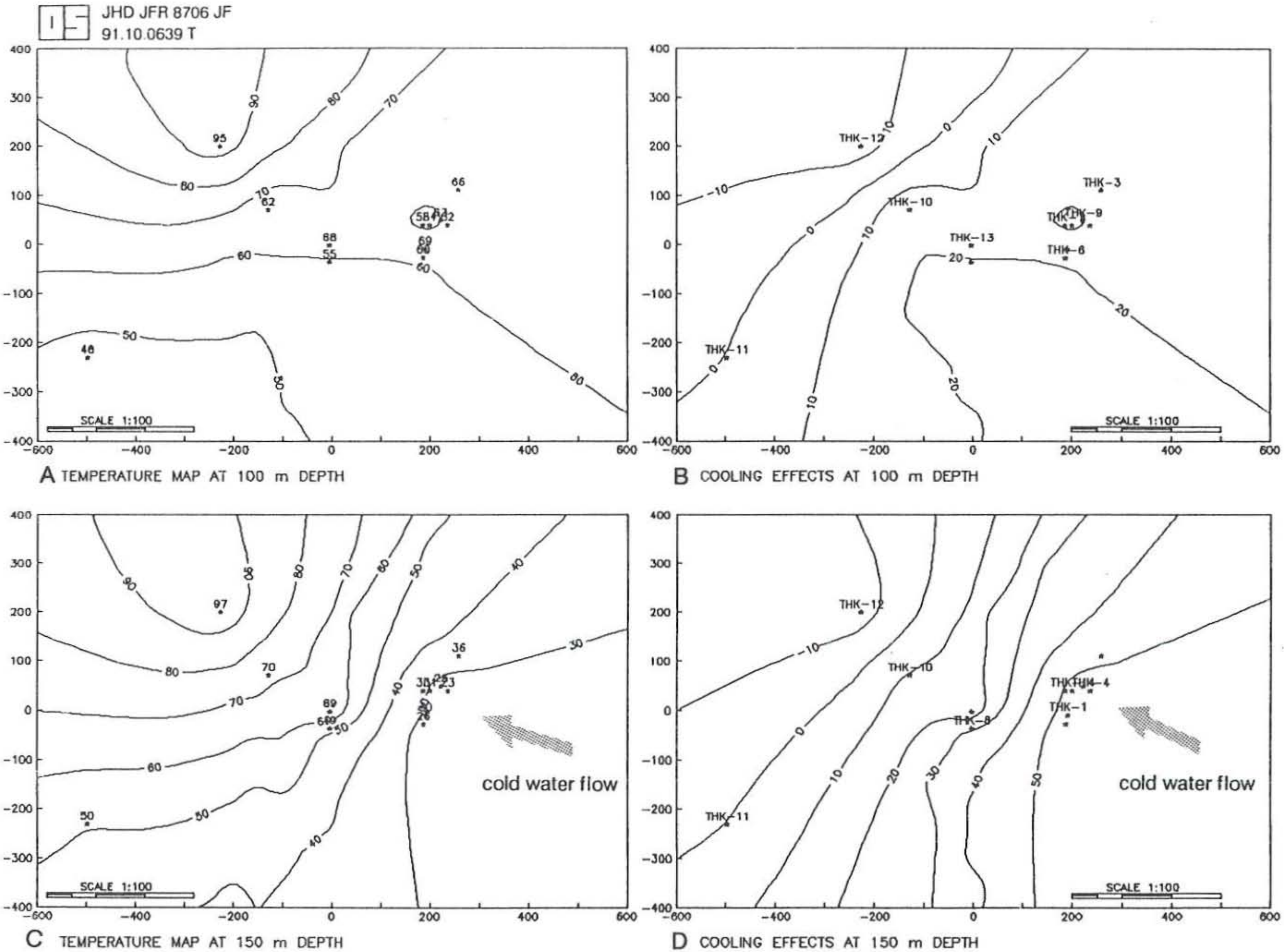


FIGURE 13: Temperature maps at 100 and 150 m depth in °C

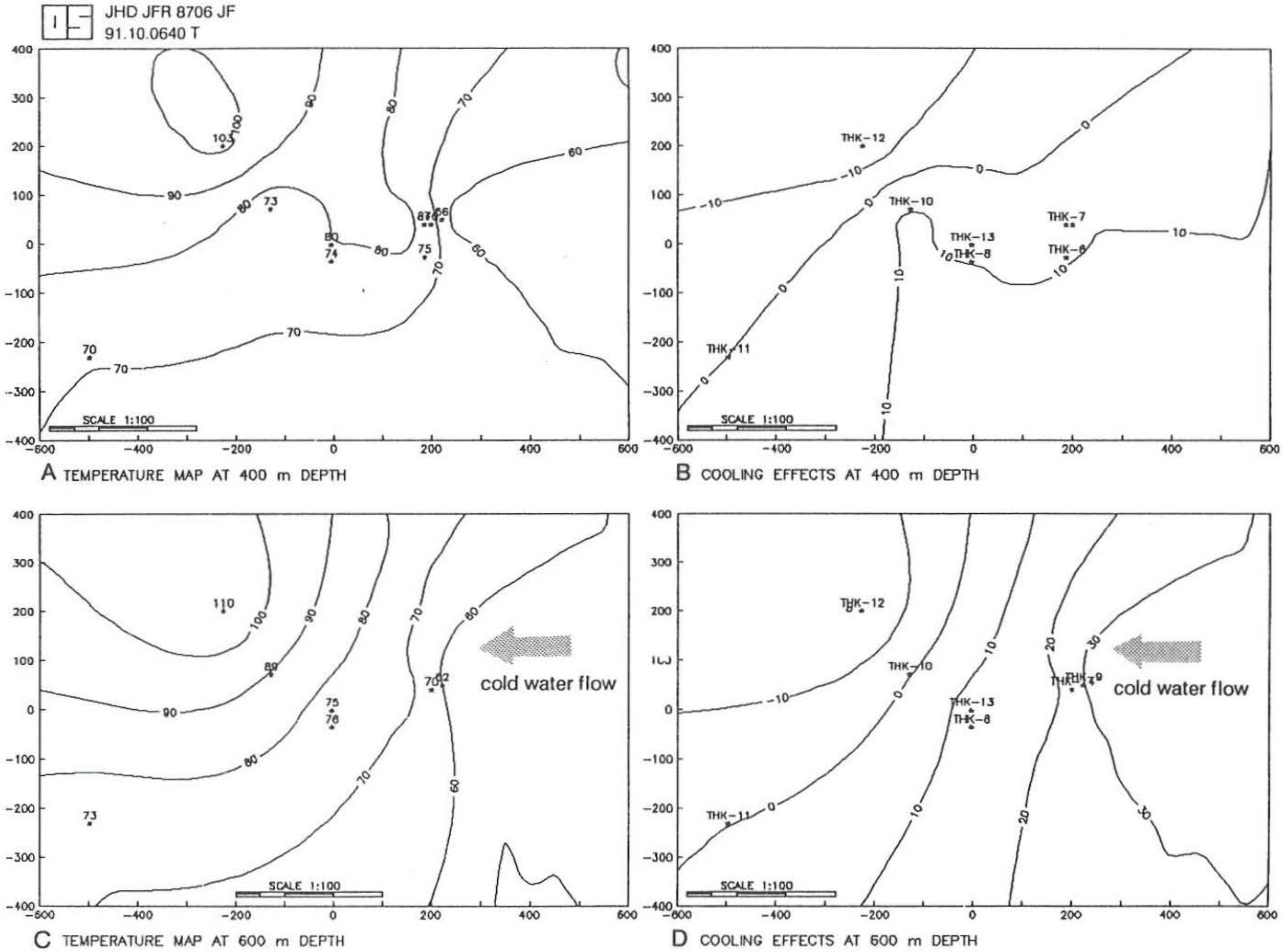


FIGURE 14: Temperature maps at 400 and 600 m depth in °C

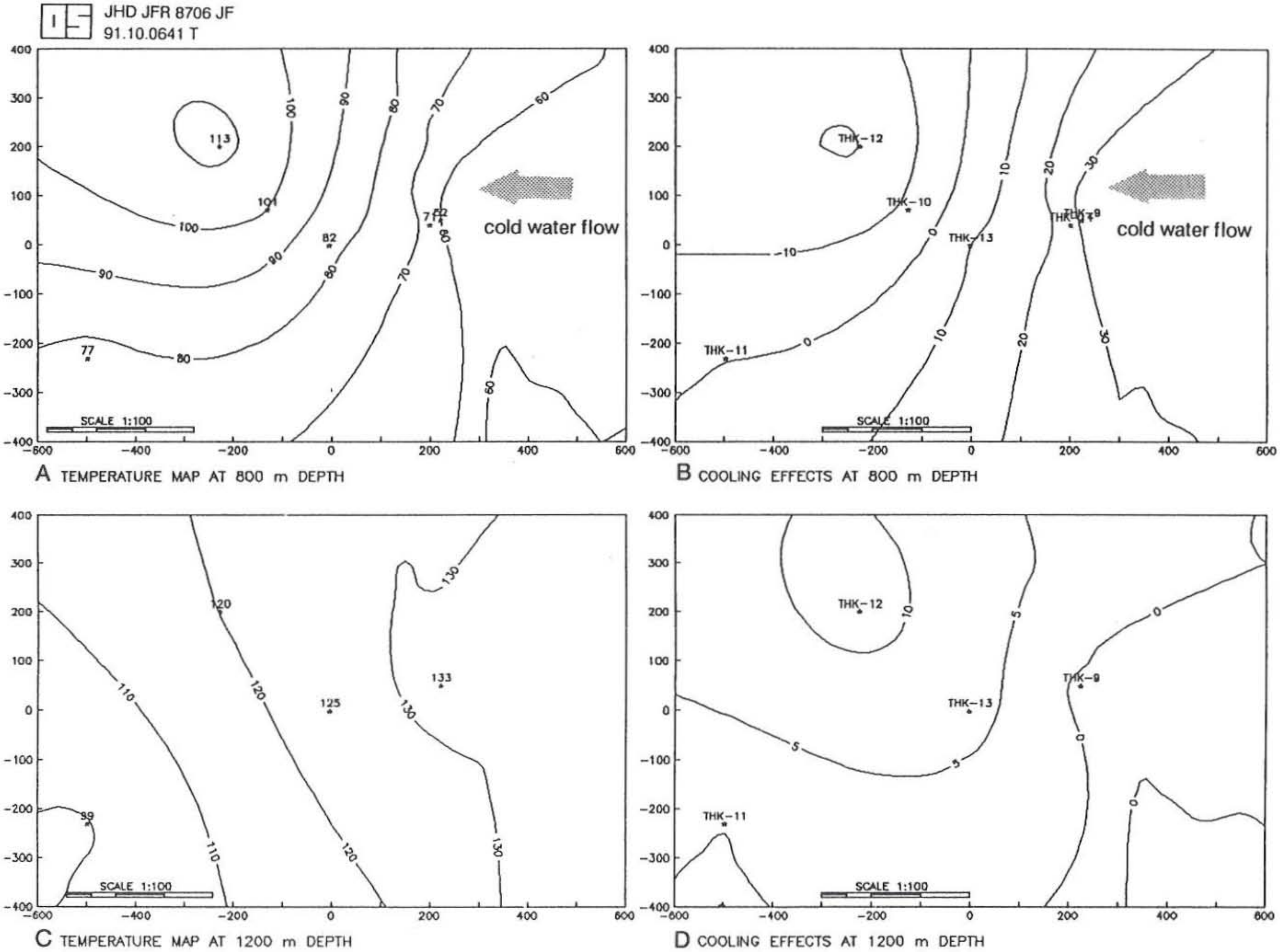


FIGURE 15: Temperature maps at 800 and 1200 m in °C

Cooling of around 30°C is observed at 600 m depth in the eastern part of the field. At well THK-10 it is about 10°C. Flow direction is also from east to west. Similar temperature distribution is seen at 800 m depth, which means that the cooling in the depth interval 500-1000 m is constant due to internal flow. A comparatively uniform temperature distribution at 400 m depth, very close to the initial temperature, proves that the cooling in the upper geothermal system is at the two levels previously mentioned. The temperature behaviour at 100, 150 and 400 m depths from 1950 to 1990 is shown in Figure 17. No cooling effects are observed in the lower geothermal system below 1200 m.

