



## **ANALYSIS OF TEMPERATURE AND PRESSURE MEASUREMENTS AND PRODUCTION DATA FOR BERLÍN GEOTHERMAL FIELD, EL SALVADOR**

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### **ABSTRACT**

The Berlín geothermal field is one of two geothermal fields in exploitation in El Salvador, located approximately 110 km east of San Salvador, the capital city. Since 1968, thirty-eight wells have been drilled in the field. Sixteen of the wells are productive, nine are connected to the Berlín power plant, two are used as reinjection wells, in order to complete the reinjection capacity, and five wells are waiting to be connected to the third condensing unit. Temperature and pressure logs from the production wells have been analyzed. The main feed zones were identified and formation temperature and initial pressure profiles estimated. The temperature decline in the production wells was analyzed, using the temperatures profiles and considering the connection between the production zone and the reinjection into well TR-12A. Well test data from well TR-4C were analyzed by the semi-logarithmic, Horner plot and type curve methods. The data used for the analysis come from the recovery period (build-up) when the well was shut in after production, and recovery period (fall-off) after injection was stopped, between the 12<sup>th</sup> and 13<sup>th</sup> of May, 2004. Comparable results were obtained using the three methods and a skin factor in the range of +2.5 to +3.2 was estimated. Finally, lumped parameter modelling was applied to study and predict the behaviour of the reservoir pressure during exploitation.

### **1. INTRODUCTION**

El Salvador is located on the southern coast of Central America, where the Cocos plate is subducting underneath the Caribbean plate, forming an east-west tectonic graben. The Berlín geothermal field is one of two fields in exploitation in El Salvador. It is located 110 km east of San Salvador, the capital City, in the District of Usulután, 5 km from Berlín City (Figure 1). The Berlín geothermal field has been under exploitation for electrical energy generation since 1992 when two backpressure units were installed with a total capacity of 10 MWe. It was planned to use wells TR-2 and TR-9 as producers and TR-1 as a reinjection well of the separated water. Due to the limited absorption capacity of well TR-1, it was decided to put only one unit online, using well TR-2 as a producer and well TR-9 as a

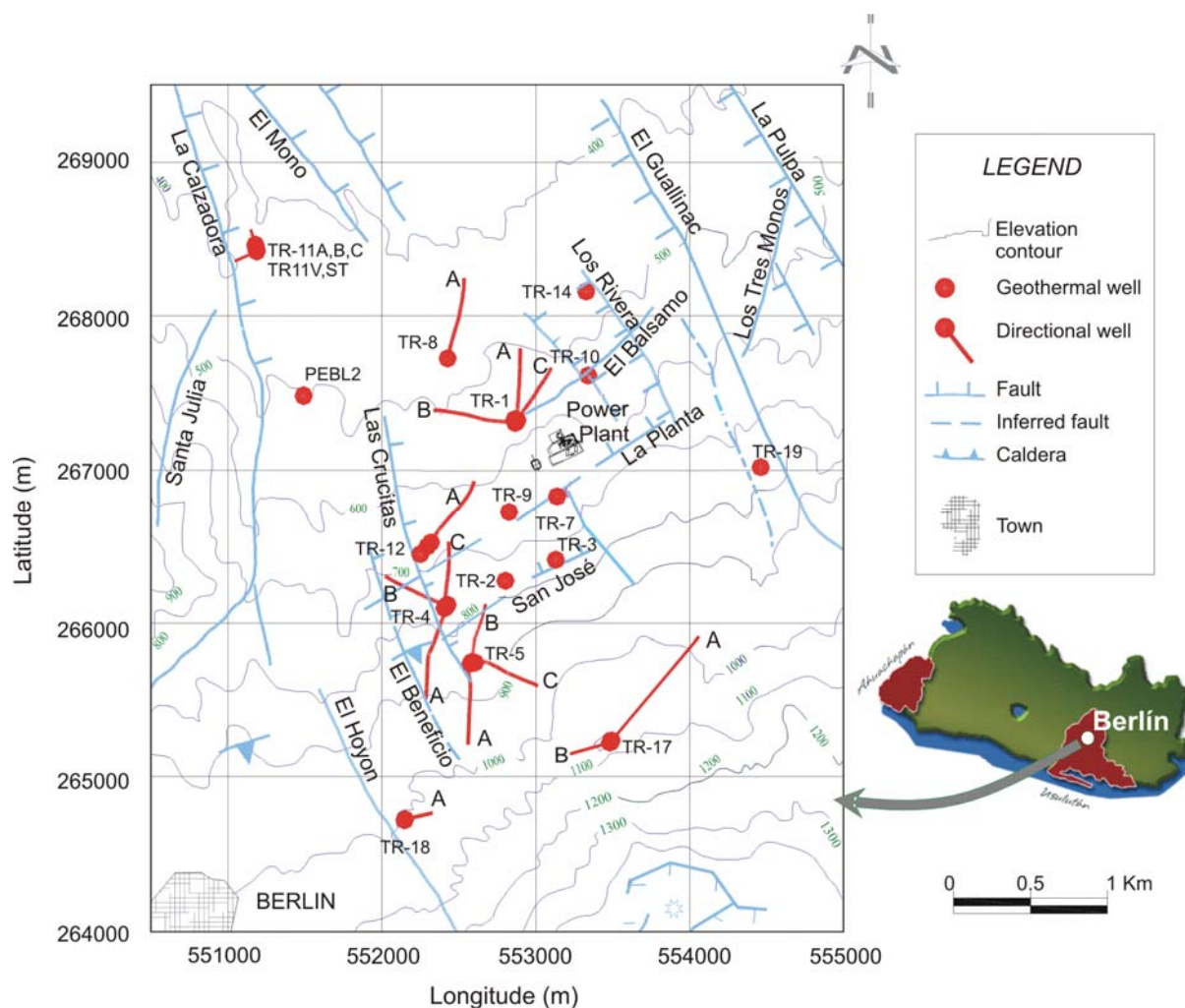


FIGURE 1: Well location in the Berlín geothermal field

reinjection well for a short period of time (Montalvo and Axelsson, 2000). From 1993 to 1995 three deep wells were drilled (TR-8, TR-10 and TR-14) for reinjection purposes, and the two backpressure units were put online in February 1995 with wells TR-2 and TR-9 as producers. The separated water was reinjected into wells TR-1, TR-8, TR-10 and TR-14.

Electroconsult (ELC) in 1993 carried out a feasibility study on installing a condensing power plant in Berlín with a capacity of 50 MWe. The study gave positive results which encouraged further geoscientific investigations and development of the resource. In 1994, Geothermal Energy New Zealand Ltd. (GENZL) conducted geological investigations and a magneto-telluric survey. These studies confirmed the extension of the potential field south of the present production area (Rivas, 2000).

