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THE TEMPERATURE DISTRIBUTION IN THE SELTJARNARNES FIELD, SW-ICELAND; THE RESERVOIR TEMPERATURE IN THE PODHALE FIELD, S-POLAND

Beata Kepinska
Polish Academy of Sciences,
Minerals and Energy Economy Research Centre,
J.Wybickiego 7, 31-261 Kraków,
POLAND

ABSTRACT

The report presents the temperature variation within two geothermal fields: Seltjarnarnes in SW-Iceland and Podhale in S-Poland. This study is based on the interpretation of temperature measurements in geothermal wells. For the Seltjarnarnes field the temperature logs performed in eleven boreholes during 29 years of drilling and exploitation were interpreted. The thermal gradient and formation temperature distribution within the field is given as well as the location of the main feedpoints and aquifers. No cooling was observed in the wells during the whole production period. However, the increasing salinity of the produced fluid due to seawater infiltration into the shallower aquifer suggests a possible temperature decrease of the produced fluid with time. Furthermore, the up-to date results of the temperature logs in the next production well, drilled in June-Oct. 1994 are presented. They contributed to further understanding of the field, allowing a more exact delineation of the thermal anomaly, which seems to have a very limited extent. For the Podhale field the results of the temperature simulation within the main reservoir and the predicting of the future wellhead temperature are presented, based mainly on the four years monitoring of the geothermal doublet operating in this field. Some conclusions concerning temperature distribution within the field are given. Generally, the reservoir and formation temperatures are supposed to be slightly higher than was assumed before, which is important for the planning and exploitation of the next geothermal plants.

1. INTRODUCTION

This report is the outcome of a research and practical study carried out during the second part of the six month's training course of the 1994 UNU Geothermal Training Programme at Orkustofnun - National Energy Authority in Reykjavik, Iceland.

The report consists of two parts. In the first one the temperature variation in the Seltjarnarnes geothermal field, which is located on the western outskirts of Reykjavik, SW-Iceland, is presented. The main purpose of this part is to get acquainted with basic methods and classical approaches to the elaboration and interpretation of the temperature measurements from the borehole logs and tests, which constitute the most important information about the geothermal system. The data used is derived from the temperature logs carried out during 29 years of exploration and exploitation in the field. The author also had practical experience of temperature logging and working with data from the new production well, being drilled during the writing of this report. The current results are included into the report.

The second part of the report relates to the Podhale low-temperature field in S-Poland. So far, the methods of conducting and interpreting data from the temperature logs and tests are based mainly on the experience from the oil and gas exploration which in some cases are not sufficient for the geothermal wells. Therefore an attempt was made to adapt some methods and solutions used in Iceland to interpret the data coming from the temperature logs, short term well tests during and after drilling, results of four years monitoring of the first geothermal doublet operating in the Podhale field. In addition, the results of the surface thermal surveys and preliminary petrographic study were taken into account. The study deals with the temperature evaluation within the main reservoir, predicting the future wellhead temperature of the produced fluid. Some assumptions related to the actual formation temperature in the field are also given. The obtained results can be useful in further planning the geothermal exploration, development and utilization.

2. THE TEMPERATURE DISTRIBUTION IN THE SELTJARNARNES FIELD, SW-ICELAND

The Seltjarnarnes geothermal field is one of the three major geothermal systems located within the Reykjavik area. The others are the Laugarnes and Ellidaar fields. It is located on the tip of the peninsula with the same name, on the western outskirts of Reykjavik, the capital of Iceland (Figure 1). For the last 29 years it has been exploited, providing hot water for the central heating system of the town, Seltjarnarnes.

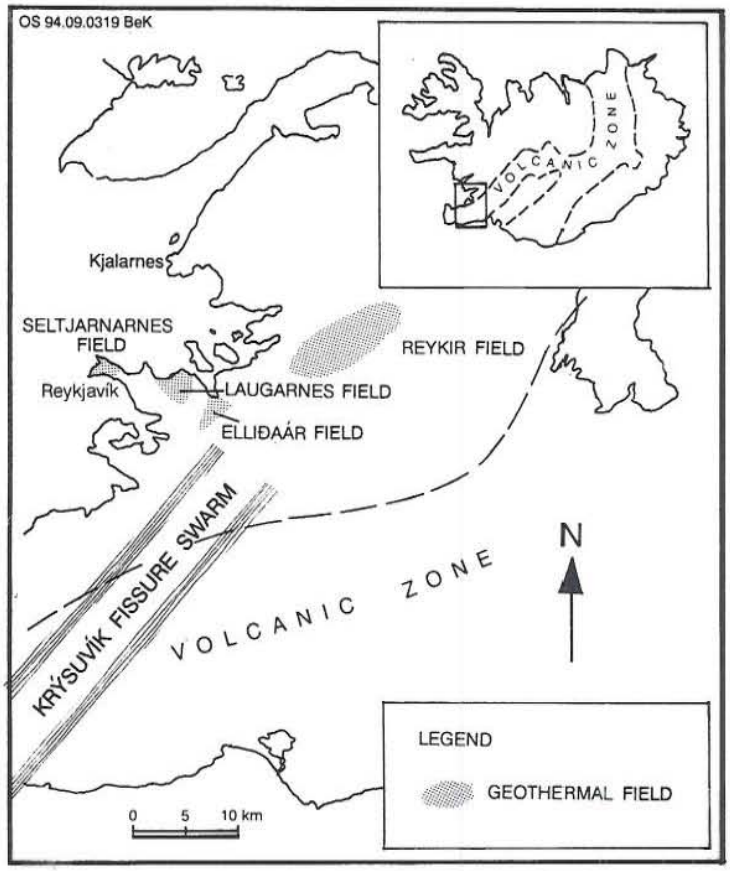

FIGURE 1: Location of the Seltjarnarnes geothermal field (modified after Tomasson et al., 1975)

This study focuses on the thermal aspects of the field, including the shallow thermal gradient delineation, the identification of the feedpoints and aquifers, analysis of the temperature logs in the wells drilled previously and in the borehole presently being drilled. The work is based on interpretation of the temperature logs, selected from nearly 100 curves run in the 5 shallow and 6 deep boreholes drilled in the field since 1965. The results of the analysis of seven log, run so far in well SN-12 which was being drilled during completion of this report were also taken into account.

2.1 General overview

2.1.1 Geological outline

The Seltjarnarnes field is located within a low-temperature geothermal region, that is where the temperature at a depth of 1 km does not exceed

150°C. Similar to other fields in the Reykjavik region, it is situated on the southern margins of the deeply eroded Kjalarnes central volcano, which was active in Quaternary. The Reykjavik area is made of Plio-Pleistocene formations (2.8 to 1.8 m.y. old), which flank the active rift zone in SW-Iceland, represented by the Krisuvik fissure swarm. However, on the surface are young horizontal interglacial olivine tholeiite basalts, which extend down to the depth of 30-50 m. Underneath these lava flows there are mostly marine sediments of up to 60 m thick, layered on a major unconformity. Below the unconformity the succession consists of about 500 m of alternating lava sequences interbedded with thin sediments, and underlain by about 500 m thick hyaloclastite formations. A basalt lava succession, intersected by dolerite intrusions, dominates below the hyaloclastites. The general dip of the strata appears to be 3-12 degrees to the southeast. A simplified geological cross-section through the Seltjarnarnes field is shown in Figure 2.

The thermal gradients in shallow drillholes in the geothermal fields of the Reykjavik area reach 300-400°C/km. These high values are due to localized transport of water from the thermal systems towards the surface. Outside the fields the shallow thermal gradient is about 100°C/km. The temperature gradients

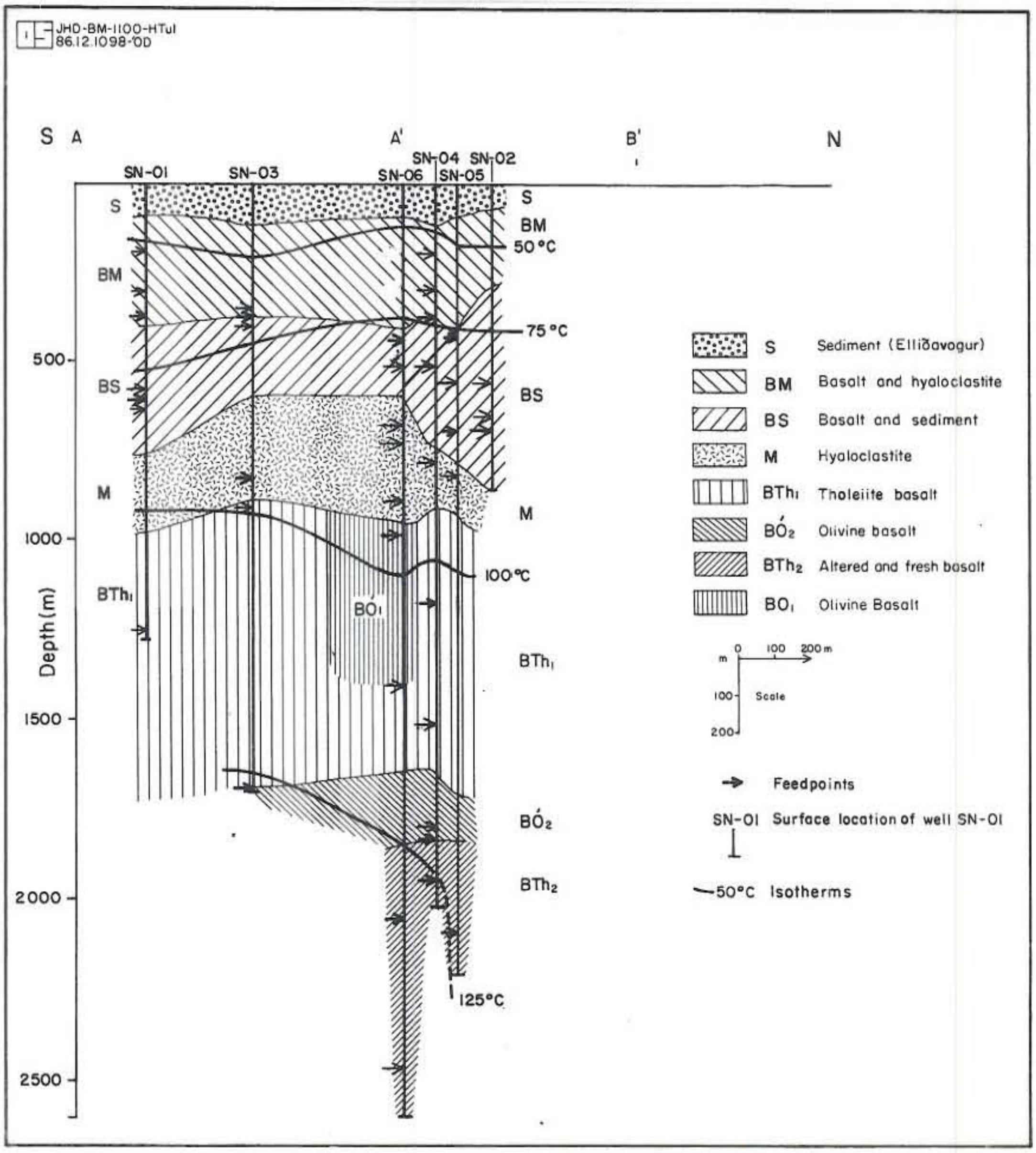

FIGURE 2: Subsurface geology within the Seltjarnarnes field (Tulinius et al., 1987); location of cross-section is shown in Figure 5

measured in deep wells in SW-Iceland indicate increasing values towards the volcanic zone from 50°C/km in Tertiary formations to 165°C in early Quaternary rocks (Tomasson et al., 1975). The alteration mineralogy in Seltjarnarnes and adjacent fields indicate that these were originally high-temperature fields with temperatures of 200-300°C.

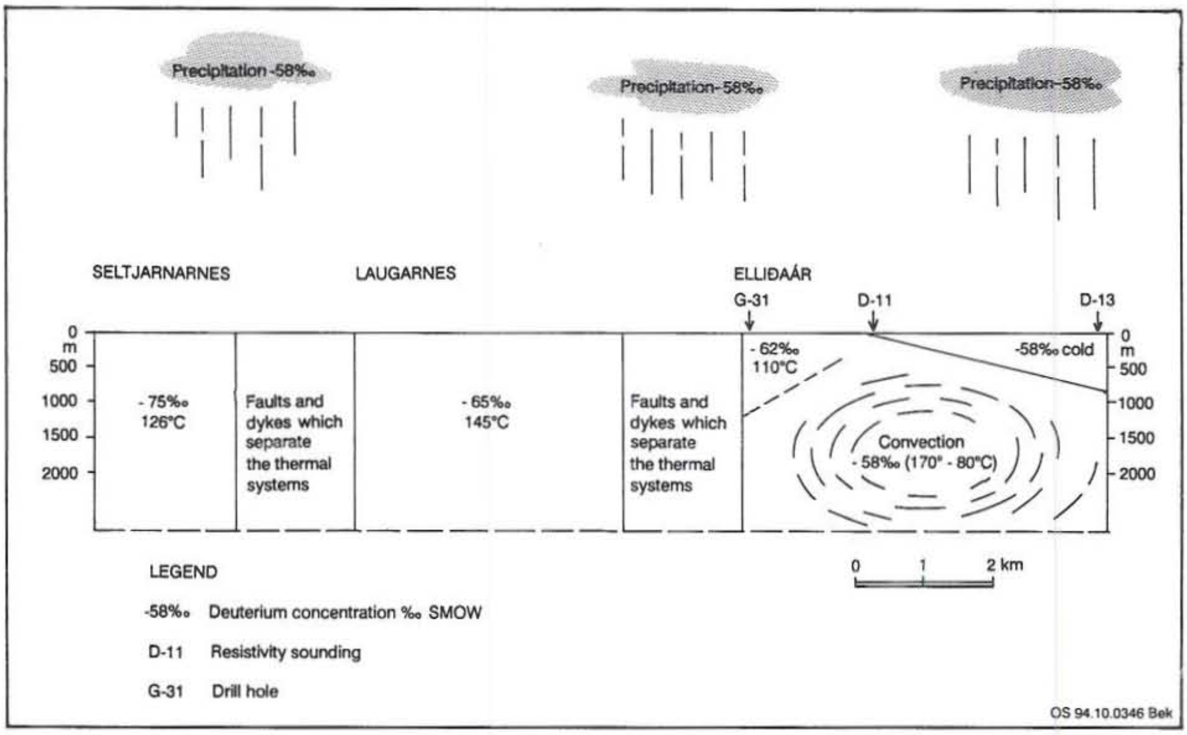

FIGURE 3: Schematic section through the Reykjavik geothermal fields (Tomasson et al., 1975)

The Seltjarnarnes field forms a single hydrological system (Figure 3), separated from the Laugarnes field by a low permeable or impermeable barrier, probably a swarm of dykes and associated faults, that have been confirmed by thermal, chemical and isotopic data. Furthermore, this was supported by the thermal gradient low between these two fields and the fact, that no or little pressure changes occurred in the Seltjarnarnes field due to production in the Laugarnes field (Tulinius et al., 1987). The geothermal water has meteoric origin with a possible recharge area situated in the southernmost part of the glacier Langjokull, 80 km to the northwest (Arnason, 1976). The water infiltrates down to the depth of 3-4 km. Under the Seltjarnarnes field it ascends through fissures, more permeable than the surrounding area. A part of the produced fluid comes from the local seawater recharging from the southwest into the reservoir at shallow levels (Tulinius et al., 1987).