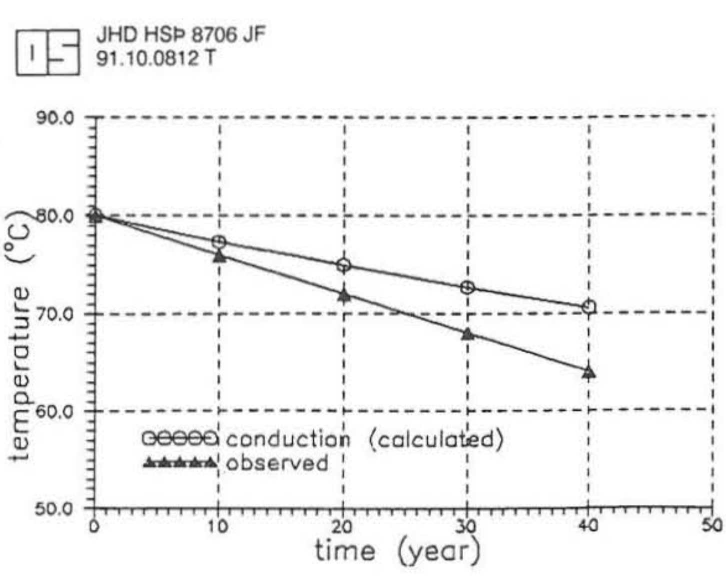


FIGURE 16: Cooling with time at 100 m depth

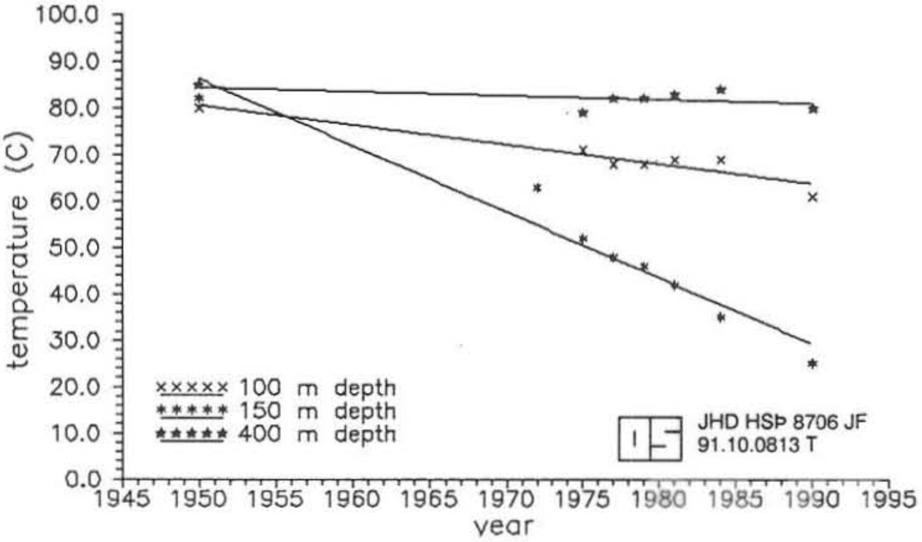


FIGURE 17: Cooling in the Selfoss geothermal area during the years 1950 to 1990. The temperature in 1950 is the initial temperature T_{in}

The temperature distribution in the southwestern part of the field, around well THK-11, is different from other parts as can be seen in the temperature maps at several levels. This conclusion is based on the temperature measurements. But it is supported by chemical analysis of water samples. The temperatures are quite uniform and constant over time (Figure 18) and represent the average initial temperature distribution in this part of the field (Figure 9b). The differences in the temperatures between the southwestern part of the field and the main production area are evident by comparing Figure 9a to Figure 9b. The differences in the initial values of the chlorine content in samples of thermal water taken from well THK-2, situated at the Thorleifskot farm, and from well THK-11 are shown in Table 2. Thus, it is concluded that the origin of the thermal water in the southwestern part of the field differs from that in other parts.

TABLE 2: Chlorine in wells THK-2 and THK-11

Borehole (no.)	Time (date)	Chlorine (mg/l)
THK-2	24-8-1950 28-10-1951	425 349
THK-11	28-9-1982 19-12-1982	273 260

3.1 Temperature cross-sections

For a better understanding of the flow patterns in the Selfoss geothermal area, temperature cross-sections were constructed. The locations of the cross-sections are shown in Figure 2. Cross-section I is from southwest to northeast in the field and includes wells THK-11, 8, 7, 14, 9 and 3 (Figure 19a). Temperature cross-section II is from northwest to southeast in the field and includes wells THK-12, 10, 13, 6 and 1 (Figure 19b).

The highest temperature, in the upper section, 90°C is observed in well THK-12 (Figure 19b). Hot water is coming from the lower geothermal system below 1200 m depth. Temperatures decrease rapidly at shallow depths towards wells THK-10, 13, 6 and 1. A better view of the cold water intrusion to the geothermal system is shown in cross-section I. The main cold water flow is at 150 m depth and this front has reached well THK-8. Cooling below 500 m depth is also noticeable from this picture.