In 1999 the two backpressure units were replaced by two condensing units of 28 MWe each. Unit I started commercial production in April 1999 and Unit II in July the same year. In order to supply the necessary steam, 6 new production wells were drilled and for providing the reinjection capacity 12 more wells were drilled during 1997-1999.

The potential of the Berlín geothermal field was reassessed by GENZL (PB Power, GENZL Division, 2000) with the result that the field was estimated to sustain  $152 \pm 42$  MWe for 25 years. In the year 2000, Geotermica Salvadoreña (GESAL) carried out an additional geoscientific survey in the southern part of the geothermal field in order to assess a possibility of installing the third 28 MWe condensing unit (GESAL, 2000).

At the moment the third condensing unit is being developed with a capacity of 44 MWe. Five production wells have been drilled in order to achieve the steam and 3 new reinjection wells will be drilled for providing the necessary reinjection capacity. Finally, a binary cycle unit is also being developed, with an estimated capacity of 8 MWe. The total installed capacity of electrical generation in Berlín geothermal field is presently 56 MWe but will increase to 108 MWe when the third condensing unit and the binary cycle plant have been commissioned.

This report presents an analysis of temperature and pressure measurements and production data of the Berlín geothermal field, a detailed evaluation of initial temperatures and pressure reservoir, such as a brief analysis of the changes in the temperatures and pressure conditions due to reinjection into the production zone, and also due to exploitation. Hydrological parameters are estimated for well TR-4C by using a well test analysis, and a lumped parameter model was made in order to simulate the observed pressure changes due to production from the field. Lastly, the future performance of the field is predicted for 20 years.

## **2. BERLÍN GEOTHERMAL FIELD**

### **2.1 General information on the Berlín geothermal field**

The Berlín geothermal field is a liquid-dominated system with temperatures in the range of 280-300°C according to measured temperatures in the production wells. The enthalpy varies from 1200 to 1400 kJ/kg, with a steam fraction of 20-30% at 11.5 bar-a separation pressure. The production wells in the Berlín geothermal field have been drilled to a depth between 1000 and 2600 m, and the reinjection wells to a depth of 500-2500 m. The elevation of the Berlín geothermal field ranges between 445 m a.s.l. in the reinjection area (well TR-11) and 1080 m a.s.l. in the production area (well TR-17).

During the 1990's a conceptual model of the Berlín geothermal field was developed. It has been refined over the last years when more information has become available. According to available information, the heat resource is located underneath the Berlín caldera with an upflow coming from the south part of the caldera; the hot fluid flows laterally north/northeast along the graben faults (Figure 2).

### **2.2 Geology**

The Berlín geothermal field is located on the northern flank of the Berlín-Tecapa volcanic complex, inside a system of faults in the southern part of the east-west oriented Central American graben. The Berlín-Tecapa volcanic complex is formed by the caldera of the Berlín strato volcano, and composed of a series of peripheral volcanic cones that expelled andesitic lava and scoria that emerged around the craters in the southeast part of the old Berlín volcano caldera (Correia et al., 1996).

Regionally the most important fault system is oriented NNW-SSE and is responsible for the formation of the Central American graben, as well as the active Quaternary volcanic chain in the country. The Laguna de Alegría, Cerro de Alegría and Cerro Pelón are some of the most recent volcanic edifices; they are aligned along the same course, indicating that this tectonic system is active and does not only exist in the Berlín zone, but in the whole country. All the hydrothermal manifestations in El Salvador are found within the Quaternary volcanic chain located at the southern margin of the Central American graben. The Berlín geothermal field is controlled by a northwest-southeast trending fault system (Figure 1). It is considered the most recent, active and important, because this system permits the ascent of fluid from depth to surface. The majority of the hydrothermal manifestations and the Berlín geothermal field itself are found inside this structure (Renderos, 2002).

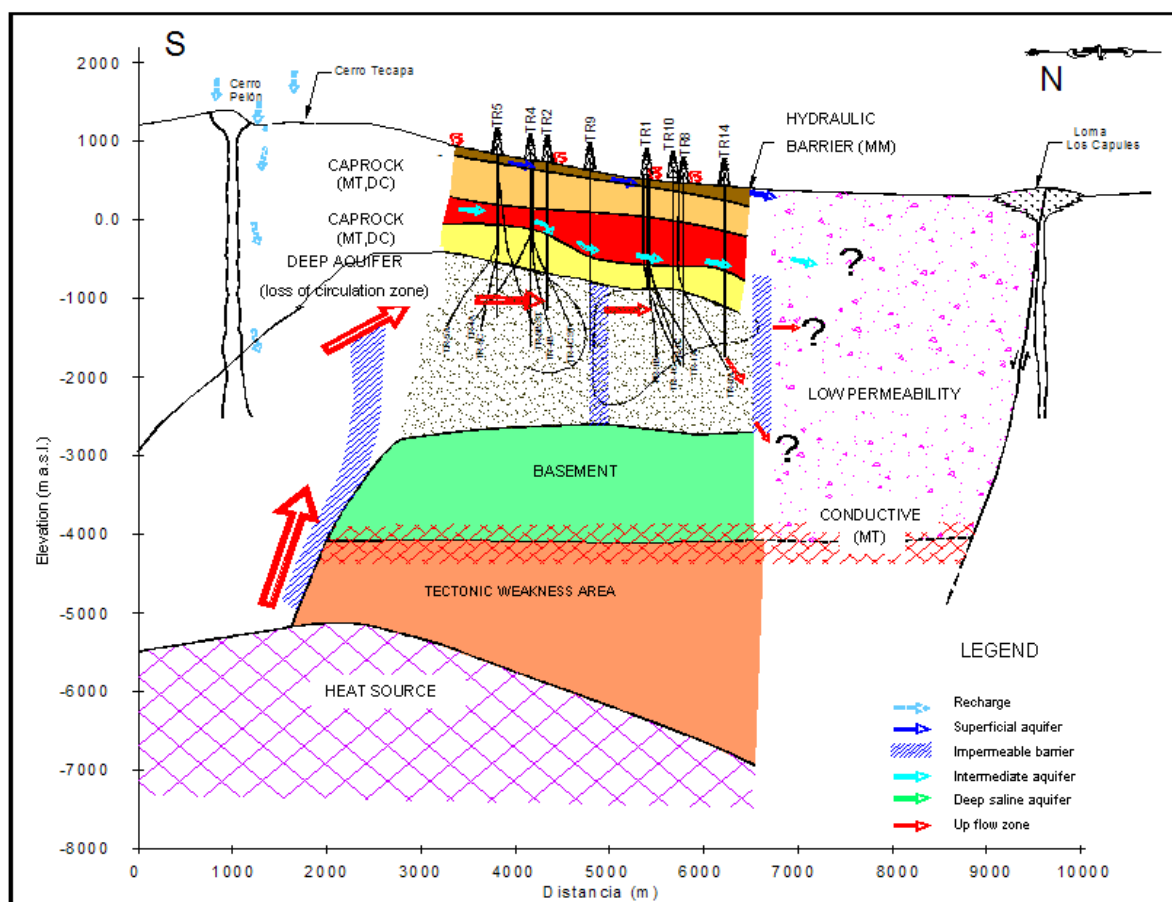


FIGURE 2: Conceptual model for Berlín geothermal field

### 2.3 Hydrothermal alteration

The intensity of hydrothermal alteration is affected by many factors such as permeability, temperature, rock type, pressure and fluid composition, all critical factors in the alteration processes. The hydrothermal alteration in Berlín geothermal field is characterised by a mixture of secondary minerals (Table 1). The presence of pyrite and zeolites is associated with permeable zones at temperatures between 150 and 220°C. At the reservoir level, there is a good relationship between pyrite and epidote. These minerals are associated with the permeable zone at high temperatures (230-260°C).