2.1.2 Previous work

Since the exploration and production started in the Seltjarnarnes field in 1965, all available data have been collected and several reports describing the field have been published. In 1975 the first general characteristics and model of the field were given in an overview report about most of the geothermal fields within the Reykjavik area (Tomason et al., 1975). A considerable amount of specific reports have also been written on drilling, testing the wells, well logs, fluid chemistry and other aspects of the field. One of the main subjects of the studies and reports have been connected with the monitoring of salinity changes of the produced water, which are believed to be the result of cold sea water inflow at shallow depths (Kristmannsdottir, 1986). On the basis of all available data an integrated conceptual model of the Seltjarnarnes field was developed, to predict changes in pressure, temperature and chemical composition occurring in future production (Tulinius et al., 1987). Annual reports summarizing the actual state of the field are prepared regularly for the Seltjarnarnes Municipal District Heating Service. Further work has been done recently by Orkustofnun, especially work on the shallow thermal anomaly, in order to site new wells (Saemundsson et al., 1994).

2.1.3 Drilling and production history

To date eleven deep and shallow wells have been completed within the Seltjarnarnes field (Figure 4). The first wells SN-01 and SN-02 were drilled in 1965-1966. They were planned as shallow gradient wells and successively deepened. During the years 1969-1985 four more production boreholes were completed (SN-03, SN-04, SN-05 and SN-06). The next five wells, SN-07 to SN-11 were drilled in the last two years (1993-1994) in order to outline the thermal gradient at shallow depth within the field before locating a new production well, SN-12, which is presently being drilled (since July 17th 1994). The characteristics of the wells within the Seltjarnarnes field are given in Table 1.

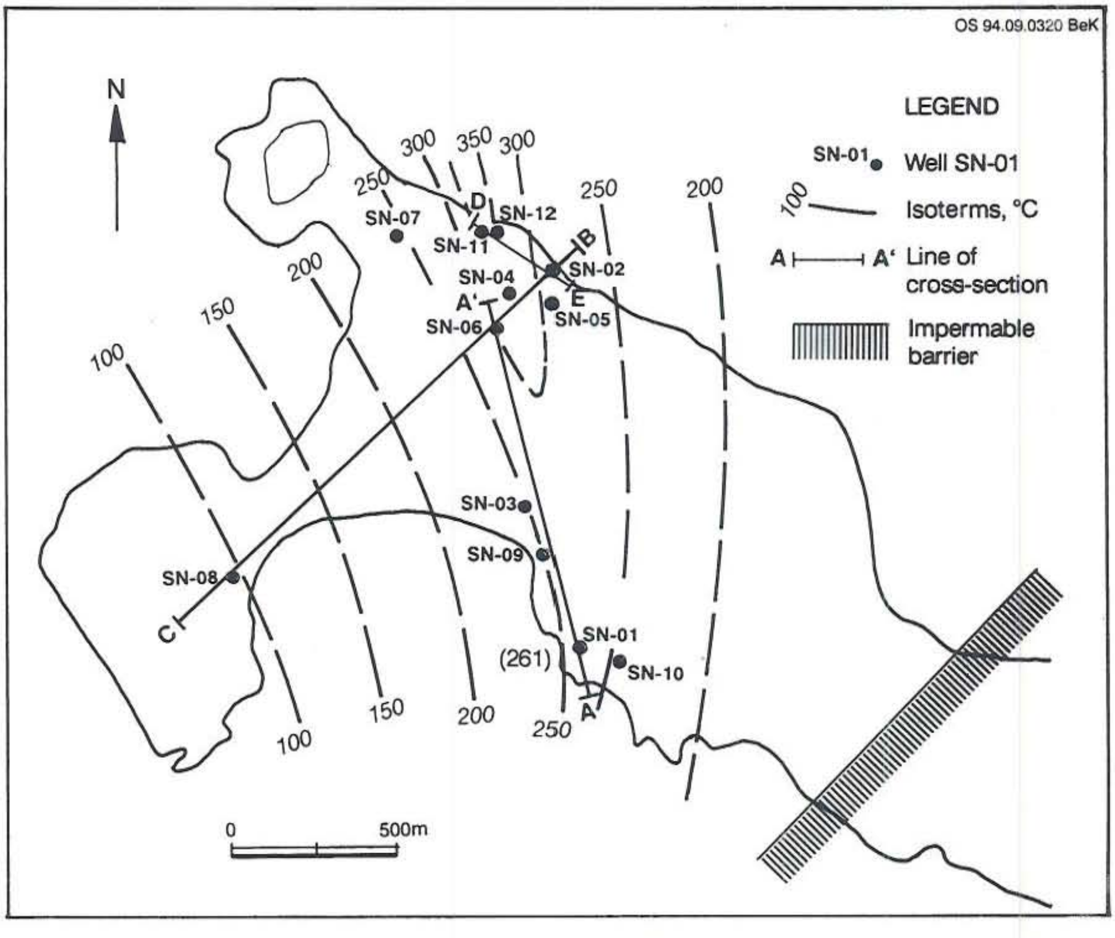

FIGURE 4: Location of wells and shallow thermal gradient in the Seltjarnarnes field

In 1972 the Seltjarnarnes Municipal District Heating Service was founded, supplied with the water from wells SN-03 and SN-04. Wells SN-05 and SN-06 were included into the system in the years 1981-1985. Currently these four boreholes discharge a maximum of 110 l/s hot water with temperature 90-117°C for space heating to the town with a population of around 4000 residents.

TABLE 1: Main characteristics of the wells within the Seltjarnarnes geothermal field

Well	Drilling time	Depth (m)	Casing (m)	Yield (l/s)	Wellhead temperature (°C)	Years of production
SN-01	04.01.65-12.07.67	1282.6	18.5	1-3	-	1967
SN-02	11.02.65-09.06.66	856.3	81.5	2-3	75-80	1966-1971
SN-03	01.11.69-12.02.70	1715.0	99.0	1-15	101-103	1970-1988
SN-04	21.02.72-05.06.72	2025.0	172.0	7-35	111-116	1973-now
SN-05	07.12.80-15.05.81	2207.0	168.0	4-30	90-100	1981-now
SN-06	07.03.84-08.02.85	2701.0	414.0	4-30	115-117	1986-now
SN-07	11.10.93-15.10.93	153.5	152.5	-	-	-
SN-08	14.10.93-19.10.93	153.1	12.5	-	-	-
SN-09	25.01.94-26.01.94	132.0	-	-	-	-
SN-10	31.01.94-01.02.94	144.6	18.0	-	-	-
SN-11	20.06.94-28.06.94	104.6	-	-	-	-
SN-12*	17.07.94-	2230.0	791.0	-	-	-

* well presently being drilled (data from 28th September 1994)

2.2 Analysis and interpretation of temperature measurements

2.2.1 Thermal gradient distribution

The local thermal gradient within the Seltjarnarnes field was calculated using temperature logs performed in eleven shallow and deep wells (Figures 5-7), but in the case of the deep wells, only the upper 150-200 m were taken into consideration (Table 2). The obtained values indicate a thermal anomaly, with the gradient in the range of 227-359°C/km (Figure 4). The surface distribution seems to be symmetrical to a line

TABLE 2: The shallow thermal gradient in the wells within the Seltjarnarnes field

Well	Depth (m)	Thermal gradient (°C/km)*	Bottom hole temperature (°C)
SN-01	1282.6	261.0	117.5
SN-02	856.3	268.0	87.0
SN-03	1715.0	240.0	133.0
SN-04	2025.0	331.0	126.5
SN-05	2207.0	330.0	138.0
SN-06	2701.0	300.0	143.7
SN-07	153.5	248.0	41.4
SN-08	153.1	91.0	19.0
SN-09	132.0	227.0	34.0
SN-10	132.0	234.0	33.9
SN-11	144.0	359.0	56.7
SN-12**	2230.0	260.0	95.3