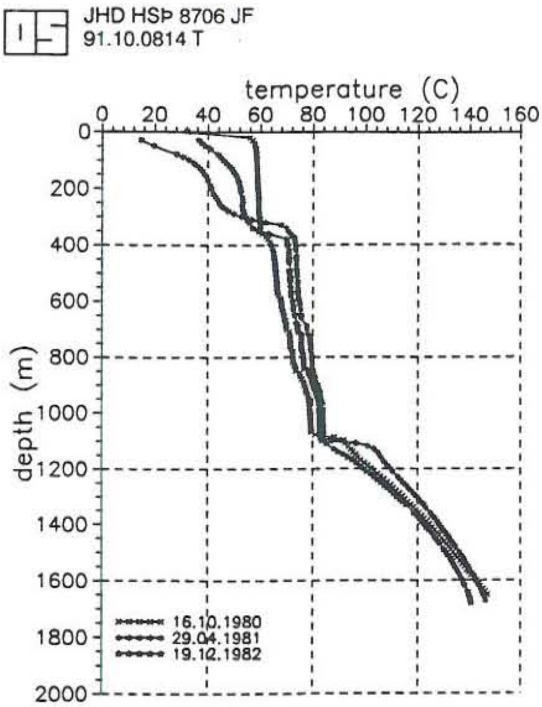


FIGURE 18: Temperature measurements in well THK-11

3.2 Three-dimensional temperature distribution

For a better three-dimensional view of the temperature distribution in the Selfoss geothermal area, three-dimensional figures of the temperature surfaces were constructed at 100 m (Figure 20a), 150 m (Figure 20b), 400 m (Figure 21a), 600 m (Figure 21b), 800 m (Figure 22a) and 1200 m depths (Figure 22b). These figures show the main features of the temperature distribution in the field. The lowest temperatures, due to gradual cooling in the upper geothermal system, are in the eastern part of the field and the cooling is migrating towards well THK-10 in the central part. The highest temperatures are in the northwestern part of the field, measured in production well THK-12, except at 1200 m depth, where the highest temperature is measured in well THK-9 (Figure 22b).