TABLE 1: Secondary minerals identified in the Berlín geothermal field (Santos, 1995)

Group	Secondary minerals
Silica	Quartz, chalcedony and opal
Chlorites	Clinochlor, prochlorite and penninite
Carbonates	Calcite
Calc-silicates	Zeolites, epidote and micas
Oxides	Magnetite and hematite
Sulphides	Pyrite

### 2.4 Geochemistry

The composition of geothermal fluid depends on many factors, the most important being temperature dependent reactions between host rock and water. However, processes of mixing, boiling and cooling

usually have a significant influence on the final composition of a geothermal fluid. The Berlín geothermal field is a liquid-dominated geothermal field with temperatures ranging from 280 to 300°C. The fluids discharged from the Berlín reservoir are classified as sodium-chloride type with chloride content rising from 3000 to 7000 ppm, pH values between 5 and 8 and TDS between 7000 and 20,000 ppm. The gas/steam ratio is usually 0.1-0.3% in steam at 12 bar-a wellhead pressure from the wells.

In the Berlín geothermal field three types of aquifers have been identified using the chemical data: (1) a low-salinity aquifer of 1600 ppm at a depth between 200 and 300 m a.s.l.; (2) an intermediate-salinity aquifer with a salinity of 6600 ppm at sea level; (3) a deeper saline aquifer with a salinity between 8000 and 12,000 ppm at a depth of -800 to -1200 m a.s.l. (Santos, 1995).

### **3. TEMPERATURE AND PRESSURE CONDITIONS IN BERLÍN GEOTHERMAL FIELD**

#### **3.1 General information on wells**

Geothermal exploration in Berlín started in the 1960's. The first deep exploratory well was drilled in 1968 to a depth of 1458 m and found temperatures close to 230°C at 1350 m. This well is located in the northern sector of the field. However, the well was not productive as it did not intersect any permeable zones. The drilling in Berlín continued from 1978 to 1981. Five additional wells were drilled to depths between 2000 and 2380 m (TR-2, TR-3, TR-4, TR-5, and TR-9). All the wells turned out to be good producers with temperatures close to 300°C, except TR-4 due to completion problems.

In the first stage of development at the Berlín geothermal field in 1992, two backpressure units were installed. Wells TR-2 and TR-9 were used as producers, and the separated water was reinjected into well TR-1. Between 1993 and 1995, three deep reinjection wells TR-8, TR-10 and TR-14 were drilled, located in the NNW-SSE trending graben 1-2 km north of the production wells. The wells encountered temperatures in the range of 240-270°C, and acceptable permeability.

In the second stage from 1997 to 1999, 18 more wells were drilled. Most of them were deviated, with an average depth of 2300 m (production wells) to 2500 m (reinjection wells). Of these, 6 wells have been used as production wells and 9 as reinjection wells for the two condensing units that went online in 1999. Three wells did not intersect any permeable zones. The next development of the Berlín geothermal field began in 2004 when it was decided to install the third condensation unit. Five new production wells have been drilled in order to achieve the steam requirements and 2-3 wells are planned for reinjection of the separated water. General information on the wells drilled in the Berlín geothermal field is shown in Appendix I. Figure 1 shows the location of wells in the area.

#### **3.2 Interpretation of temperature logs and location of feed zones**

Temperature logs are a set of temperature values recorded at different depths down a borehole. The logs can give information on temperature conditions, flow paths and feed-zones of the reservoir penetrated by the well. Caution must, however, be used when interpreting logs as measurements are not made directly in the reservoir but in the well where internal flows and boiling can cause disturbances and give misleading results, even though the well is shut-in. When a well is not flowing, the aquifers (feed zones) usually warm up more slowly after drilling, than impermeable rock, (Stefánsson and Steingrímsson, 1990).

In the Berlín geothermal field, several temperature logs have been taken during drilling, well completion and production. Information about the temperature logs from fifteen production wells were collected from various integrated test reports. The aim of this section is to interpret the temperature logs and locate the main feed zones in each well, as well as their respective temperatures.

**Well TR-2:** Vertical well, drilled to a depth of 1903 m and completed in June 1978. Figure 3 shows several temperature logs carried out during the last 20 years. The main feed zones are located between 1752 and 1852 m depth, with a temperature close to 300°C and an initial pressure close to 118 bar-g at 1752 m depth. The pressure data is shown in Table 1 in Appendix III. The initial production yield of this well was close to 90 kg/s at 1350 kJ/kg enthalpy at 10 bar-a wellhead pressure (Monterrosa, 1993). The production capacity of this well is presently close to 60 kg/s at 12 bar-a wellhead pressure, with a temperature close to 295°C. This well was connected to the condensing unit in June, 1999.

**Well TR-4:** Vertical well TR-4 was drilled in 1980 in the south part of the field to 2379 m depth, with the primary objective of increasing the steam availability from the field. This well was worked-over between August and September of 1998 due to a casing collapse detected at 110 m depth in the 9 5/8" production casing. The damage was caused by an poor cementation job at that point. After work-over the total depth recorded in the well was 2150 m.

Figure 4 shows several thermal recovery logs. The main feed zones are seen at 2017 m depth, with a temperature close to 295°C. The hydrostatic water level at shut-in conditions is located at 425 m depth. This well was utilized for reinjection of all the separated water from well TR-5, during the production test. Currently, it is utilized for reservoir pressure monitoring and will eventually be put to production when more steam is required.