* Calculated for shallow depths (150-200 m) in all wells

** Well presently being drilled (28th September 1994), values can change

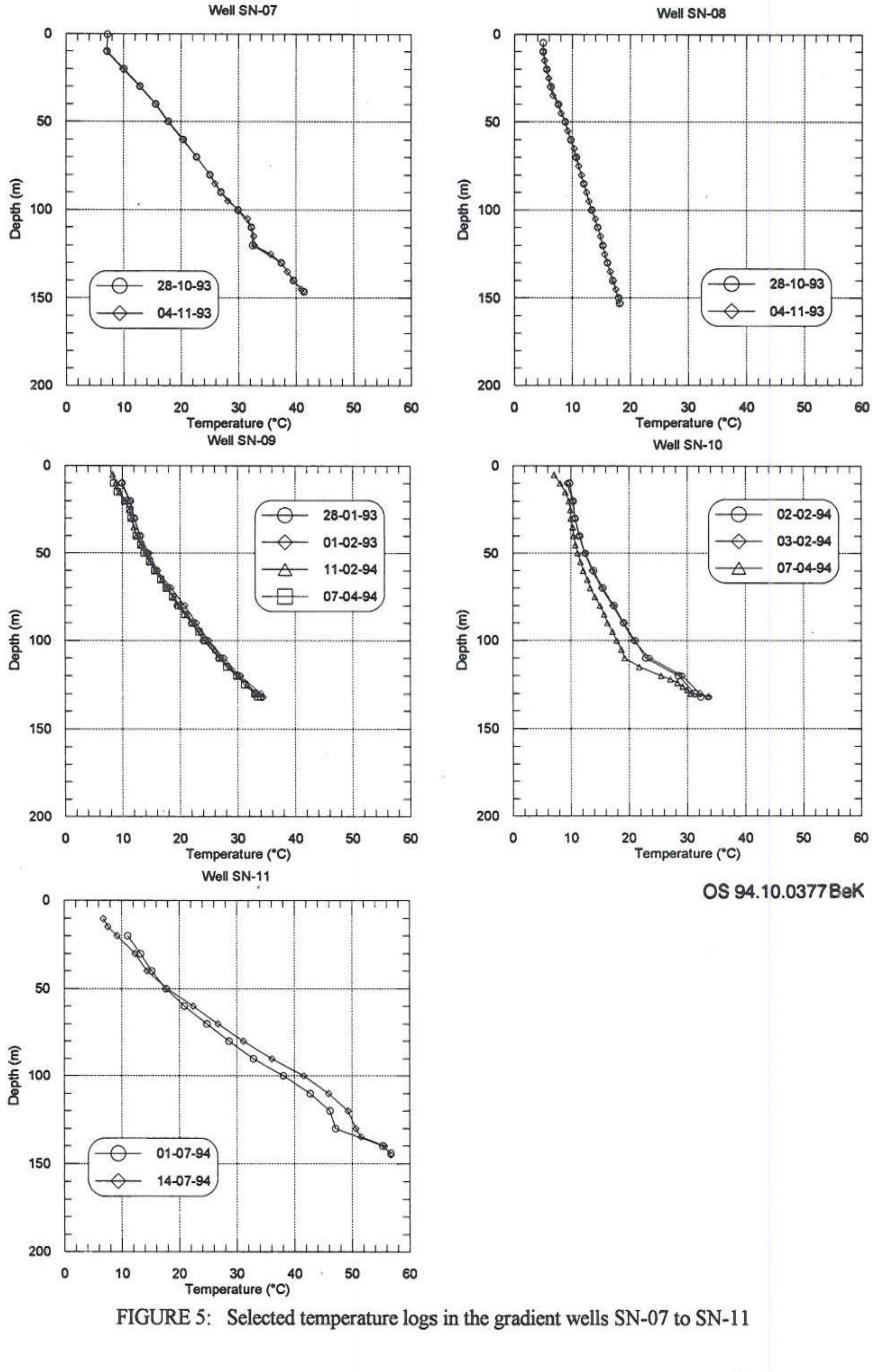

FIGURE 5: Selected temperature logs in the gradient wells SN-07 to SN-11

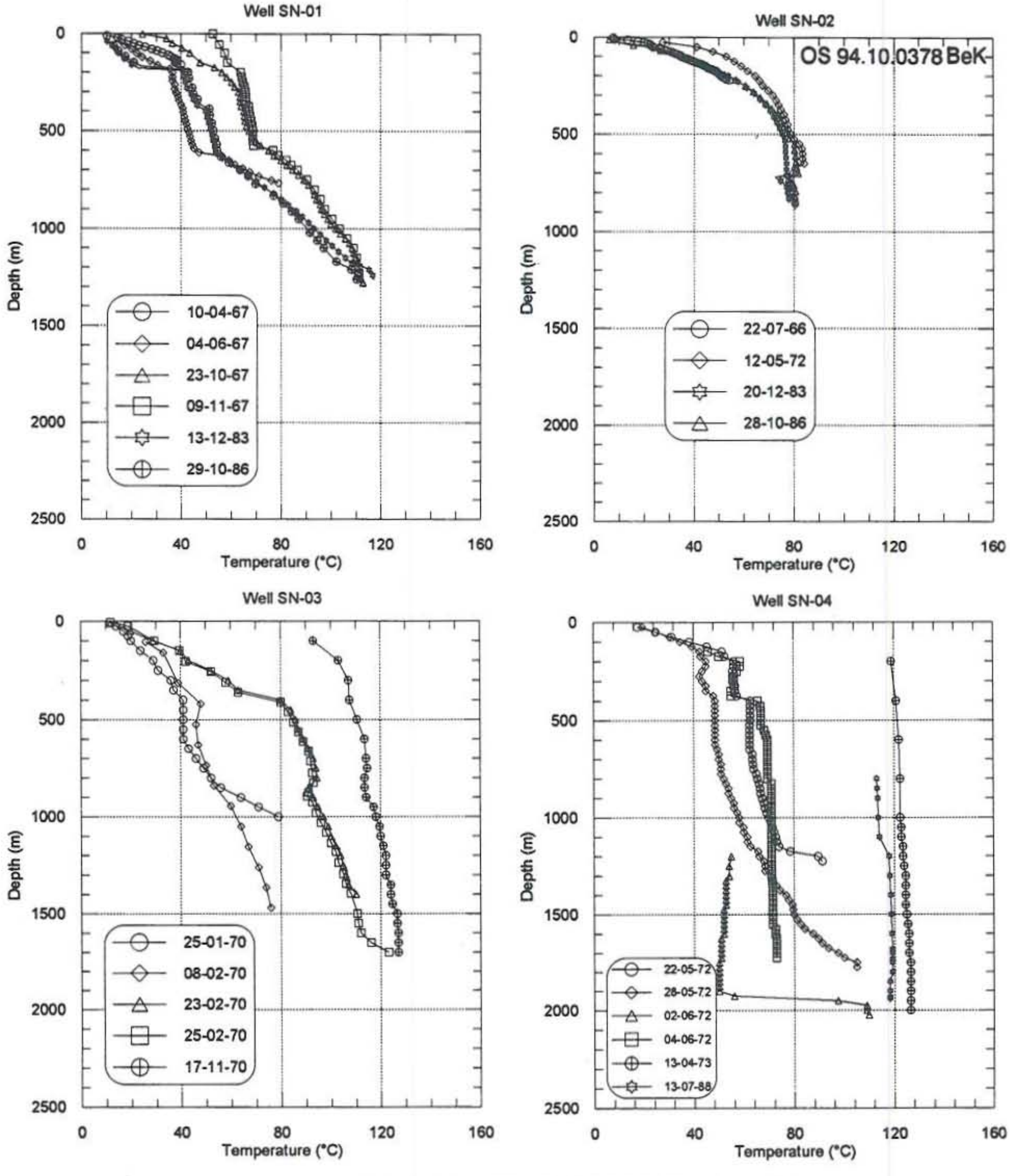

FIGURE 6: Selected temperature logs in wells SN-01 to SN-04

trending approximately N15°W through wells SN-11 and SN-09. The highest values (300-359°C/km) are observed in the northern part of the Seltjarnarnes peninsula, with an extension in the southern direction. Towards the western and the eastern parts the thermal gradient decreases, with a local minimum of about 100°C/km, nearby well SN-08 and close to supposed impermeable boundary to the Laugarnes geothermal field. The production wells SN-04, SN-05, and SN-06 are situated in the area of the highest gradient, between 250-360°C/km.

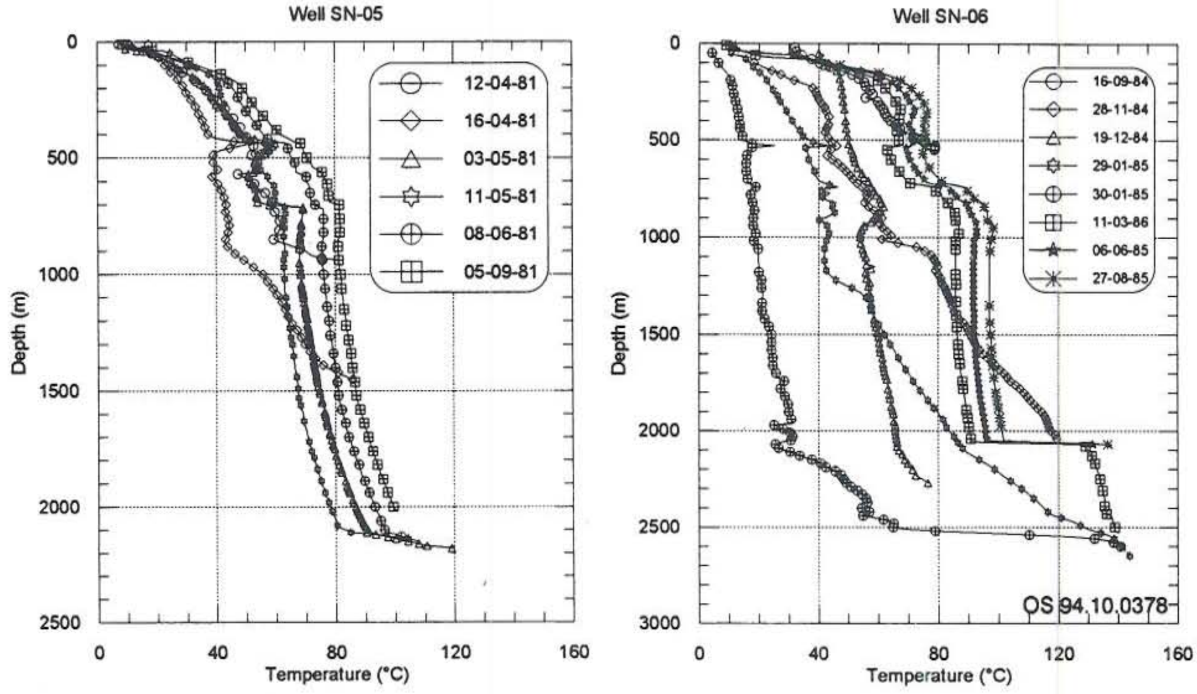

FIGURE 7: Selected temperature logs in wells SN-05 to SN-06

2.2.2 Interpretation of the temperature logs

Geological sections of all the boreholes, constructed on the basis of cutting analyses and lithological logs show that feedpoints are predominantly associated with hyaloclastites and sedimentary layers, and scoriaceous and fractured contacts of individual lava flows. In lower parts of the formation, they concentrate close to dolerite dykes and sheets. These zones are characterized by higher permeability than the surrounding successions.

The temperature logs in the production wells were run mainly during drilling or during the earliest production phase in 1965-1985. Only few logs are more recent. Lately, some measurements were conducted in well SN-06, in order to detect possible casing damages.

An interpretation of temperature logs from six production wells SN-01, 02, 03, 04, 05, and 06 is given below, based on all available data. The selected temperature logs are shown in Figures 6 and 7, and Figure 2 shows the location of the main feedpoints.

Well SN-01 was drilled in 1965 as a shallow gradient well. In 1967 it was deepened to 1282.6 m. During one year it produced about 1 l/s water. Since 1968 it has been used as an observation well (together with well SN-02). Four feedpoints were found here, at the depths of 200, 320-390, 575-635 and 1260 m. The temperature of the water was 66-117°C. Measurements carried out in 1984-1993 showed variations of water level from -35 to -75 m a.s.l. The lowering in the water level is a response of production from other wells.

Well SN-02 was drilled as a shallow gradient well in 1965, and deepened to 856.3 m in 1966. From August 1966 to October 1971 it discharged about 3 l/s water with initial artesian pressure of 13 m a.s.l. After production from well SN-03 started in 1973, flow from well SN-02 ceased, and now it is used as an observation well. Three feedpoints are located in the hole. The shallowest at 560 m with temperatures of 80°C, the next is at 680 m and is 85°C hot. The third was found at the depth of 720 m with the temperature of around 70°C, colder than the two aquifers located above. Due to the presence of a relatively cold flow from this last aquifer, a cooling in the well was recorded. After reaching the highest temperatures 78-80°C a systematic decrease of observed values was noticed down to 67°C. Temperature profiles from 1975-93 show further lowering of well temperature. The last curves from 1986 and 1993 indicated, that the equilibrium had probably been reached between the well and the surrounding formation. During the production period in 1966-71, the water table lowered from +13 to -4 m a.s.l. Further decrease, with observed minimum at -70 m a.s.l. accompanied the maximum total production of 44-56 l/s from the field in 1984-90. Present variations in water table, according to data from 1993, are in the range from -30 to -50 m a.s.l.

Well SN-03 was drilled in the south part of the field to a total depth of 1715 m in 1969-70 and was in production during 1970-86 and 1987-88. According to temperature logs, three feedpoints can clearly be distinguished in the well. The shallowest is situated at 350-400 m depth with 70-80°C water. The next is situated at 860-930 m depth, with water of temperature around 100°C. The lowest feedpoint was tapped close to the bottom of the hole (1700 m) giving 127°C hot water. All above aquifers contributed in equal parts 30-40% to the total discharge from the well. Several temperature measurements were conducted, but mostly during drilling or just after drilling, not allowing time for the well to stabilize. Only one curve was recorded after production started, in the very beginning (17.11.1970). No further logs are available after production started, therefore it is difficult to estimate the thermal response of the well to exploitation.

Well SN-04 was sited in the central part of a local thermal anomaly within the Seltjarnarnes field. The hole was completed in 1972, reaching a total depth of 2025 m. From the year 1973 until present it has been discharging 4-30 l/s water with wellhead temperature of 111-116°C. Several feedpoints were found in the well. They were especially easy to notice on the temperature profiles performed after an injection test (log from 4.06.1972). The feedpoints are situated at the following depths: 200 m with water temperature of 60°C; 300-380; 530; 800; 1180; 1550; 1840; and 1950 m (126°C). The main feedpoints situated at the depths of 1840 and 1950 m discharge about 80% of the total flow from the well. The measurements carried out during the production period from the years 1973-88 show little temperature decrease of the water. Wide fluctuations of the water level have been recorded during 1988-93, varying from -85 to -10 m a.s.l, and were connected with changes in production from the well, as from other wells.

Well SN-05 was drilled to the depth of 2207 m and was completed in 1981. From this year until present time it has been producing 4-30 l/s hot water with wellhead temperature between 90 and 100°C. The feedpoints are at the depths of 450-550, 700-870 and 2090 m (120°C). The production from each of them gives 30-40% of the total yield from the well. Temperature logs cover a relatively short period of time (12.04-5.09 1981) during drilling and shortly after completion. They indicated a down-flow from the feedpoint at 700 m depth down to the deepest feedpoint. No logs exist after production started (1982-1994), therefore no more data concerning the present state of thermal conditions in the well are accessible. Observed data from 1988-93 show a lowering of water table from -40 to -70 m a.s.l., strictly connected with the production from the area.

Well SN-06 was completed in 1985 with a total depth of 2701 m. From 1986 it has been producing 4-30 l/s water with wellhead temperature 115-117°C. The feedpoints are abundant in the 450-1000 m depth interval. The inflow from these feedpoints gives about 30% of total discharge from the well. The next feedpoint is situated at the depth of 1420 m. The deepest feedpoints are located at the depths of 2060 and 2500 m, with water temperature of 130-143°C. During the earliest period of production, according to existing measurements, the temperature of produced water increased continuously. The water level changes were from -70 to -118 m a.s.l. (data from January and March 1985 respectively). Further data from the latest years (1988-1993) show that the water table is in a similar range as in remaining wells, i.e. from -40 to -70 m a.s.l.

2.2.3 Main aquifers

The results of the temperature logs, registration of water losses and gains during drilling and geological profiles combined from cuttings show that there are several feedpoints in each production well (Figure 2). They can be classified into two main aquifers. The uppermost extends from around 300 m to the depth of 700-800 m and was found in all production wells. It is located at shallower depths in the southern part of the field than in the northern part. The temperatures are in the range of 60-80°C. The main feedpoints are around 400 m, close to the contact of two lava successions, interbedded with hyaloclastites in the upper part and by sediments in the lower. The yield of the water discharged from this aquifer in wells SN-03, 04, 05 and 06 contributes 15-35% of the total production from the field. The second main aquifer was recognized in the northern part of the field. In boreholes SN-04 and SN-05 it is situated at the depths of 1700-2150 m, and in well SN-06 even deeper, down to the depth of 2500 m. The water temperature varies in the range of 123-143°C. The discharge from it makes 30-70% of the total production from the mentioned wells. Between these two main aquifers there are numerous scattered feedpoints found at variable depths in the wells (700-1200 m), supposed to be controlled by dykes and accompanying faults.

2.2.4 Formation temperature

Evaluation of formation temperature in the geothermal field before production started was carried out on the basis of temperature logs analyses from the six deep wells, SN-01 to SN-06. Temperature measurements from drilling time, warm-up and production periods were taken into account. However, it should be pointed out that the recorded data come from different years, covering relatively long periods of time (1966-1993). Therefore, temperature in the wells drilled later could already be affected by production from wells drilled previously. In most cases the bottom hole temperature in the wells was used as the basis for the formation temperature evaluation because it can be considered to be close to the actual one. In some cases, when internal flow occurred the formation temperature was masked. Some of the wells had not yet reached equilibrium with the surrounding rocks after drilling (too short time after drilling) or are affected by production. Therefore, except for the bottom hole temperature large parts of the logs do not represent the actual formation temperature.

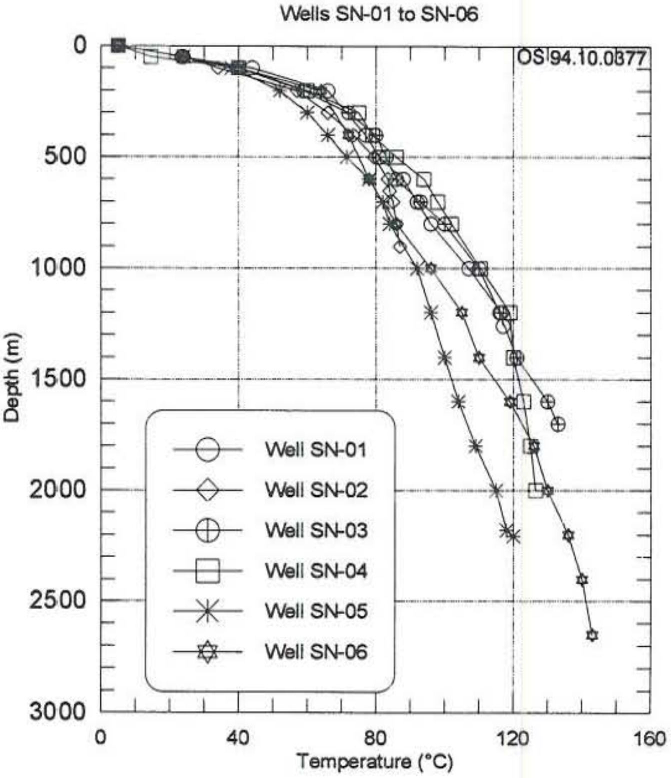

FIGURE 8: Formation temperature profiles for wells SN-01 to SN-06

Generally, the formation temperatures with depth for the six wells SN-01 to SN-06 are rather similar. One can distinguish two main sectors in each well (Figure 8). In the shallower parts, down to 200-400 m, temperature increases very rapidly with depth to 65-80°C. In this part of the formation heat transport is caused mainly by conduction. Deeper, the formation temperature increases, but not so rapidly as above, reaching the maximum temperatures of 138-140°C at the depth of 2207 m (well SN-05) and 144°C at the depth of 2650 m (well SN-06). The thermal gradient calculated for the deeper parts of the wells is in the range of 30-35°C/km. Such low value is connected with heat transport by convection that forms the geothermal system.