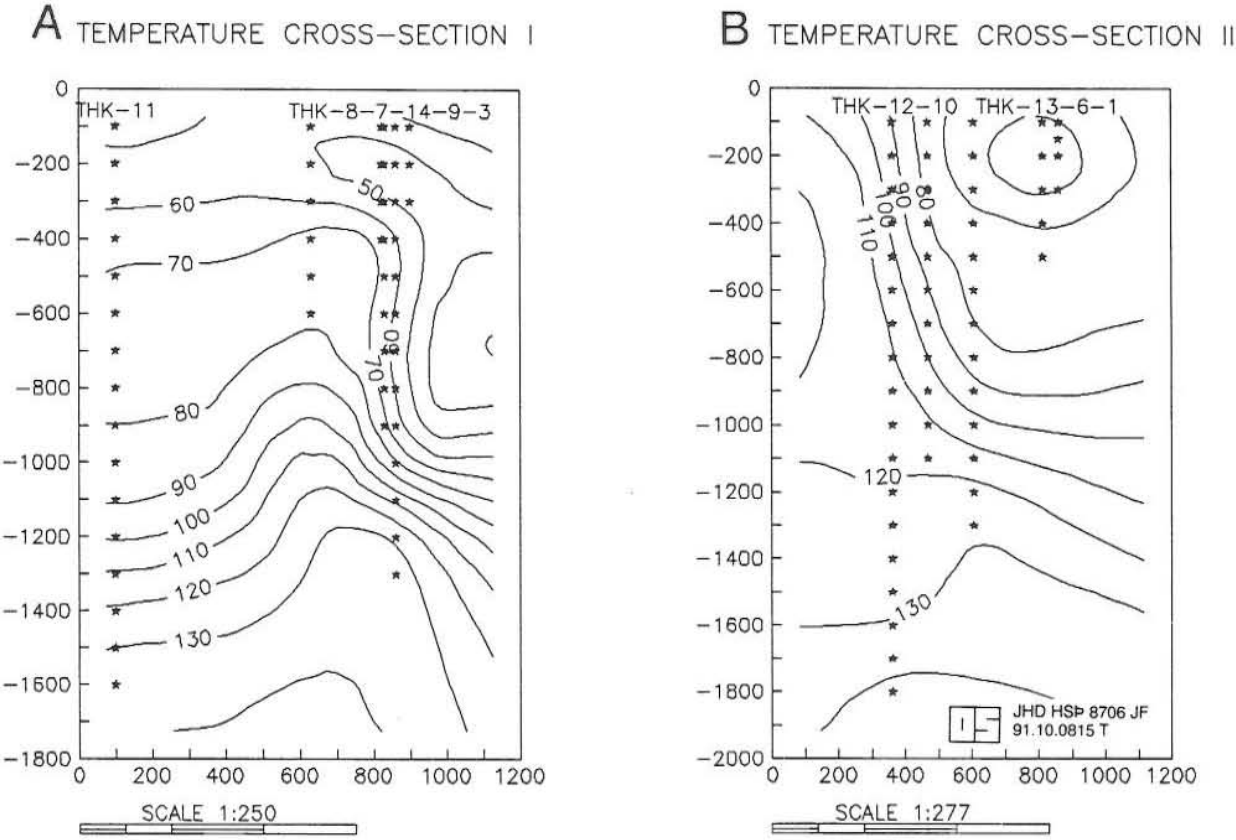


FIGURE 19: Temperature cross-sections I and II

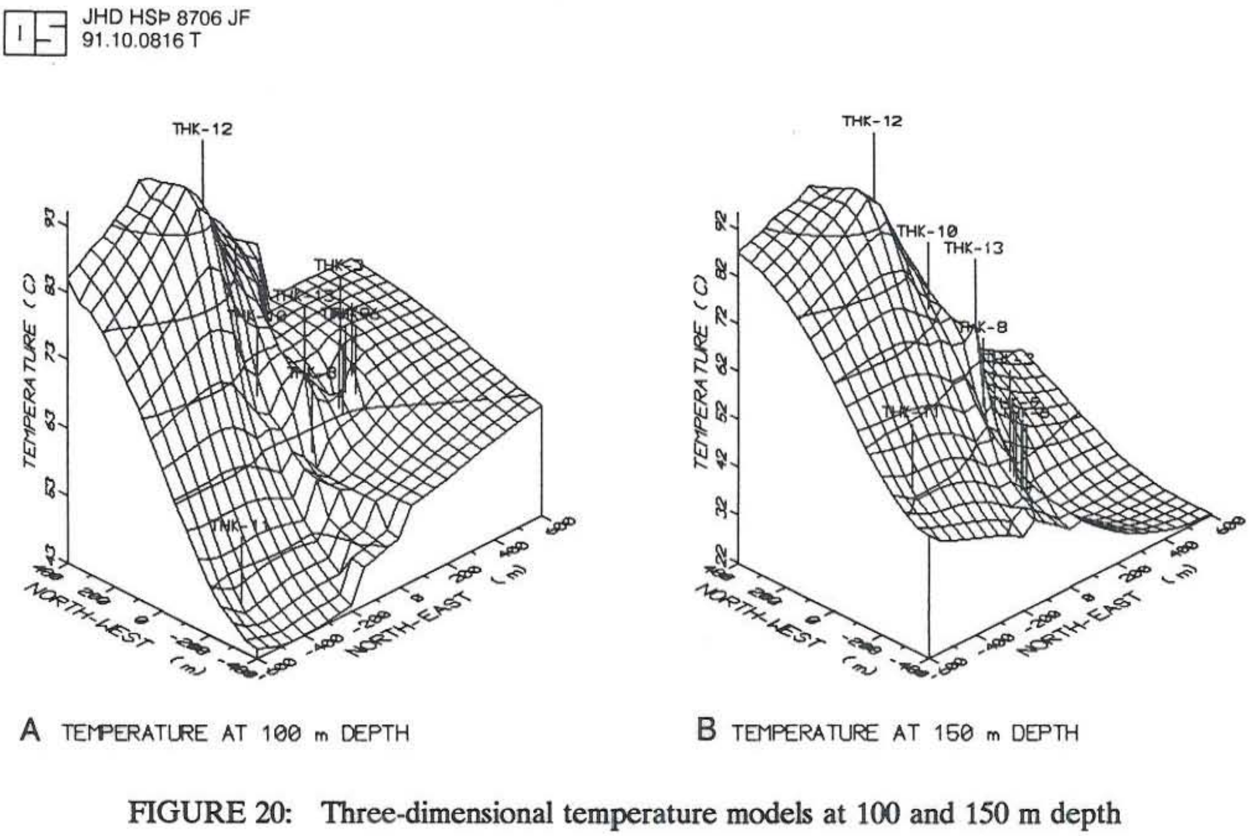


FIGURE 20: Three-dimensional temperature models at 100 and 150 m depth