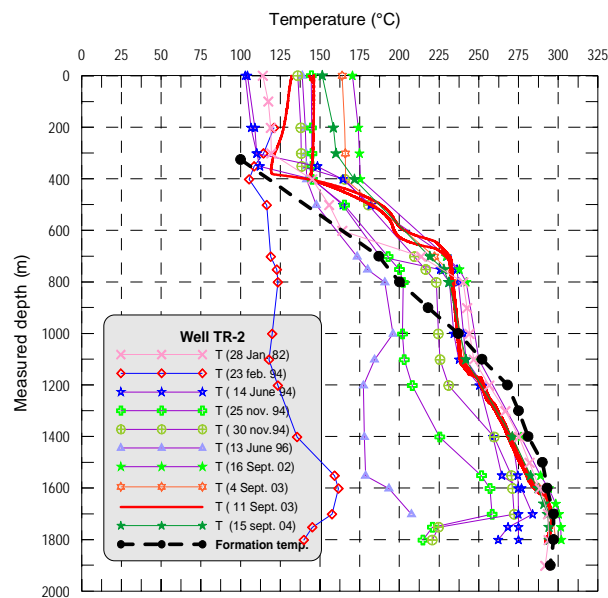


FIGURE 3: Temperature profiles  
in well TR-2

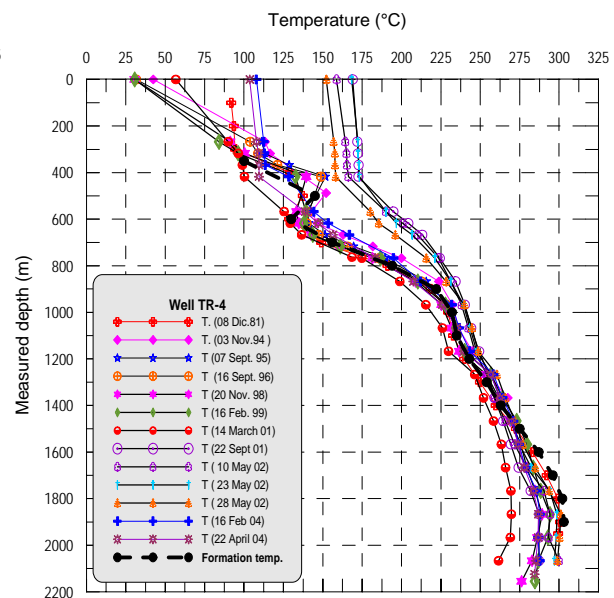


FIGURE 4: Temperature profiles  
in well TR-4

**Well TR-4A:** Directional well with an inclination angle of 30°, directed to S-04-W. This well is one of three wells drilled at the platform of TR-4. It has a total measured depth of 2157 m, but the temperature and pressure logging are recorded only to 2000 m depth. The temperature logs obtained during the thermal recovery show that the main feed zones are located between 1700 and 1925 m depth. The water level at shut-in conditions is located at 400 m depth. Figure 5 shows temperature logs in the well. Inversion temperature is observed below the feed zone. This condition is characteristic for wells with lateral flow. This well is utilized for reinjection, because the production characteristics were not considered good enough for production due to problems with the completion.

**Well TR-4B:** Directional well with an inclination angle of 25°, directed to N-56-W. Total measured depth is 2292 m. Figure 6 shows the temperature data from the well, collected during the warm-up period and under production conditions. The main feed zone is located between 2000 and 2150 m depth and the maximum temperature measured in this well is 291°C near the feed zone. The water



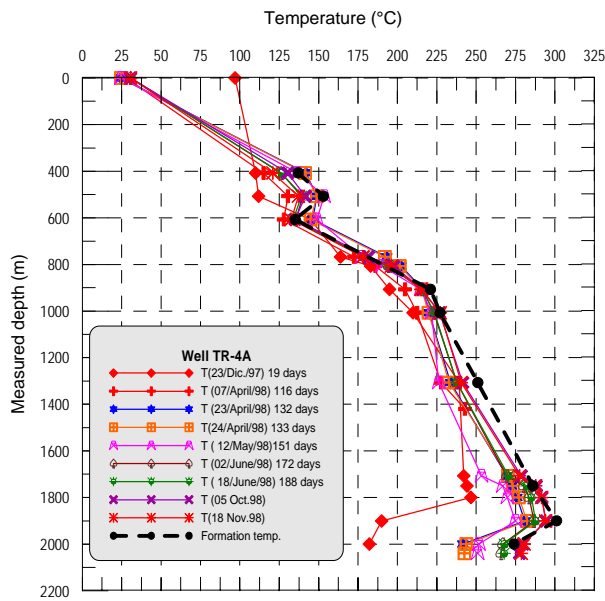


FIGURE 5: Temperature profiles  
in well TR-4A

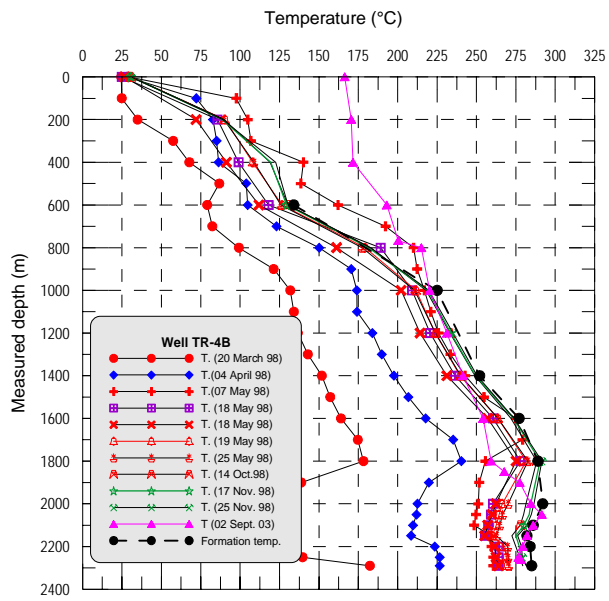


FIGURE 6: Temperature profiles  
in well TR-4B

level after shut-in is at 450 m depth. A convective zone is possibly identified from 1800 m depth to the bottom of the hole. This well was chemically stimulated in December 2001 with a very good results, showing improved production characteristics. The production potential is 54 kg/s, at an enthalpy of 1330 kJ/kg and a steam fraction of 29% at 13 bar-a wellhead pressure.

*Well TR-4C:* Directional well with an inclination angle of 22°, directed to N-05-W and a total measured depth of 2179 m. Figure 7 shows the temperature data from well TR-4C. The main feed zone is located between 2000 and 2100 m depth, and the maximum temperature measured in the well is 287°C at the feed zone. The water level after shut-in is at around 475 m depth. The well was chemically stimulated in March 2004, with very good success. It showed improved production conditions as well TR-4B. The production capacity at 13 bar-a wellhead pressure is close to 61 kg/s, the enthalpy is about 1330 kJ/kg and the steam fraction 26%.