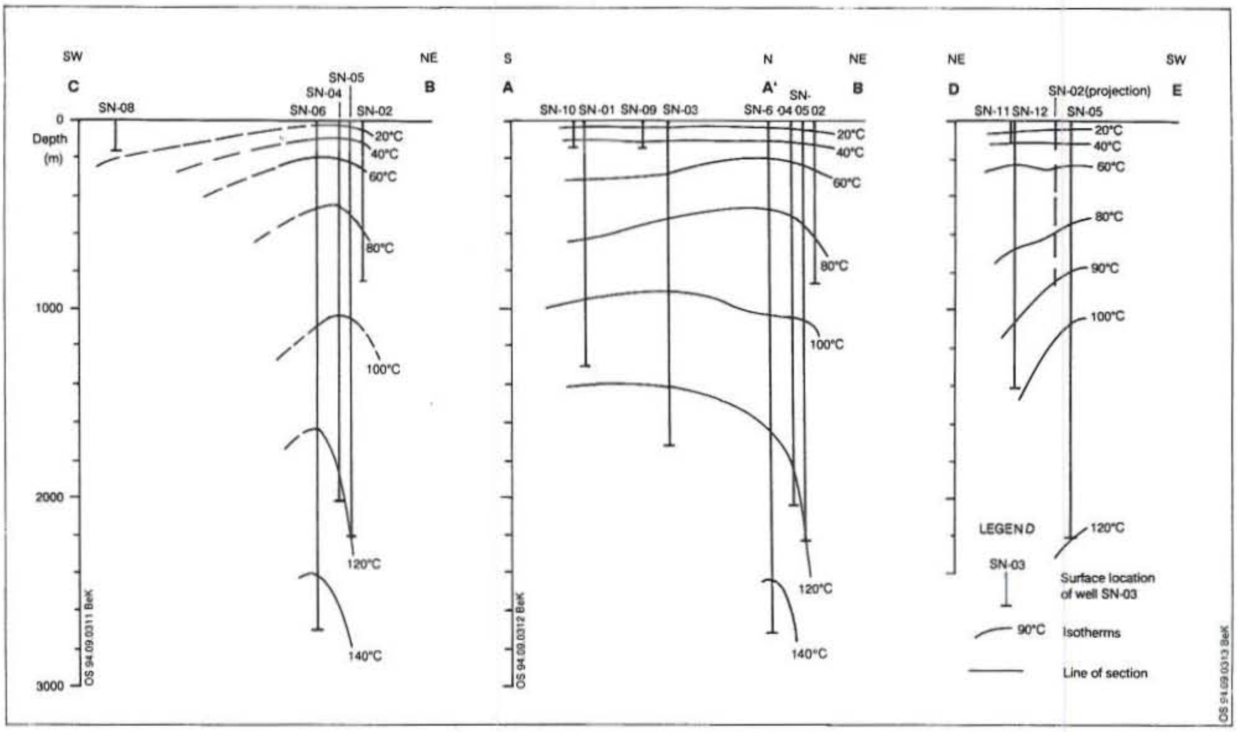

FIGURE 9: Temperature cross-sections through the Seltjarnarnes field, locations are shown in Figure 4

The concentration of almost all the wells along a straight line makes it impossible to plot a contour map of temperature at different depths in order to gain more information about the subsurface temperature distribution. Instead, some temperature sections were constructed, allowing to make some general remarks as seen in Figure 9 (for location see Figure 4). They appear to indicate a narrow, limited zone with temperatures 5-20°C higher than the surrounding formation, concentrated within the northern part of the field, close to wells SN-04, SN-05 and SN-06. Furthermore, the existing data covers a small area with the distance between the wells usually less than 500 m. On the other hand, if this zone exists, it can act like a path for heat transport, controlled by the local structures (faults, dykes?).

2.3 Well SN-12

2.3.1 Purpose of drilling

The increasing salinity of the water produced by wells SN-03 to SN-06 from the shallower aquifer situated at 300-800 m depth started to cause considerable problems with scaling and damaging of the casing and surface equipment of the wells. Thus, the drilling of the new well SN-12 was planned, in order to find a deeper aquifer (expected below the depth of 2000 m) with low salinity of the fluid, which could contribute to lowering of the total salinity of the fluid produced from the field. Well SN-12 was located on the northwestern boundary of the Seltjarnarnes peninsula, at a distance of 20 m from well SN-11 within the area of the highest shallow thermal gradient, in the range of 300-360°C/km (Figure 4). The drilling was preceded by completion of five pilot gradient wells, SN-07 to SN-11 in 1993-1994. It was planned as a production well to the depth of 2700 m. The drilling started on 17th July 1994, and during preparation of this report, had reached the depth of 2230 m on 28th of September 1994.

2.3.2 Subsurface geology

The geological profile is known from the analyses of cuttings and lithological logs (Á. Gudmundsson; pers. comm.). In the upper part (0-40 m) the youngest basalt succession with tuff layer was encountered, underlain by 40 m thick marker sediment horizon. Below, down to the depth of 780 m, the profile consists of altered tholeiite basalt succession separated by layers of basaltic breccias and thin fine-grained to coarse-grained sediments scoriaceous intercalations. Between 780 and around 1800 m, olivine tholeiite basalts interbedded by breccias layers, andesite flows (found at 780-830 m) and frequent thin layers of oxidized scoriaceous sediments were found, similar as in the upper part of the well. The thick formation of hyaloclastites, found in other wells in the Seltjarnarnes field between the two main basaltic successions at the depths of 600-1000 m, has not been recognized in well SN-12. The lowest part of the present section consists of tholeiite basalt flows interlayered by breccias and sediments. Dolerite dykes and sheets occur at 1000-1100 m depth, and below 1500 m depth, where they are abundant and form 30-40% of the profile.

2.3.3 Temperature logs

Untill September 24th 1994, seven temperature measurements had been run in well SN-12. Three of them were done during four hours on August 18th 1994, after reaching 793 m depth, and before casing the well down to 791 m. The next logging was performed on September 2nd 1994, after reaching 1416 m. After taking the first downhole profile, the probe was left at 1335 m for 72 hours to continuously record the warm-up of the well, until September 5th 1994, when the fifth log was run. The next two logs were done on September 23-24th 1994, when the drilling had reached 2170 m. Between carrying out the last two successive loggings, the probe was left at the bottom to record the heating-up of the well. Figure 10 shows all the temperature logs which had been carried out from the beginning of drilling until September 24th 1994.

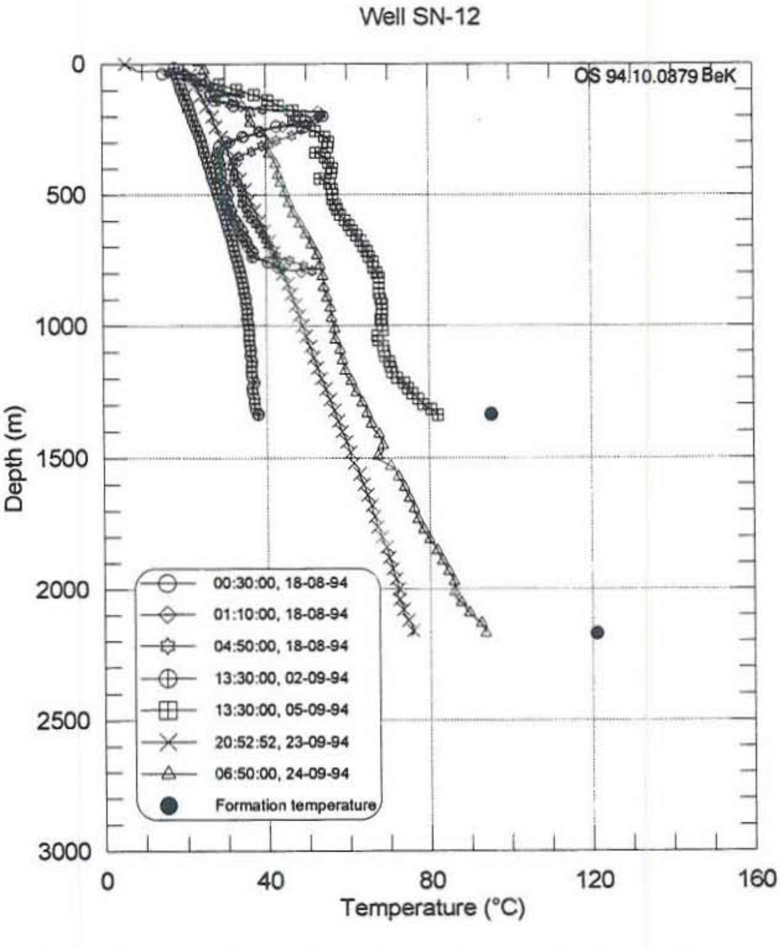

FIGURE 10: Temperature logs and formation temperature in well SN-12

The logs indicate feedpoints at 100-200, 350, 400, 750, 1050, 1500 and 2010 m. The shallowest feedpoint corresponds with a feedpoint in well SN-11 at 120-130 m. The feedpoints from 350-750 m correlate with feedpoints at 550-620 m in well SN-02, which is the closest deep well to well SN-12. The feedpoint from 2010 m probably belongs to the deepest aquifer in the field, situated below 1700 m. Similarly, like in other wells in the field, the feedpoints are located either in sedimentary layers or close to dykes or sheets.

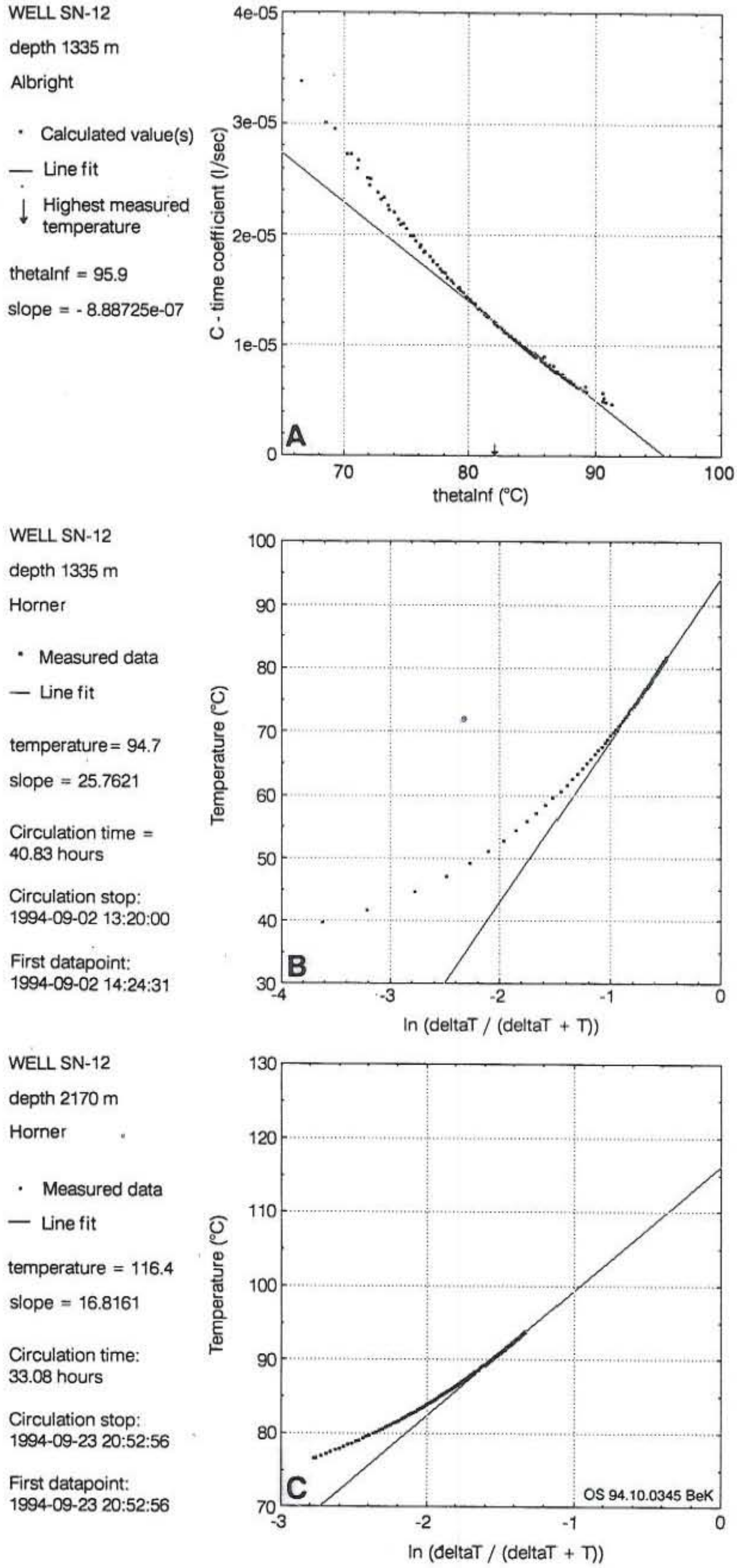

FIGURE 11: Results of estimations of formation temperatures in well SN-12 at 1335 m depth, using a) Albright method; b) Horner method; and c) at 2170 m depth, using the Horner method

2.3.4 Thermal gradient

The thermal gradient computed for the upper 200 m depth of well SN-12 is around 260°C/km. These values are significantly lower than one might expect after the results obtained from well SN-11, which is situated 20 m away and characterized the highest gradient measured within the whole field. Also the shallow thermal gradients in the production wells SN-02, SN-05 and SN-06, situated within the same part of the field have values close to 300°C/km (Figure 6 and 7). There are two possible explanations, either the well had not yet reached equilibrium with the surrounding formation when the temperature was measured, or this well is situated outside the zone of the highest temperature at depth.