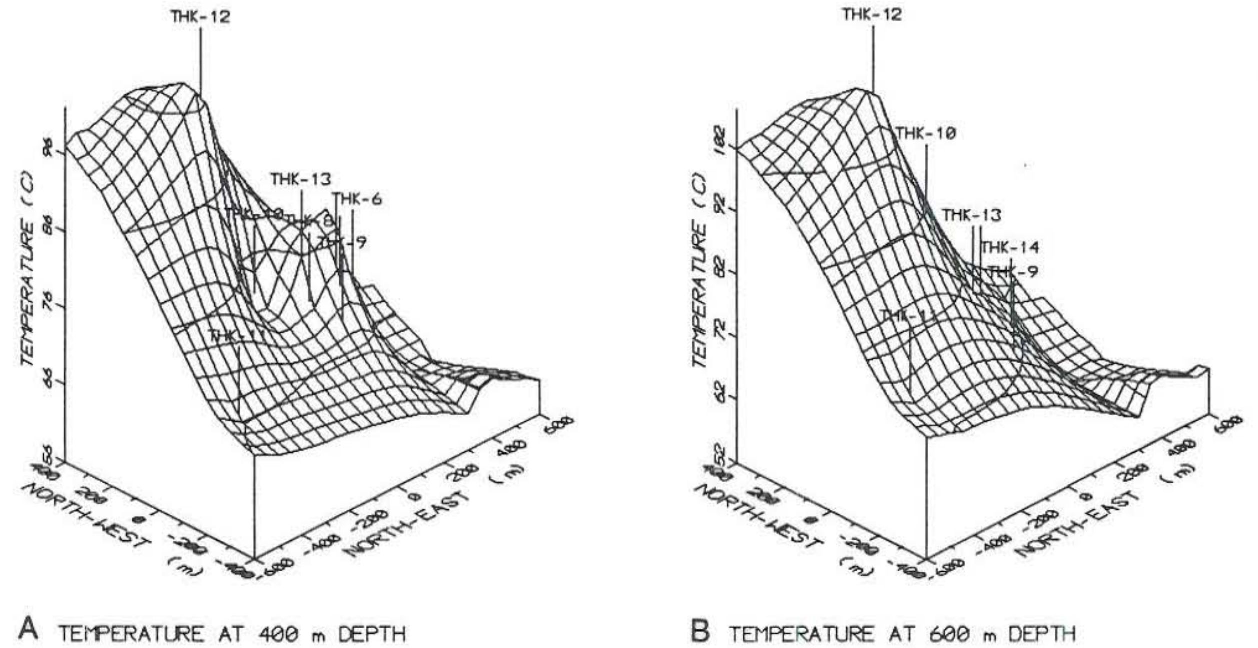


FIGURE 21: Three-dimensional temperature models at 400 and 600 m depth

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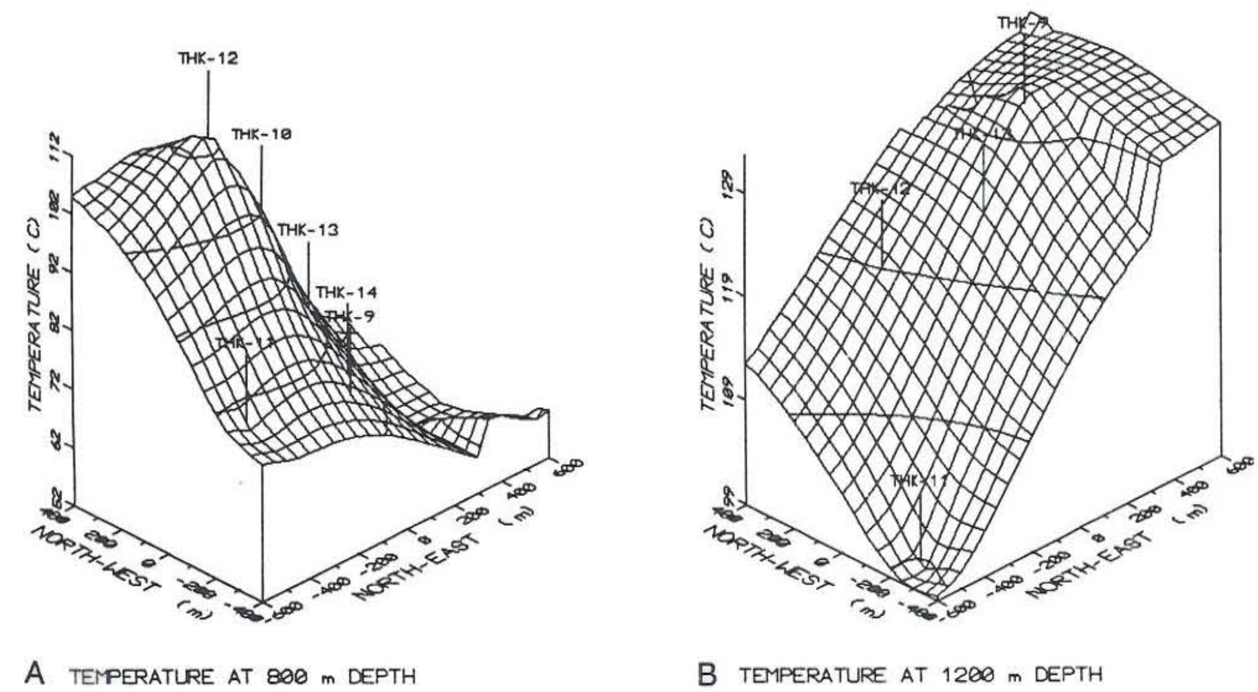