*Well TR-5:* Vertical well, drilled to a depth of 2086 m and completed in July 1981. Figure 8 shows the temperature logs recorded in this well. The main feed zone is located between 1753 and 1953 m depth. The maximum temperature measured is close to 300°C at 2003 m depth (Monterrosa, 1993). This well was connected to the power plant in June of 1999. The initial production was close to 63 kg/s, the enthalpy 1400 kJ/kg and the steam fraction 32%, at 11 bar-a wellhead pressure. The production capacity of the well is probably close to 25 kg/s, the enthalpy at 1280 kJ/kg, at 12 bar-a wellhead pressure, with a steam fraction of 16%.

*Well TR-5A:* This well was drilled on the same platform as well TR-5. It is a directional well with an inclination angle of 32°, directed to S-03-W. The kick-off point is at 974 m depth. The well was drilled to a total depth of 2321 m. The well was repaired due to an obstruction close to the liner hanger, and at the same time the well was chemically stimulated with the aim of improving the production rate. After repairs it was possible to run logging tools to the bottom of the well and measure recovery temperature and pressure profiles. Temperature logs are shown in Figure 9.

During drilling the main permeability was found between 2001 and 2151 m depth. The formation temperature of the feed zone is close to 298°C. The measured pressure in the main feed zone is about 122 bar-a. The production capacity of the well is close to 104 kg/s, with an enthalpy of 1250 kJ/kg and a steam fraction of 21%, at 12 bar-a wellhead pressure. This well shows a negative temperature gradient near the bottom, which indicates horizontal flow in the reservoir.

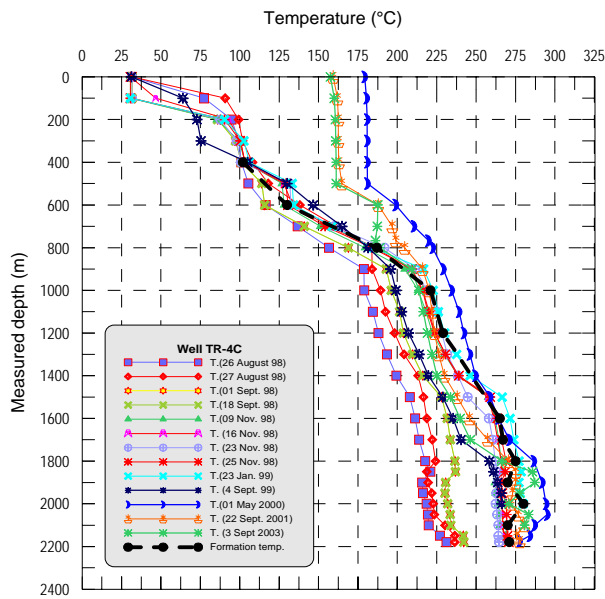


FIGURE 7: Temperature profiles  
in well TR-4C

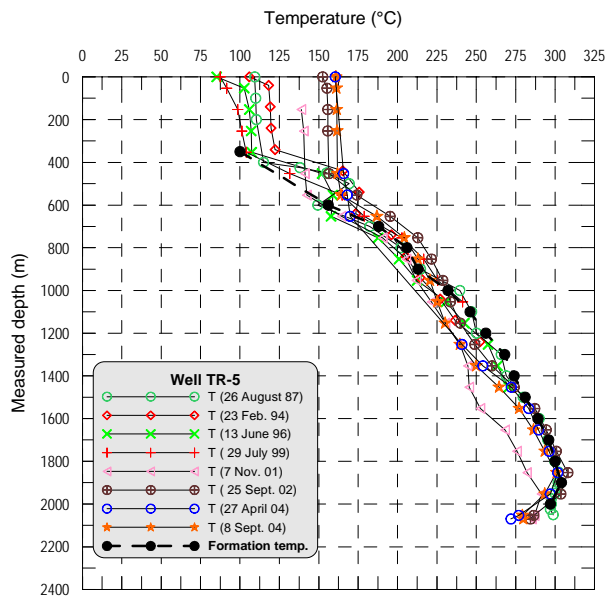


FIGURE 8: Temperature profiles  
in well TR-5

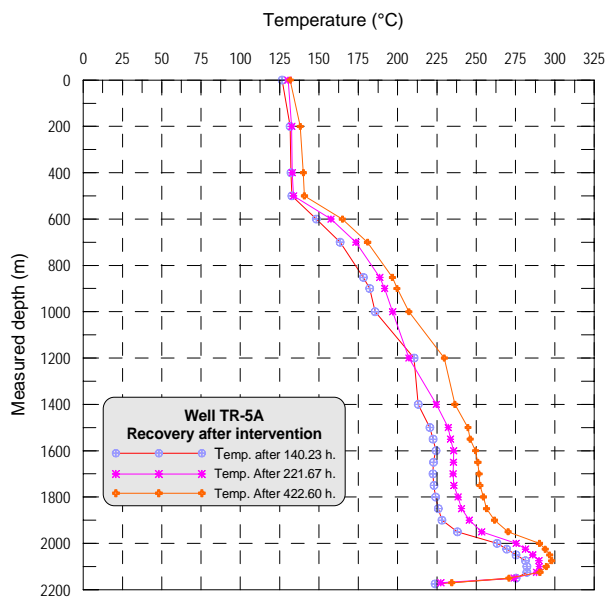


FIGURE 9: Temperature profiles  
in well TR-5A

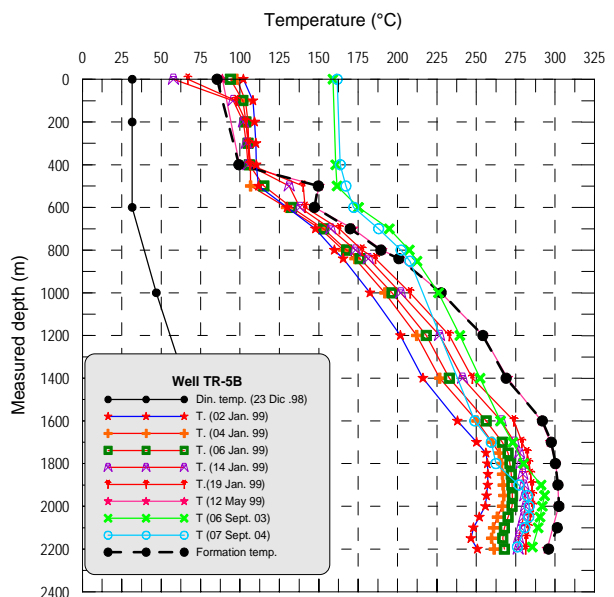


FIGURE 10: Temperature profiles  
in well TR-5B

*Well TR-5B*: Directional well with an inclination angle of  $16^\circ$ , directed to N-17-E. The kick-off point is at 1155 m depth. The total measured depth is 2208 m. Temperature profiles during the warm-up period might indicate a convective system below 1700 m depth. The main feed zone is located between 2150 m depth and the bottom. The temperature in the feedzone is close to  $300^\circ\text{C}$ . The water level after shut-in is located close to 480 m depth. This well shows an inversion temperature behaviour near bottom, similar to well TR-5A. This condition might indicate a lateral or filled path in the reservoir close to the well. Figure 10 shows the temperature profiles during the warm up period and after the start of exploitation. The production capacity of this well is about 38 kg/s with an enthalpy of 1300 kJ/kg and a steam fraction of 26%, at 12 bar-a wellhead pressure.