2.3.5 Formation temperature

Data coming from the second and third set of the temperature logs, carried out from the 2nd to 5th of September and from the 23rd to 24th of September 1994, were used to evaluate the formation temperatures at the depths of 1335 and 2170 m respectively. The calculations were done using the program BERGHITI, which serves for post drilling thermal recovery analysis of wells and for estimations of formation temperatures using the Horner plot and the Albright method (Helgason, 1993). Results are shown in Figure 11. The formation temperature at the depth of 1335 m is 94.7-95.9°C. The calculated value around 116°C for the depth of 2170 m (using Horner plot) is supposed to be underestimated, because of short time of the recorded warm-up period (10 hours), which was also supported by comparison with the former results from the other wells. Therefore the formation temperature at the depth of 2170 m was corrected using the procedure suggested by Roux et al. (1980), which resulted in obtaining a value around 121°C.

Comparison with the temperature distribution within the field based on the data from the earlier wells shows, that well SN-12 is cooler than the surrounding wells SN-02, SN-04, SN-05 and SN-06. However, these preliminary results must be checked against data from further drilling and logging in well SN-12, especially as they show a slightly different picture of the thermal field than earlier assumptions. The area with the highest thermal gradient and the highest formation temperatures is confined to the closest vicinity of wells SN-04 and SN-06 and well SN-12 may be situated outside this zone. The other explanation for the obtained results is, that a cooling in the upper part of the formation surrounding well SN-12 has taken place, due to seawater infiltration since the start of production.

2.4 Conclusions

The Seltjarnarnes field is characterized by a narrow, elongated zone of a high surface thermal gradient up to 300-360°C/km, which crosses the peninsula striking roughly N-S. A minor culmination is observed near the north coast, where all the production wells SN-03 to SN-06 are located, and well SN-12 where drilling started in July 1994. This part of the field is probably controlled by a denser system of dykes and accompanying fractures at greater depths.

There are two main aquifers in the field, tapped in all the production wells. The shallower one is located at 300-800 m and the deeper one was found below 1700 m. The third zone of scattered aquifers occurs at 700-1200 m.

During nearly 30 years of production from the field, no cooling in the wells has been observed. The temperature of the produced fluid from particular wells remains stable in the range of 90-117°C. Nevertheless, one may expect a temperature decrease, because of a systematic increase in the salinity of the water coming from the shallower aquifer, due to the seawater infiltration into the system. Usually, these changes precede the temperature changes in geothermal systems.

To date, the results of the temperature logs from well SN-12 suggest, that it may have been placed out of the zone of the highest local thermal gradient. However, the results of the formation temperature estimate show, that the temperature in the aquifer expected to be tapped at 2000 m will probably not be lower than 120-140°C.

3. THE RESERVOIR TEMPERATURE IN THE PODHALE FIELD, S-POLAND

The main purpose of the study of the Podhale field was to apply the classical methods of analyzing and interpreting temperature data coming from post-drilling logs in the wells, short term well tests, monitoring of the geothermal doublet and, additionally, the surface thermal investigations and preliminary petrographic study, in order to gain basic information about the temperature in the main reservoir. Subsequently, the future wellhead temperature of the produced fluid and initial formation temperature in the field were estimated. In spite of the fact, that the geothermal waters are planned to be used in the local district heating system, the subjects that were considered appear to be one of the most important and urgent to solve.

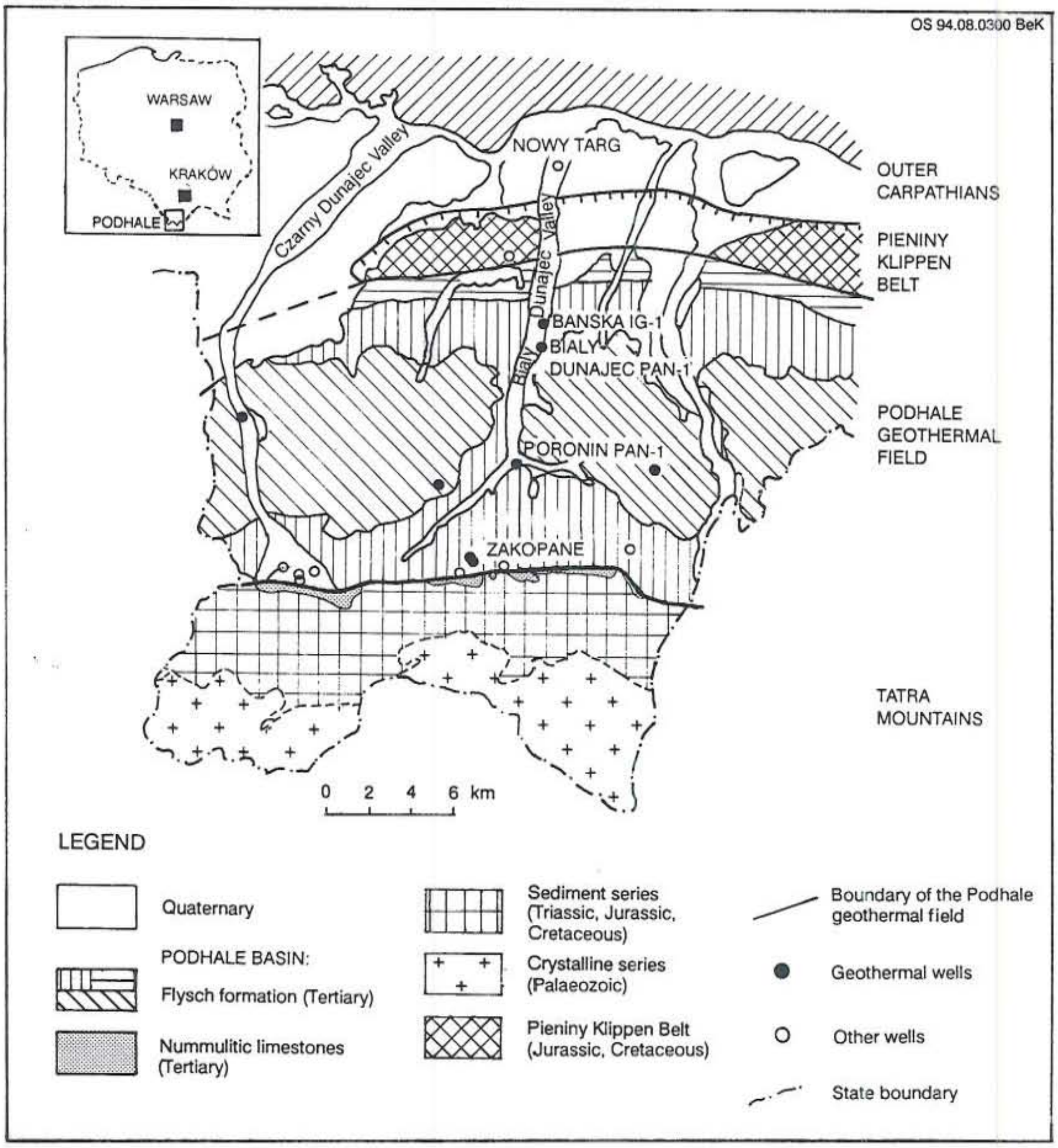

FIGURE 12: The Podhale geothermal field, location and simplified geology (based on Malecka, 1982)

3.1 General overview

3.1.1 Geological outline

The Podhale geothermal field is situated in the southern part of Poland, at the north foothills of the Tatra mountains. It occupies the central part of the geological and morphological unit of an area of 475 km^2, while the rest, around 520 km^2, extends to the territory of Slovakia (Figure 12). The Podhale basin belongs to the Inner Carpathians. It originated during Tertiary (Palaeogene) age, as a result of tectonic activity and deposition in the latest phase of alpine orogenesis. The oldest basement consists of Mesozoic carbonaceous and clastic sediments, forming several tectonic units. The discordantly overlying Palaeogene rock system consists of the Upper Eocene-Oligocene flysch formation with an observed thickness of about 2.5-3 km, underlying by Middle Eocene carbonaceous conglomerates and limestones with variable thickness (0-350 m). The basin is an asymmetric unit. Hydrologically, it is closed towards the north by the Pieniny Klippen Belt and open southwards. The main recharge area is postulated in the south, on the outcrops in Tatra mountains. The outflow of the water is artesian.

3.1.2 Thermal characteristics

The average thermal gradient within the Podhale geothermal field is in the range of 1.9 - 2.1°C/100 m which is slightly lower than in other regions of the Polish Carpathians, where it was calculated to be 2.3°C/100 m. The heat flux was evaluated at 55.6 mW/m^2 (Plewa et al., 1992).

The thermal parameters of rocks vary considerably, depending on petrological type of sediments. In particular, it relates to thermal conductivity of the caprock (sandstones, mudstones and shales) - the measured values range from 1.2 to 4.2 W/(m°C), while the heat capacity is around 840-920 J/(kg°C). For the main reservoir rocks, i.e. limestones and dolomites, these parameters were found in the range of 2.9-4.4 W/(m°C) and 840-1000 J/(kg°C), respectively.

Some parts of the field were covered by surface temperature investigations. The surveys detected thermal anomalies (2-3°C higher than average background values) above the systems of deep faults, crossing Palaeogene caprock and Mesozoic basement. Recorded anomalies were interpreted as the result of increased heat flow along the planes of tectonic discontinuities, probably due to up-flow of hot waters from great depths (Pomianowski, 1988).

3.1.3 Exploration and development history

In the end of the 19th century a natural spring with 20°C water was found at the south boundary of the Podhale field. On the whole, during the years 1963-1991 fifteen shallow and deep wells have been drilled (Figure 12). In the first exploration well, situated in Zakopane town, two geothermal aquifers were tapped. The artesian outflow of 14 l/s was obtained, with the wellhead temperature 35-36°C. The water is used in outdoor swimming pools.

An extensive exploration started in 1979 with the drilling of the well Banska IG-1. Several aquifers have been recognized, among them the most promising being found at the depth of 2565-2683 m in Middle Eocene and Middle Triassic conglomerates, limestones and dolomites. In 1981 during the testing of free outflow, it discharged 16 l/s water with wellhead temperature of 72°C and artesian pressure of 24 bars. The total dissolved solids of the water were found to be 3 g/l.

During the years 1988-1991 five more wells were completed. Similarly like the Banska well, they were situated in the deepest central part of the Podhale basin. In all of them geothermal aquifers were found, with wellhead temperatures of discharged water in the range of 40-86°C and artesian pressure. The flowrate varied from 3-6 to 60 l/s.

The first geothermal plant has been operating in the Podhale region since 1990. It consists of the doublet of a production well Banska IG-1 and an injection well Bialy Dunajec PAN-1. Presently the production well discharges about 7-8 l/s water with temperature at 82°C and artesian pressure 27 bars. Heat is extracted by the heat exchangers and supplied to greenhouses, wood-drying chambers, fish ponds and to district heating systems for several houses. More houses will be connected to the heating network in the near future. Further geothermal plants are planned, making it possible to eliminate coal combustion within the whole Podhale region.

3.2 Reservoir temperature assessment

The temperatures in the reservoirs encountered in the Podhale field have been evaluated following the results from the temperature loggings and drill-steam tests. However, the experience indicates that these methods often give values lower than the actual. For geothermal wells the accurate estimation of the reservoir temperature is one of the most important problems to solve, because this factor affects the planning of the type of utilization and the temperature changes in the produced fluid with time. Thus, in this study an attempt was made to apply the method of simulation often used in geothermal wells in order to assess the temperature in the main aquifer in the Podhale field.

3.2.1 Theoretical assumptions for the reservoir temperature simulation

A temperature simulation within the main reservoir was performed on the basis of empirical and analytical relations that are used to compute steady-state of one- or two-phase flow in geothermal wells. Calculations were executed using the multi-feedzone geothermal simulator HOLA. Detailed description of the formulation used in the simulator is given by Bjornsson (1987) and Bjornsson et al., (1993). The simulator reproduces the measured temperature and pressure profiles in flowing wells for a given discharge conditions. It solves numerically the differential equations that describe the steady-state energy, mass, and momentum flow in a vertical pipe. The HOLA simulator was developed in the Fortran language and can be executed on IBM PC/XT/AT computers by the Microsoft 5.1 Fortran compiler. In this study only a part of the available programme was used, modified to the geometry and conditions of the wells into consideration.

The governing steady-state differential equations for mass, momentum and energy in a vertical well are given as follows:

$$\frac{dm}{dz} = 0 \tag{1}$$

$$\frac{dP}{dz} - \left[\left(\frac{dP}{dz}\right)_{fri} + \left(\frac{dP}{dz}\right)_{acc} + \left(\frac{dP}{dz}\right)_{pot}\right] = 0 \tag{2}$$

$$\frac{dE_t}{dz} \pm Q = 0 \tag{3}$$

where

m = total mass flow from the well (kg/s);
z = depth coordinate (m);
P = pressure (Pa);
E_t = total energy flux in the well (J/s);
Q = ambient heat losses over an unit distance (W/m);
$(dP/df)_{fri}$ = pressure gradient due to wall friction (Pa/m);
$(dP/dz)_{acc}$ = pressure gradient due to acceleration of the fluid (Pa/m);
$(dP/dz)_{pot}$ = changes in gravitational load over dz (Pa/m);
+, - = upward and downward flow, respectively

The flow calculations for a single phase fluid in vertical pipes are carried out with linear equations, assuming that fluid physical properties are constant. The energy gradient is given by:

$$\frac{dE_t}{dz} = m\frac{d}{dz}[h + 0.5u^2 + g(L_w - D)] \tag{4}$$

where

G = mass velocity in the well (kg/(m²s));
u = average fluid velocity (m/s);
h = fluid enthalpy (J/kg);
g = acceleration of gravity (9.82 m/s²);
L_w = total length of the well (m);
D = depth to a grid node in the well (m)

The heat flux losses into the ambient, valid when the term $\mathring{\omega}t/r^2_w >> 1$, are given as

$$Q = 4k\pi(T_w - T_r)[\ln(\frac{4\alpha t}{r_w^2} - 2\gamma)]^{-1} \tag{5}$$

where

k = thermal conductivity of rocks (W/(m°C));
T_w = fluid temperature inside the well (°C);
T_r = ambient initial temperature (°C);
$\mathring{\omega}$ = thermal diffusivity (m²/s);
t = time (s);
r_w = well radius (m);
γ = 0.57721... = Euler's constant.

Equation 5 is an approximation of the actual heat flux, reasonable since the term dE_t/dz is usually much larger than Q.