FIGURE 22: Three-dimensional temperature models at 800 and 1200 m depth

4. RESULTS AND CONCLUSIONS

The main task of this work was to estimate the initial and present temperature distribution in the Selfoss geothermal field with emphasis on the gradual cooling observed in the field during the past 40 years of exploitation. From the analysis and interpretation of temperature measurements the results can be summarized as follows:

1. The average initial temperature in the Selfoss geothermal area could be estimated successfully.

2. Two geothermal systems are present. The upper system is above 1000 m depth with a temperature range of 80-96°C. The lower system is below 1200 m depth with temperatures between 130 and 150°C.

3. The present temperature distribution in the field was compared with the initial temperature distribution.

4. The rate of cooling at different levels during the last 40 years of exploitation was estimated.

5. Maps of the temperature distribution and cooling effects were constructed at 100, 150, 400, 600, 800 and 1200 m depths.

6. Temperature cross-sections and three-dimensional temperature models were constructed.

7. The lowest temperatures are observed in the eastern part of the field, at Thorleifskot. The gradual cooling there is more than 50°C. The cold water front has proceeded in a westerly direction and has now reached production wells THK-13 and 10 in the central part of the field with a cooling effect of 10°C. The highest temperatures are still measured in the northwestern part of the field, in well THK-12. The temperature distribution in the southwestern part is different and cooling has not been observed there. This conclusion is based both on temperature measurements in well THK-11 and chemical analysis of water samples.

8. The main reason for the cooling is a cold water intrusion taking place in the upper geothermal system at two levels, in the depth interval 100-400 m with the strongest influence at 150 m depth, and below 500 m depth with internal flow down to 1000 m depth. The flow direction is from east to west and the cold water is flowing through sedimentary layers. No temperature changes were observed in the lower geothermal system below 1200 m depth where temperatures range between 130 and 150°C.

Final recommendation: In order to mine out more hot water from the Selfoss geothermal area in the future, it is necessary to drill below 1200 m depth to reach the lower geothermal system. Probably the best location for such a new well is in the northwestern part of the field at the farm Laugardaelir.

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REFERENCES

Bodvarsson, G., 1951: Report on the Hengill Thermal Area. J. Engin. Ass. Iceland, 36, (in Icelandic with English summary), 1-48.

Carslaw, H.S., and Jaeger, J.C., 1950: Conduction of heat in solids. Clarendon Press, Oxford, 386 pp.

Hersir, G., and Flovenz, O.G., 1982: Head-on resistivity profiling at Selfoss. Orkustofnun, report OS-82067/JHD-13B (in Icelandic), 29 pp.

Tomasson, J., 1967: On the origin of sedimentary water beneath Westmann Islands; Jokull 17, 300-311.

Tomasson, J., 1980: Selfoss geothermal area S-Iceland. The using of chlorine as an indicator of an inflow of cold groundwater into the geothermal reservoir. Proceedings of 3rd International Symposium on Water-Rock Interaction, Edmonton, Canada, July 1980, 107-109.

Tomasson, J., and Halldorsson, G.K., 1981: The cooling of the Selfoss geothermal area, S - Iceland. Geothermal Resources Council, Transactions vol. 5, 209-212.