**Well TR-5C:** This was the third well drilled on the platform TR-5. It was drilled down to 2336 m depth in 1998. During the drilling and the warm-up period the main feed zone was identified between 2001 and 2331 m depth, with a maximum temperature close to 300°C (Figure 11). It is a directional well with an inclination angle of 25°, directed to S-70-E. The kick-off point is at 933 m depth. This well was repaired between June and July of 1999 due to leakage on the 9 5/8" production casing. The leakage was located between 225 and 240 m depth.

The initial production capacity of the well was estimated as 35 kg/s at 11 bar-a wellhead pressure, with an enthalpy of 1375 kJ/kg and a steam fraction of 28%. The well was chemically stimulated in September 2001. It showed improved production to 85 kg/s, with an enthalpy of 1280 kJ/kg and a steam fraction of 24% at 12 bar-a wellhead pressure. The well also shows a small inversion near the bottom. The behaviour is similar to wells TR-5A, TR-5B, and TR-5, indicating that the wells are drilled into a system with lateral flow paths.

**Well TR-9:** Figure 12 shows temperature logs recorded in the well. The main feed zone is located between 1549 and 1849 m depth. The maximum temperature is 290°C at 1649 m depth. This well was used as a reinjection well from February 1992 to May 1993, which resulted in some reservoir cooling by the injected fluid at the temperature 180°C (Monterrosa, 1993). The temperature logs recorded after reinjection was stopped show a cooling of 30°C at 1649 m depth. After production started, the well has been recovering thermally, but the measured temperatures are still below the initial temperature measured in the well.

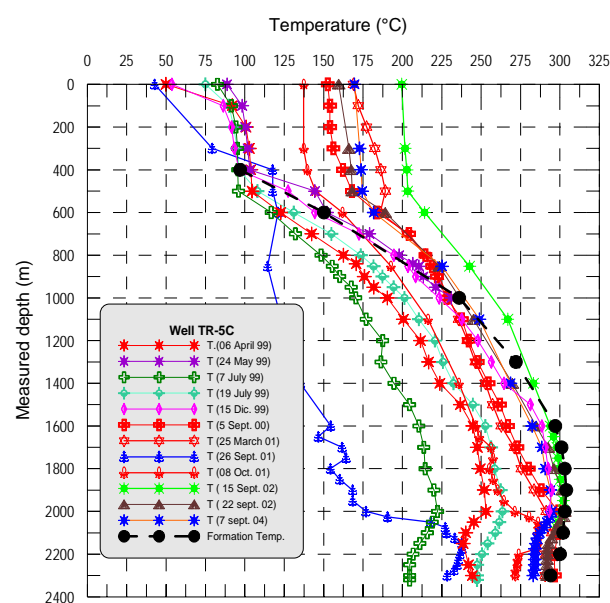


FIGURE 11: Temperature profiles  
in well TR-5C

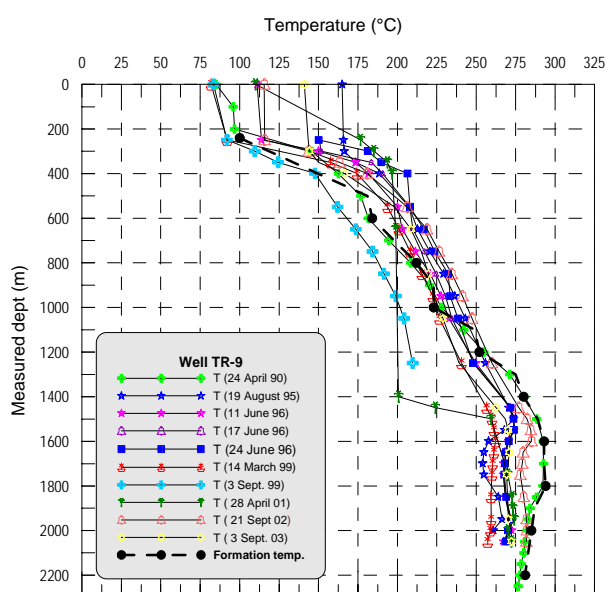


FIGURE 12: Temperature profiles  
in well TR-9

**Wells TR-17, TR-17A and TR-17B:** These wells were drilled to supply steam for the third condensation unit project in Berlín. The platform is located in the southern part of the field at an elevation of 1080 m a.s.l. The more important findings during the drilling of these wells and other relevant information are presented in Appendix I. These wells have not yet been connected to the steam gathering-system.

**Well TR-17:** Was drilled as a production well in the southern part of the field. It was completed in December 2003 to a total depth of 2600 m. The temperature logs recorded during and after drilling are shown in Figure 13. They show that the main feed zones are located at 1375, 2000, and 2400 m depths.