Assuming the constant wellbore radius and one feedzone (as is the case of the Banska well), Equation 4 reduces to

$$\frac{dE_t}{dz} = m\frac{dh}{dz} = mc_w\frac{dT}{dz} \tag{6}$$

where

c_w = heat capacity of the fluid (J/(°C kg)).

Combining Equations 3, 4, 5 and 6 gives

$$mc_w\frac{T_2 - T_1}{\Delta z} = \Omega(\hat{T}_w - \hat{T}_r) \tag{7}$$

for

$$\Omega = 4k\pi[\ln(\frac{4\alpha t}{r^2_w}) - 2\gamma)]^{-1} \tag{8}$$

where

Ω = ambient thermal conductance (W/(m°C));
T_1, T_2 = nodal temperatures along the well (°C);
T_w, T_r = mean fluid and reservoir temperatures of the two adjacent nodes (°C);
Δz = nodal distance in the well (m).

Equation 7 is solved by iteration in small, finite steps along the well characterized by the nodal temperatures T_1 and T_2, allowing one to find the fluid temperature over the well distance for given reservoir and surface temperatures. This was the basic equation for estimating the reservoir temperature using the wellbore simulator HOLA.

3.2.2 Characteristics of the main reservoir

To date the exploration results indicate that the main geothermal reservoir occurs in the limestone-dolomite formations of the Middle Triassic along with overlying Middle Eocene limestones and conglomerates (Figure 13, Table 3). In the central part of the Podhale basin it was tapped at the depths 1768-2556 m. The thickness varies from 87 m in well Poronin PAN-1 to 350-400 m in well Bialy Dunajec PAN-1. The wells discharge from 3-4 l/s water with temperatures around 45°C to 16-60 l/s with temperatures of 82-86°C. The artesian pressure ranges from 19 to 27 bars. In conformity with results of temperature logging and short term well tests the reservoir temperatures in the wells Bialy Dunajec and Banska were evaluated at 86-88°C. The total dissolved solids range from 1 to 3 g/l. The reservoir rocks are tectonically broken up and very often form breccias, crosscut by numerous vein systems. Thus secondary permeability plays the main role in water circulation while primary permeability found from solid core fragments usually does not exceed 1-2 mD (Sokolowski et al., 1993).

TABLE 3: Characteristics of the main reservoir within the Podhale geothermal field

Well	Total depth (m)	Main aquifer (m)	Wellhead		Max. flowrate (l/s)	Total diss. solids (g/l)
			T(°C)	P(bar)		
Banska	5265	2565-2683	82	27	16	2.9-3.1
Bialy Dunajec	2394	2112-2384	86	20	60	2.6-2.7
Poronin	3003	1768-1855	45	19	3	1.0

3.2.3 Temperature measurements

Two main methods of temperature logs in boreholes are used in Poland. In non-steady conditions during drilling the logging is conducted for short runs (50-250 m), and usually does not cover the whole interval previously drilled. The measurements after finishing drilling are assumed to be performed in steady conditions, in the terms of equilibrium with the surrounding wells. The average time for the stabilization of the thermal field was assumed to be 10-14 days after completion or cleaning the well (Plewa, 1984). Some temperature data are derived also from the short term well tests using packers, which are conducted during and after drilling for selected intervals in the wells, in order to evaluate the reservoir parameters of the encountered fluids. The temperatures recorded are related to the depth of installing the thermometer.

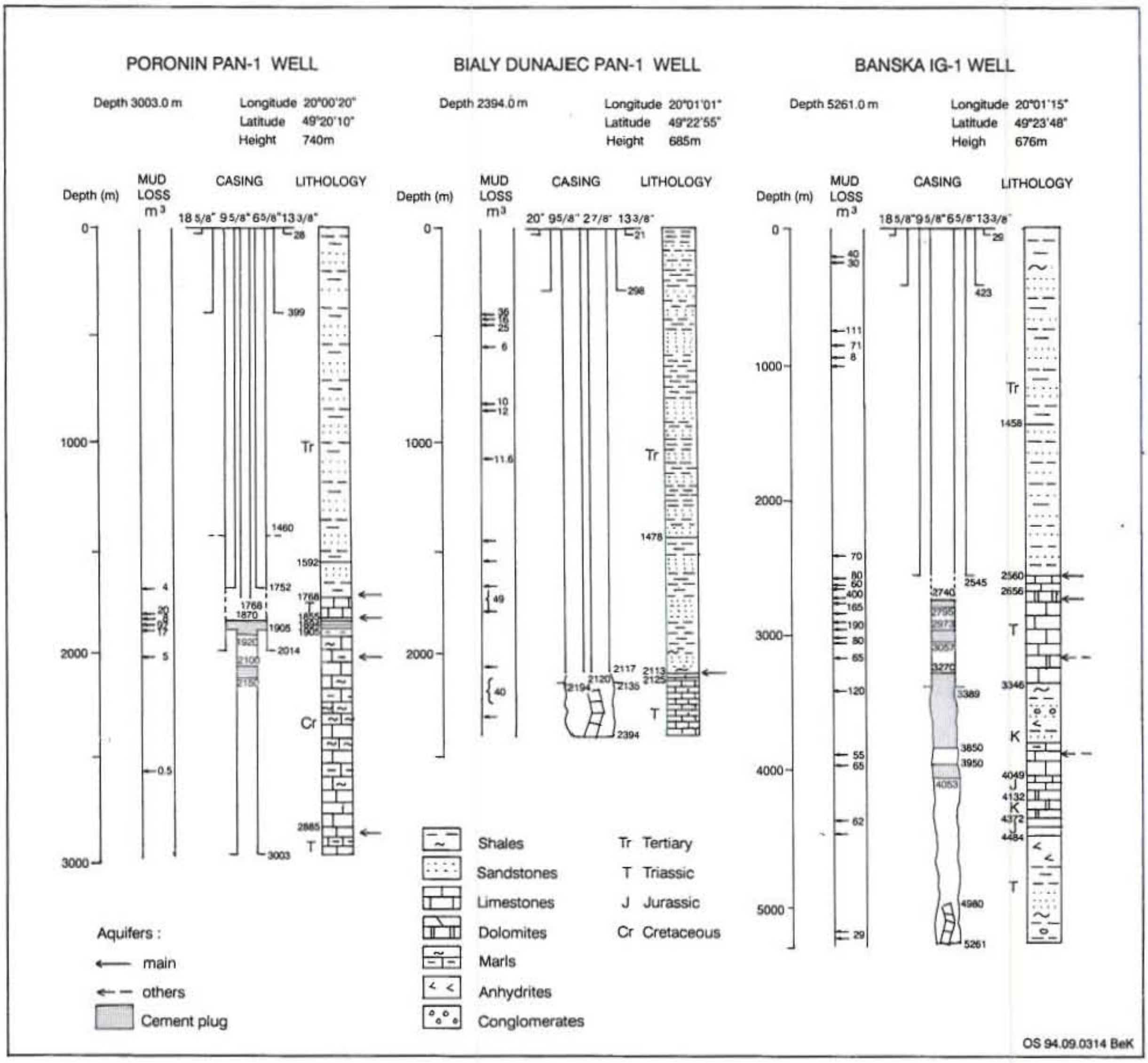

FIGURE 13: Geology and main aquifers in Poronin, Bialy Dunajec and Banska wells (after Sokolowski et al., 1993)

However, it must be pointed out that previous methodology is mainly based on experience from the oil and gas exploration, and may not be representative for geothermal wells where circulation losses, heat convection within aquifers, water circulation inside or outside the wells occur which results, among other things, in the longer time for warm-up period after drilling, as is the case in wells with the Podhale geothermal field. The results of the temperature log surveys in three wells: Banska, Bialy Dunajec and Poronin are depicted in Table 4 and Figure 14.

The Banska well: The total drilling time was 19 months. Abundant mud losses were observed, from which almost 70% (1030 m^3) entered the main aquifer. The temperature logging was conducted 30 days after finishing drilling and 12 months after the last mud losses in the well were recorded. The well was already cased and cemented. Some changes of the slope are seen on the curve, indicating a heat convection at the depth of 2600-3200 m, where the main aquifer is located. The deviation towards slightly higher values above these depths can be interpreted as heating up the capric formation by an aquifer from below ('blanket effect'), or by circulating water. The temperatures of the water entering the well during several short term well tests was estimated according to the results from the logging after drilling. Using such a method, the temperature in the main aquifer situated at the depth of 2560-2683 m was evaluated to be 86°C. The temperature at the deepest recorded point, 4790 m, was 127.5°C.

TABLE 4: Temperatures recorded during short term well tests

Interval tested (m)	Depth of thermometer (m)	Temperature (°C)	Mud losses	Lithology
Bialy Dunajec well				
1468-1528	1424	50	100-500 l/s	Flysch
1468-1554	1427	48	100-500 l/s	Flysch
1842-1878	1850	75	-	Flysch
2087-2135	2098 2125	78 88	6 m^3/h	Flysch, limestones
2135-2155	2130	83	15 m^3/h	Limestones, dolomites
2135-2199	2170	86	20 m^3/h	Limestones, dolomites
Poronin well				
2014-2432	2038	70	-	Marls,shales,limestones
2731-2823	2776	95	-	Limestones

The Bialy Dunajec well: Nearly continuous losses of mud and circulated water were recorded during the 10 months of drilling, with a total amount of 300 m^3. Around 40 m^3 were lost into the zone of unconformity between Palaeogene and Mesozoic formations (top of the main reservoir). The temperature logging was only performed during drilling, i.e. in non-steady conditions. Some additional information comes from the short term well tests, while the temperatures of fluid entering the well from the main aquifer below 2112 m were 83-88°C and one can assume, that the initial temperature in the reservoir was not lower than these values.

The Poronin well: The temperature log was run 4 days after finishing drilling, which lasted 9 months. The last mud losses occurred 103 days before. They totalled 250 m^3, including 63 m^3 which was lost into the main reservoir. The temperature recorded on the bottom (3003 m) was 71°C. Additional information about temperature distribution comes from short-term well tests, where the recorded temperatures were 2-10°C higher than obtained from the logging after drilling completion.

These results suggest, that available data is insufficient for estimating the initial reservoir temperature, because nearly all measurements have been conducted in non-steady conditions. Thus, they tend to show lower values than the actual rock temperature.

3.2.4 Simulation of the reservoir temperature

The solution described in 3.2.1 was applied to assess the reservoir temperature of the water flowing from the Banska well, using the results obtained during four years of monitoring. Additionally, the estimation of the reservoir temperature in the Bialy Dunajec and Poronin wells was made. Because of the short time of observations and other borehole operations, the calculated results for the latest two wells are treated as approximations.

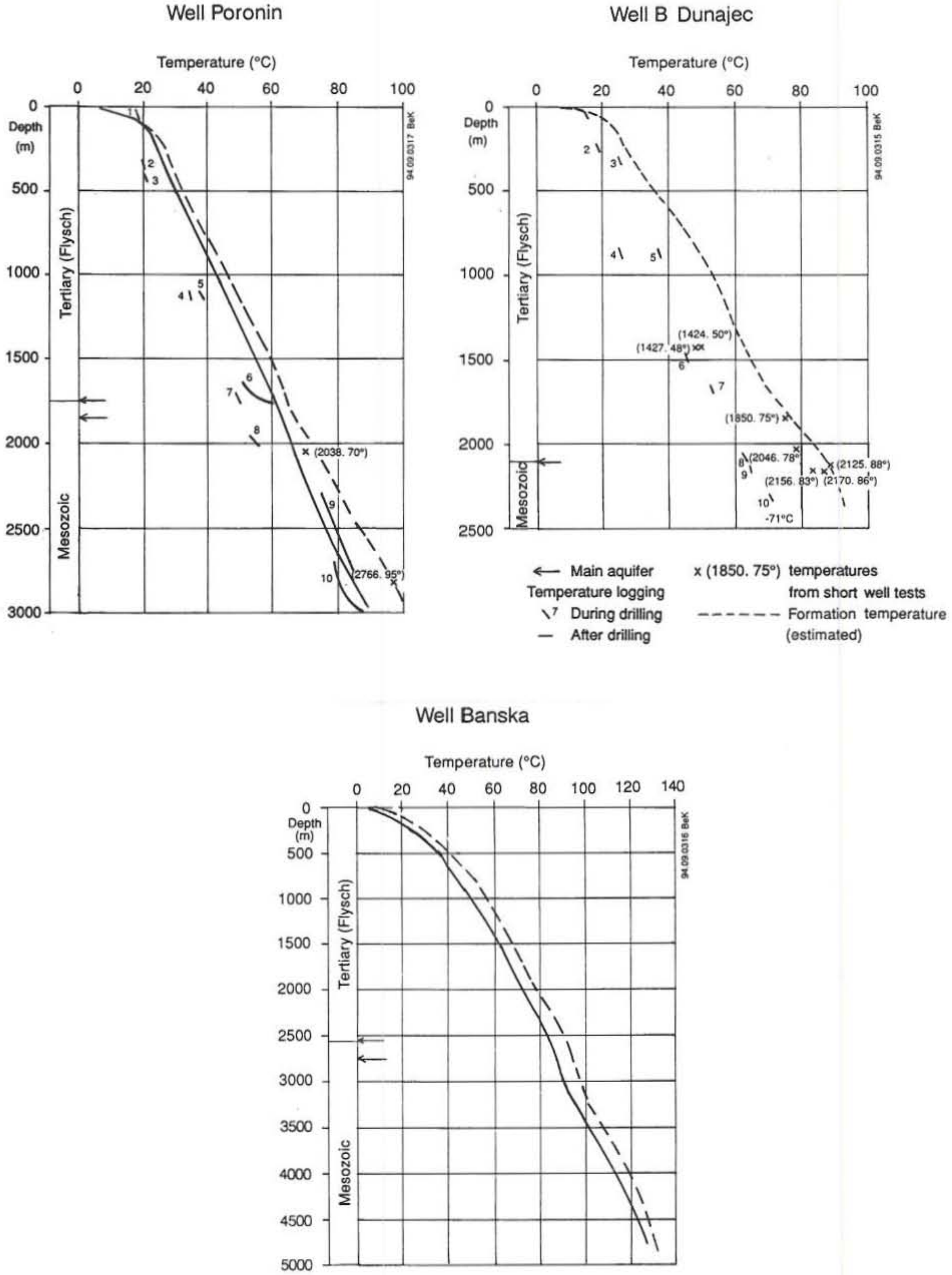

FIGURE 14: Temperature logs in the Poronin, Bialy Dunajec and Banska wells and estimated formation temperatures