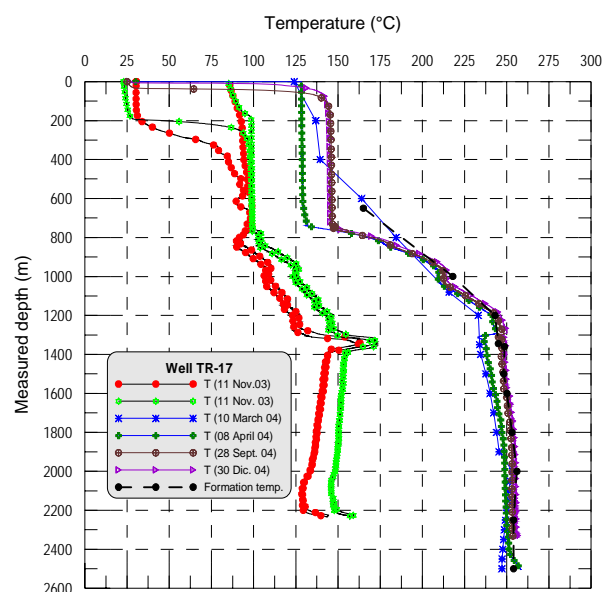


FIGURE 13: Temperature profiles  
in well TR-17

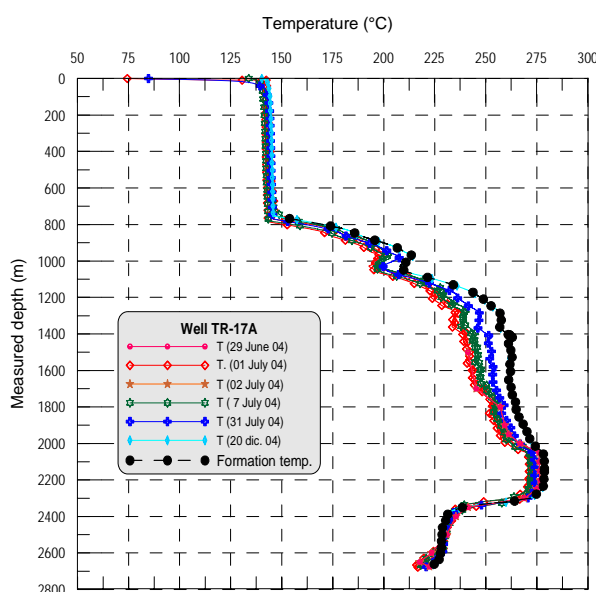


FIGURE 14: Temperature profiles  
in well TR-17A

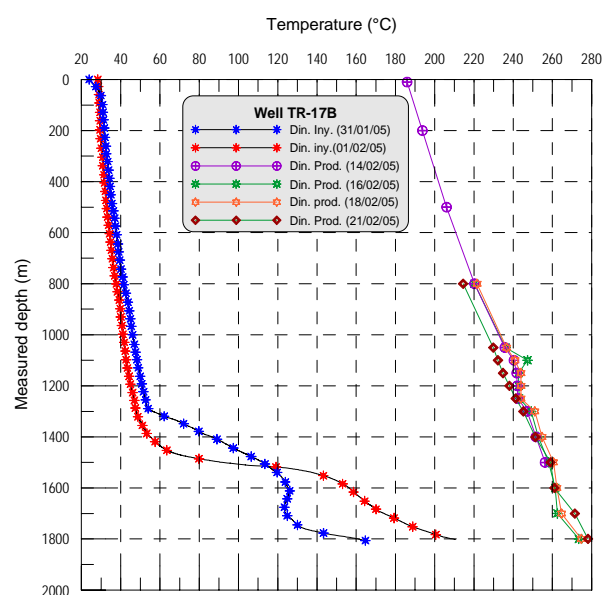


FIGURE 15: Temperature profiles  
in well TR-17B

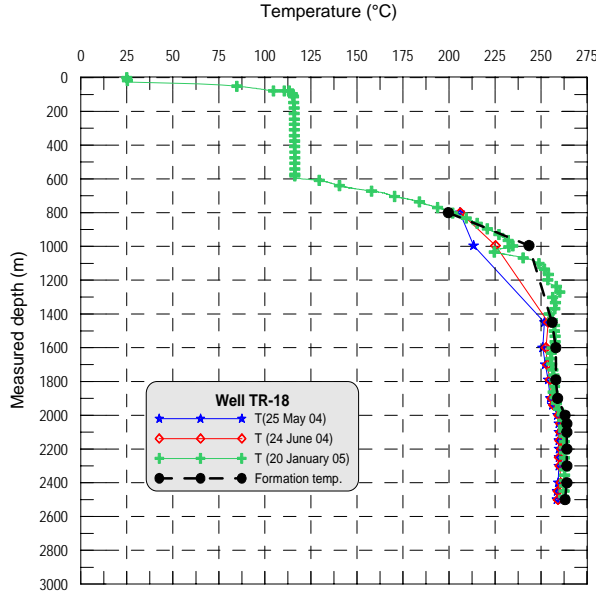


FIGURE 16: Temperature profiles  
in well TR-18

*Well TR-17A:* Directional well, directed towards N-40-E with an inclination angle of  $28.75^\circ$ . It was completed in June 2004 to a total depth of 2690 m. The temperature logs recorded during drilling and warm-ups are shown in Figure 14. They show that the main feed zone is located between 2050 and 2350 m depths, with a temperature close to  $280^\circ\text{C}$ . A second feed zone is located from 2550 m depth to the bottom with a temperature close to  $230^\circ\text{C}$ . This temperature reversal indicates that the well has been drilled through the main reservoir.

*Well TR-17B:* Drilled from December 2004 to January 2005 to a total depth of 1845 m. This well is directional, with an inclination angle of  $21.75^\circ$ . The kick-off point is at 1115 m depth. Figure 15 shows the temperature logs in dynamic condition during injection and well discharge. The main feed zone in this well is located between 1545 m depth and the bottom.

*Well TR-18:* Vertical well, which was drilled from September 2003 to February 2004 to a total depth of 2660 m. The temperature logs after drilling and during the warm up period (Figure 16) show that

the temperature in the feed zone at 1900 m is close to 265°C.

*Well TR-18A*: Directional well, directed to N-17-E with an inclination angle of 21.75°. It was completed in July 2004 to a depth of 1085 m. The kick-off point is at 621 m depth. Only one temperature and pressure log were recorded after drilling, due to completion problems. On the basis of the temperature and the pressure profile (Figure 17) and the circulation losses during drilling, it is determined that the feed zones are located below 1000 m depth.

### 3.3 Estimation of formation temperatures in wells

Formation temperatures serve as a base for a conceptual model of a geothermal reservoir but are also important in making decisions upon well completion. However, due to cooling by circulation fluid during drilling, it is not possible to measure the formation temperature directly during drilling. Even if months or years have passed, boiling or convection may occur in the well, hiding the formation temperature.

A computer software program, BERGHITI, has been developed at Orkustofnun (Helgason, 1993). It is used for post-drilling thermal recovery analysis of wells and for the estimation of formation temperatures. It offers two methods of calculation: the Albright method and the Horner plot method.

The *Albright method* is used for direct determination of bottom-hole formation temperatures during economically acceptable interruptions in the drilling operation. This method assumes an arbitrary time interval, shorter than the total recovery time that the temperature relaxation depends only on the difference between the borehole temperatures and formation temperature. This method is commonly applied to warm-up time series shorter than 24 hours.

The *Horner plot method* is a simple analytical technique for analyzing maximum bottom hole temperatures to determine the formation temperature. The basic criterion for the technique is the straight line relationship between the maximum bottom hole temperature,  $T$ , and the logarithm of relative time,  $\tau$ , given by

$$\tau = \frac{\Delta t}{\Delta t + t_0} \quad (1)$$

where  $\Delta t$  = The time passed since circulation stopped;  
 $t_0$  = The circulation time.

It is evident that  $\lim_{\Delta t \rightarrow \infty} \ln(\tau) = 0$ . Using this and the fact that the system must have stabilised after infinite time, a plot of down-hole temperatures as a function of  $\ln(\tau)$  yields a straight line. Extrapolating the line to  $\ln(\tau) = 0$ , we are able to estimate the formation temperature. Note that this method is only valid for wells with no internal flow, thus applying only to conductive warmup.