The input wellhead parameters, assumed to be the same for all the wells, were as follows:

rock density, ρ = 2650 kg/m^3
rock heat capacity, c_r = 900 J/(kg°C)
rock thermal conductivity, k = 2.5-3.5 W/(m°C)
average surface temperature, T_s = 8°C

TABLE 5: The Banska well - results of monitoring (Sep. 1991 - Sep. 1992 non-correct data; see text)

Year	No.	Month	Wellhead temperature (°C)	Aver. water prod.	
				(m^3/h)	(l/s)
1990	1	Nov	62.5	21.0	5.8
	2	Dec	63.5	22.0	6.1
1991	3	Jan	64.0	23.4	6.5
	4	Feb	66.0	24.9	6.9
	5	Mar	68.0	24.8	6.9
	6	Apr	68.0	24.5	6.8
	7	May	68.5	24.8	6.9
	8	Jun	68.0	23.9	6.6
	9	Jul	68.0	23.6	6.5
	10	Aug	68.0	24.0	6.6
1992	24	Oct	75.0	27.9	7.7
	25	Nov	75.0	31.0	8.6
	26	Dec	75.5	32.0	8.8
1993	27	Jan	77.5	31.9	8.8
	28	Feb	78.0	30.8	8.7
	29	Mar	78.5	28.9	7.9
	30	Apr	79.0	29.7	8.2
	31	May	79.5	27.8	7.7
	32	Jun	80.5	26.7	7.4
	33	Jul	80.5	25.2	7.0
	34	Aug	80.5	25.5	7.1
	35	Sep	81.0	25.3	7.0
	36	Oct	81.0	26.0	7.2
	37	Nov	81.0	27.6	7.6
	38	Dec	81.5	28.8	8.0
1994	39	Jan	81.5	29.9	8.3
	40	Feb	81.5	29.6	8.2
	41	Mar	81.9	28.9	8.0
	42	Apr	82.0	28.5	7.9
	43	May	82.0	28.1	7.8
	44	Jun	82.0	27.8	7.7
	45	Jul	82.0	27.5	7.6
	46	Aug	82.0	27.5	7.6

The Banska well: The temperature data, which were mainly used in this study, come from the four year's monitoring of the geothermal doublet Banska-Bialy Dunajec, operating since November 1990. From the beginning the flowrate, wellhead temperature and pressure of the produced and injected water have been monitored. The results of monitoring the production well Banska are listed in Table 5. The data recorded in the earliest phase (November 1990 - September 1992) were lower than actual trend of parameters' distribution during the time, in spite of additional operations (injecting coldest water with temperature 30-40°C into the well Banska from the well Bialy Dunajec in November and December 1990, non-stable flowrate, shutting the well during reconstructions and changing the surface equipment, inaccurate data recording). Generally, during the last 22 months of operating the doublet (October 1992 to August 1994), in the terms of stable flowrate 7-8 l/s and wellhead pressure 26.5-27.0 bars, a gradual increase of wellhead temperature was observed; from 75°C in October 1992 to 79°C in April 1993. Subsequently, the temperature started to stabilize, which resulted in small increments (not more than 0.5°C) in successive months.

The reservoir temperature simulation was carried out for various combinations of assumed parameters and for reservoir temperature from the interval 86-100°C. The constant well radius was 0.08 m, and the depth of the top of the main aquifer (feedzone) was 2560 m. The input parameters for four considered cases of the simulation are listed in Table 6. The results are shown in Figure 15.

TABLE 6: The Banska well - parameters for the reservoir temperature simulation

Case	Parameters assumed			
	Flowrate (kg/s)	Heat capacity (J/(kg°C))	Thermal conductivity (W/(m°C))	Reservoir temperature (°C)
A	7-8	900	2.5-3.5	86
B	7-8	900	2.5	90-91
C	7-8	900	3.0	91-92
D	7-8	900	3.5	92-94

Case A: First, the simulation was done for assumed reservoir temperature of 86°C, as this value was treated as the actual one. The results indicated that this value is estimated too low. In each parameter combination, the wellhead temperature had to reach the level of 78-79°C in 3-4 months after flowrate stabilization, i.e. in January-March 1993, and after that time the temperature stabilization at 78-79°C should be observed.

Subsequently, the simulation was carried out for assumed reservoir temperatures in the range of 87-100°C and different values of thermal conductivity of rocks. The obtained results are as follows:

Case B: For rock thermal conductivity of 2.5 W/(m°C) the reservoir temperature is in the range of 90-91°C.

Case C: For rock thermal conductivity of 3.0 W/(m°C) the reservoir temperature is in the range of 91-92°C.

Case D: For rock thermal conductivity of 3.5 W/(m°C) the reservoir temperature is in the range of 92-94°C.

The three cases B-D give the reservoir temperature between 90 and 94°C during the latest 1-2 years of production. For these cases a good conformity between observed and simulated values was obtained. A rapid increase of temperature is calculated during the first period of production (1-3 months, depending on the flowrate) and then strives to stabilization, with slightly increasing values, of less than 0.2°C/month.

The Bialy Dunajec well: The borehole Bialy Dunajec serves as an injection well. In October and November 1990, after finishing drilling, a stimulation was performed in order to improve the permeability of the main aquifer. A total of 60 m^3 of diluted HCl-acid was injected. The post-reaction liquid was pumped out from the well. After one month the injection test was performed, pumping 120 m^3 water into the reservoir. The free outflow was monitored during four days, starting four days after the injection test. The well was flowing for only 1 hour each day. The flowrate was 53-60 l/s, with wellhead pressure 18-21 bars. The temperature started from 57°C and increased to 86°C. However, the measurements were taken in unstable conditions due to cooling within the aquifer and the well, as a result of stimulation and injection. Additional cooling effect was caused by bigger heat losses into the ambient due to non-continuous flow from the well, than by continuous flow.

The actual parameters for the reservoir temperature simulation were mass flow from the well 55 kg/s and wellbore radius 0.15 m. The depth to the feedzone (top of the main reservoir) was 2120 m. For the reservoir temperature simulation the assumed mass flow was 55 kg/s and wellbore radius 0.15 m. The depth to the feedzone (top of the main reservoir) was assumed to be 2120 m. The results of simulation show, that the initial reservoir temperature was certainly not lower than 87-89°C for the assumed thermal conductivity 2.5-3.5 W/(m°C) (Figure 16). The temperatures recorded during short tests and found in the range 83-88°C at 2125-2170 m appear to support the results of the simulation (Table 4, Figure 14). According to the results of the simulation for the Banska well and in the terms of relatively high mass flow from the Bialy Dunajec well, one can expect, that the wellhead temperature would stabilize in the first days of continuous production, at a level slightly higher than 86°C. A more accurate evaluation of the reservoir temperature would be possible if wellhead data from successive time periods were available. However, the Bialy Dunajec well was designed as an injection well and no further monitoring of the outflow was performed.

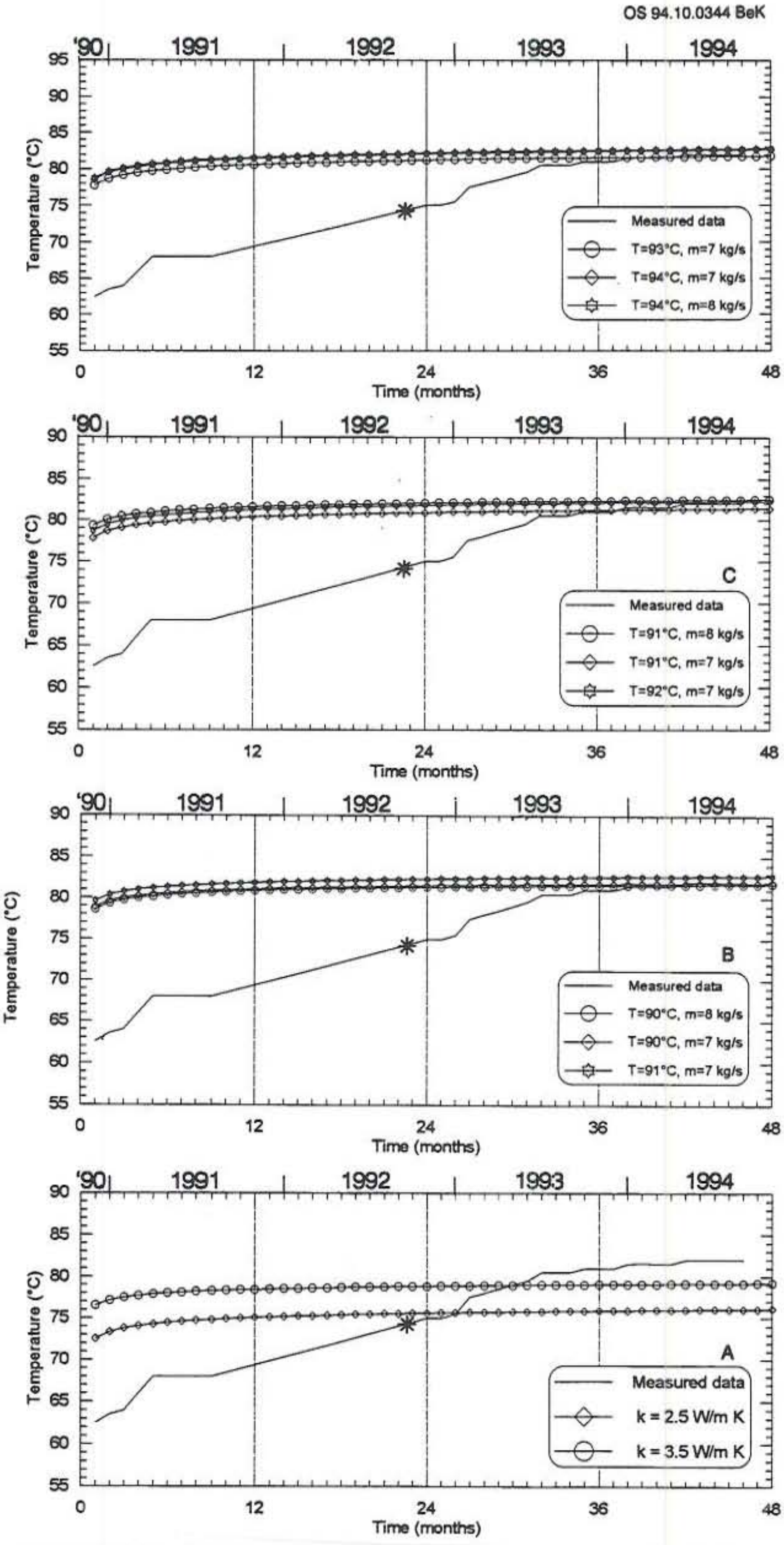

FIGURE 15: The Banska well, reservoir temperature simulation, cases A-D (* the first datapoint measured in stable conditions)

The Poronin well: Continuous monitoring of artesian flow from the well was done during 11 days (8-19 January 1990) as the last step of testing after drilling completion. The casing was perforated at the depth of the main aquifer. The flowrate increased from 0.03 l/s at the beginning to 3 l/s in the last four days, and wellhead temperature increased from 37 to 45°C.

The pressure reached 19 bars. The actual parameters assumed for the temperature simulation were as follows: mass flow from the well 3 kg/s, wellbore radius 0.8 m, depth to the feedzone (top of the main aquifer) 1760 m. The results show (Figure 16) that the minimum reservoir temperature varies from 57 to 60°C, being dependent on the assumed thermal conductivity. In the range of 2.5-3.5 W/(m°C). Referring to results of simulation for wells Banska and Bialy Dunajec, it was expected to be a few degrees higher, because, again, in the terms of non-steady and small mass flow the heat losses along the well were bigger.

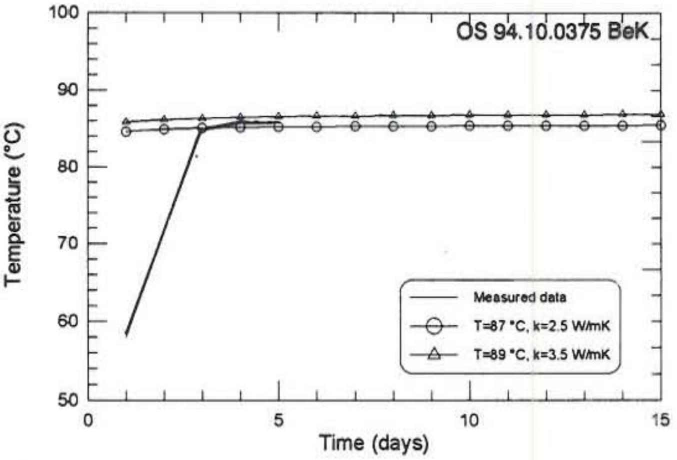

FIGURE 16: Reservoir temperature simulation for the Bialy Dunajec well

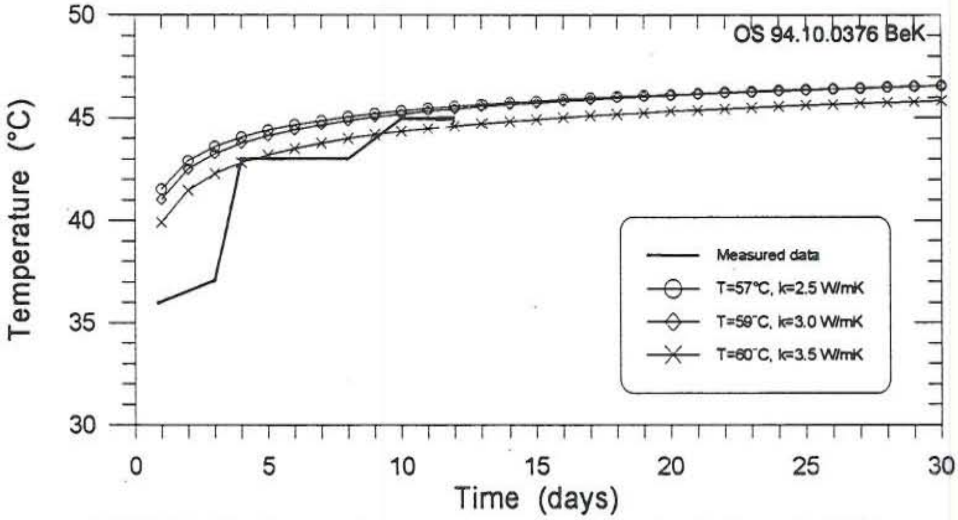

FIGURE 17: Reservoir temperature simulation for the Poronin Well

3.2.5 Predicting future wellhead temperature

On the basis of the results obtained from the reservoir temperature simulation in the well Banska, the wellhead temperature increase for the next 20 years was calculated for various constant mass flowrates in the range of 60-200 m³/h (16-107 kg/s). Since the results of the simulation are based on four years of monitoring, the prediction for the assumed time horizon seems to be credible. The results from previous work using the AQUA Program (Gladysz, 1991) indicated that a small temperature decline during the first 20-25 years of production should be expected, caused by waste water injection into the Bialy Dunajec well. For mass flowrate of 20-100 l/s the temperature decrease was calculated to be 0.2-8.0°C (for the reservoir temperature 86°C). In this present work, it was ignored for sake of simplicity. Also any other effects were not taken into consideration, such as drawdown or cooling in the well, due to the production from the field.

For each flowrate value two variants are considered:

Variant A (pessimistic): Reservoir temperature, T_r = 90°C;
Rock thermal conductivity, k = 2.5 W/(m°C).

TABLE 7: The Banska well, prediction of wellhead temperature (°C), variant A

Years	Mass flow (kg/s)					
	8.0	**16.0**	**26.8**	**40.1**	**53.6**	**107.2**
1	82.1	84.9	87.5	88.3	88.8	89.4
5	83.0	85.4	87.8	88.5	88.9	89.4
10	83.4	85.6	87.9	88.6	88.9	89.5
20	83.6	86.7	88.0	88.6	89.0	89.5

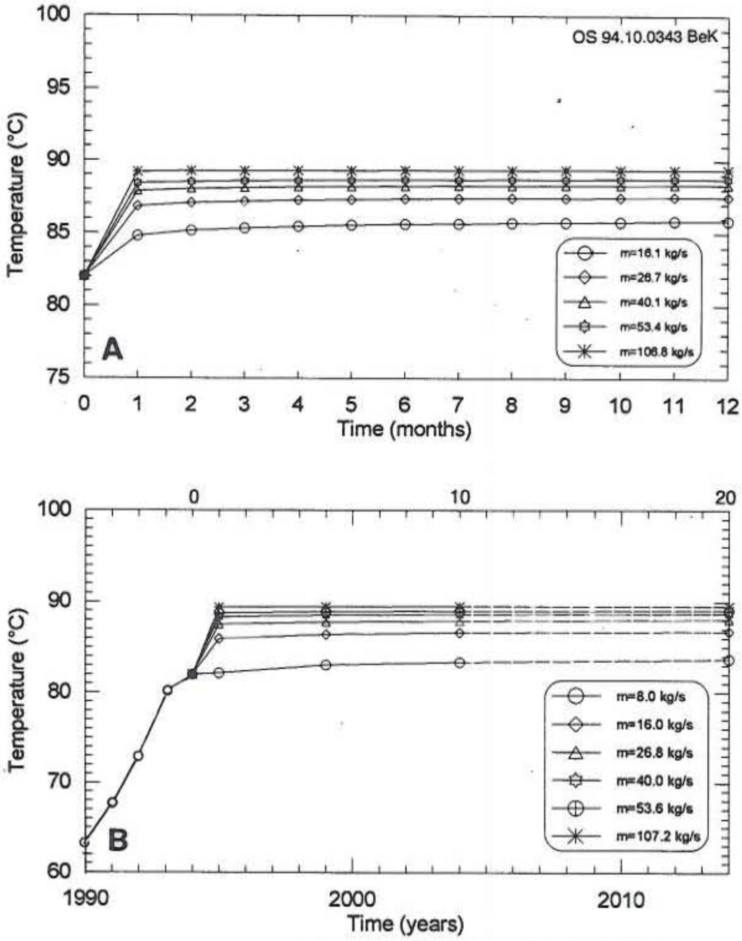

FIGURE 18: The Banska well, prediction of wellhead temperature for variant A; a) during the first year; b) during 20 years

The results of the calculations are shown in Table 7 and Figure 18. After increasing the flowrate, an increase of wellhead temperature can be expected during the first month of production, at least from 82.0 to 84.9°C for a mass flow of 16.1 kg/s and to 89.4°C for a mass flow of 107.2 kg/s. For all flowrate values, the simulation shows the stabilization of wellhead temperature during the next 20 years of production, with a total increase of less than 1°C.

Variant B (optimistic):

Reservoir temperature, T_r = 94°C;
Rock thermal conduct.= 3.5 W/(m°C).

Results of calculations are shown in Table 8 and Figure 19. As in the previous variant, the maximum increase of the wellhead temperature will be observed during the first month after increasing the mass flow from the well, from 82.0, to 83.5°C for the mass flowrate 8 kg/s and to 93.1°C for the mass flowrate 106.8 kg/s. During the next 20 years of production the temperature will stabilize, with the values very close to those reached after the first month.

TABLE 8: The Banska well, prediction of wellhead temperature (°C), variant B

Years	Mass flow (kg/s)					
	8.0	16.1	26.7	40.1	53.4	106.8
1	83.5	88.3	90.5	91.6	92.2	93.1
5	84.2	88.9	90.9	91.9	92.4	93.2
10	84.7	89.2	91.1	92.0	92.5	93.2
20	85.1	89.4	91.2	92.1	92.6	93.3

3.2.6 Petrographic study

The short preliminary petrographic study of the limestones-dolomites forming the main aquifer in the Bialy Dunajec well was done. The observations show that the rocks are crosscut by 2-3 generations of veins. The main mineral assemblages identified in particular generation are as follows: calcite; calcite with dispersed sulphide grains; calcite with pyrite and quartz. The youngest generation of veins might be associated with the present hydrothermal activity. In a thin section from 2000 m depth interstitial quartz was found, placed within calcite veins. It's deposition from hydrothermal fluids is referred at temperatures not lower than 180°C (in Icelandic environment). The next information related to temperature of hydrothermal fluids is supported by the occurrence of dolomite crystals within calcite veins, recognized in thin sections coming from 2370 m. They are most likely connected with the latest phase of diagenesis (or may even have a postdiagenetic origin) and were formed by metasomatism of calcite in the presence of pore fluids with temperature not lower than 120°C (Lorenz, 1984). In some cases the fluid inclusions are found, entrapped in calcite and quartz crystals. However, they are too small to measure the homogeneous temperature. A careful search for fluid inclusions for measuring the homogeneous and melting temperatures is recommended in the future, in order to establish the temperature changes occurring in the geothermal reservoir.

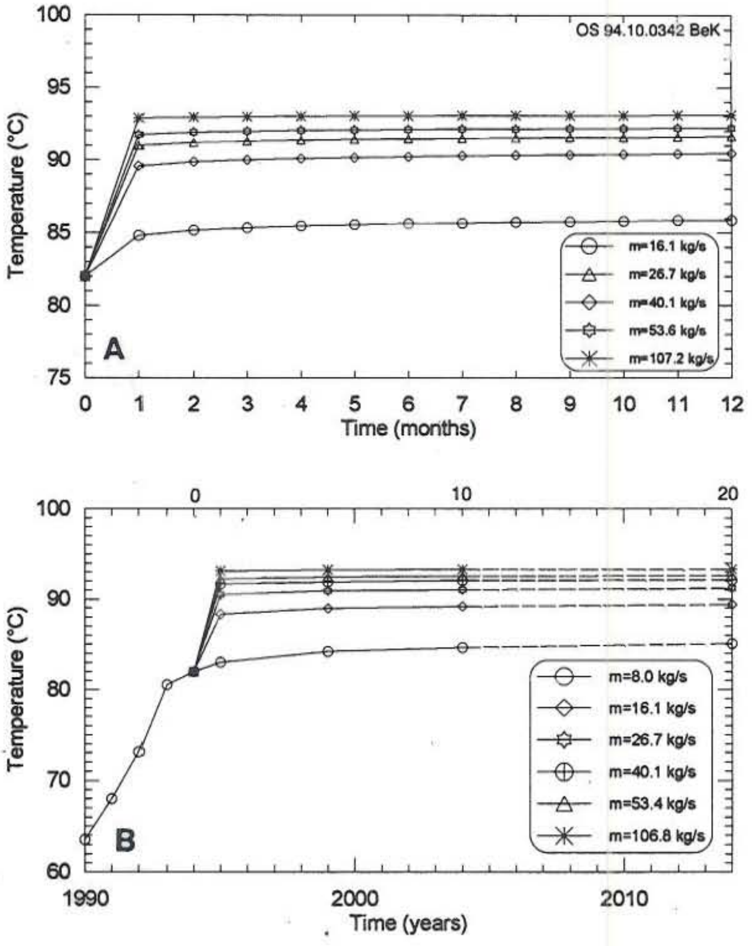

FIGURE 19: The Banska well, prediction of wellhead temperature for variant B; a) during the first year; b) during 20 years

The results of a preliminary petrographic study on the vein mineralogy varrant a more detailed future study. This should include time relations of the veins based on their crosscutting relationship. Also, a search for fluid inclusions should be undertaken and they measured for homogenization and melting temperatures in order to trace temperature and salinity changes of the geothermal fluid with time.

3.2.7 Formation temperature

The results of the simulation (Figures 15-17), the temperature data from the short term well tests (Figure 14, Table 4) and temperature logs recorded after drilling (Figure 14) were used to estimate the initial formation temperature in the surroundings of the wells. The main assumptions were as follows:

1. The equilibrium (or semi-equilibrium) state was present within the formation before drilling;
2. The water entering the wells during short tests represented temperatures of the formation.

The obtained picture, even when treated like an approximation, only allows to make comparison with previous knowledge related to the temperature distribution within the Podhale geothermal field. The formation temperature seems to be higher than prior assumptions, especially close to the main reservoir. The temperature cross-section (Figure 20) shows that higher values can be expected than previously calculated. It is highly probable, that the temperature culminates above or close to faults and fractures, where the up-flow of hotter fluid is expected.

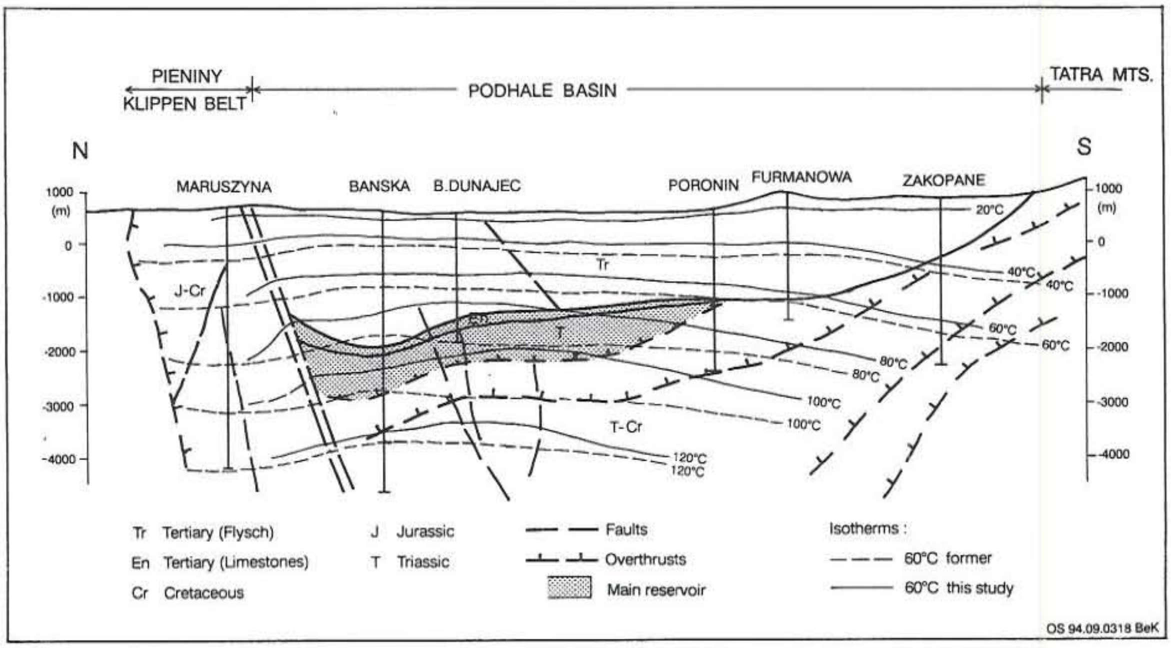

FIGURE 20: Temperature cross-section through the Podhale geothermal field (modified after Sokolowski et al., 1993)

3.3 Conclusions

Results of this study show, that the temperature within the main reservoir in the central, deepest part of the Podhale geothermal field reaches 90-94°C, or up to 8°C higher than previously estimated. These values (higher than results from the thermal gradient) confirm the up-flow of heat from the deepest parts of the Mesozoic basement along faults and fractures and it's emplacement within the reservoir. In particular, this refers to the Bialy Dunajec well, where one can expect reservoir temperatures to be even higher than 89-90°C.

Obtained results can be important for designing and exploiting the geothermal plants planned to be constructed. They allow an increase of the amount of supplied heat and, furthermore, limit the risk connected with expected temperature decline during the predicted time interval.

Further detailed studies of the thermal regime within the Podhale field involve applying a set of complex methods. First of all, the application of bottom hole measurements is suggested in order to estimate the precise reservoir temperature. Subsequently, the mineralogical and geochemical methods appear to be very useful in identifying the hydrothermal conditions of this field.

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NOMENCLATURE

c_r = rock heat capacity (J/(kg°C))
c_w = fluid heat capacity (J/(kg°C))
D = depth to a grid node in the well (m)
g = acceleration of gravity, 9.82 m/s^2
G = mass velocity in the well ($kg/(m^2s)$)
E_t = total energy flux in the well (J/s)
h = fluid enthalpy (J/kg)
k = rock thermal conductivity (W/(m°C))
L_w = total length of the well (m)
m = total mass flow (kg/s)
P = pressure (Pa)
Q = ambient heat losses over an unit distance (W/m)
r_w = well radius (m)
t = time (s)
T_1, T_2 = nodal temperatures along the well (°C)
T_w = fluid temperature inside the well (°C)
T_r = ambient initial temperature (°C)
T_w = mean fluid temperature of the two adjacent nodes (°C)
T_r = mean reservoir temperature of the two adjacent nodes (°C)
T_s = average surface temperature (°C)
u = average fluid velocity (m/s)
z = depth coordinate (m)

α = thermal diffusivity (m^2/s)
γ = Euler's constant, 0.57721...
ρ = rock density (kg/m^3)
Ω = ambient thermal conductance (W/(m°C))

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