When the Horner method is not applicable, the formation temperature has to be estimated from temperature logs during and after drilling. There, the bottom hole temperature (BHT) is the most reliable. This is because the bottom of the well, at the time of each measurement, has undergone less

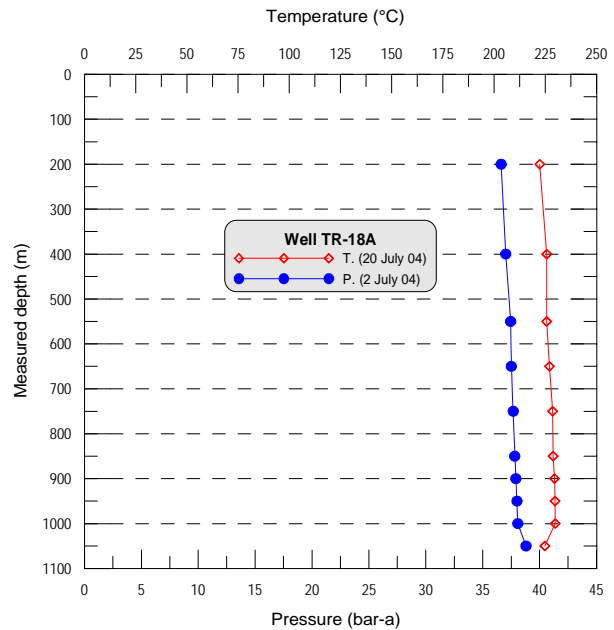


FIGURE 17: Temperature profiles in well TR-18A

cooling than any part of the well above. Therefore, it gives a temperature close to the formation temperature, but usually slightly lower. Sometimes a segment of the log can, in addition, be assumed to be close to formation temperature.

In some wells in the Berlín geothermal field, temperature equilibrium was clearly achieved during the warm-up period. In such cases the last temperature log is assumed to show the formation temperature. The Horner method was applied systematically to the downhole temperature data collected from Berlín geothermal field. Figure 18 shows the estimated formation temperatures from all production wells, and Figure 19 shows an example of an excellent fit of a semi-log straight line relationship during warmup in well TR-4A at 1900 m depth.

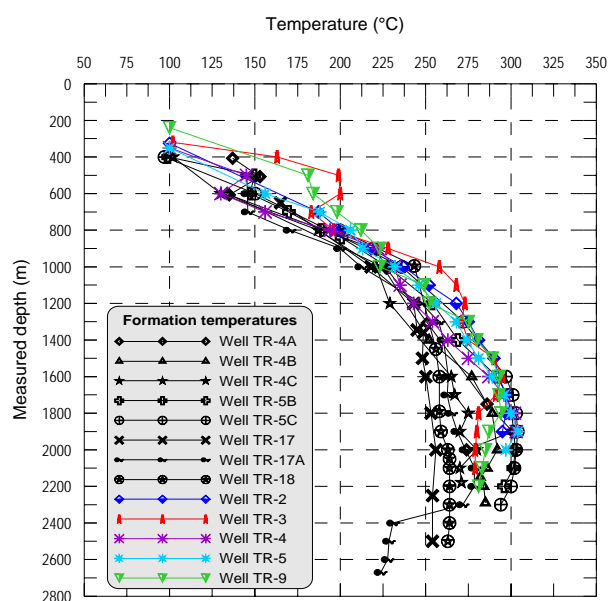


FIGURE 18: Estimated formation temperatures in Berlín wells

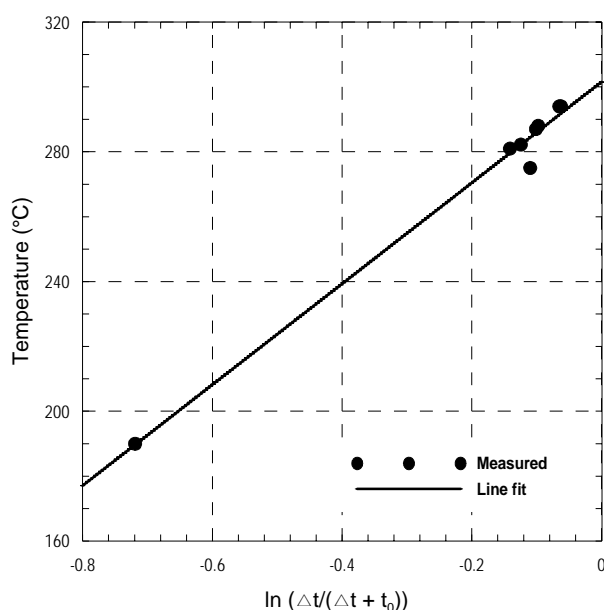


FIGURE 19: Formation temperature at 1900 m in well TR-4A

### 3.4 Estimation of initial reservoir pressure

The pressure logs obtained during the completion test and recovery period for some wells in Berlín geothermal field are shown in Appendix II. The figures also show the pivot point and the initial pressure for each well. This is in good agreement with the location of the main feed zone in the wells according to temperature logs analyzed.

The initial reservoir pressure was calculated by the PREDYP program. The program calculates pressure in a static water column, if the temperature of the column is known (Björnsson, 1993). Water levels were adjusted in the calculation until the calculated profile matched the pivot point pressure. Figure 20 shows the initial pressures in Berlín wells.

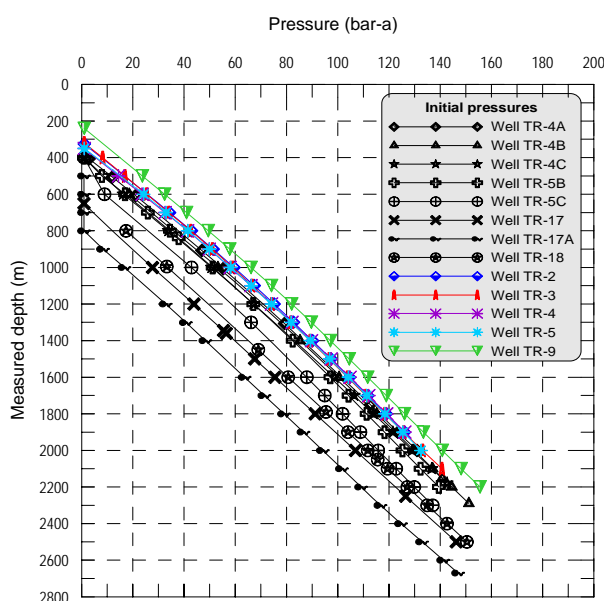


FIGURE 20: Estimated initial pressure in Berlín wells

Table 1 in Appendix III, shows the estimated formation temperature and initial reservoir pressures in the Berlín geothermal wells drilled before 1993 (Monterrosa, 1993). Table 2 in Appendix III shows the results of this analysis.

### 3.5 Initial temperature and pressure distribution

Figures 21 and 22 show the estimated formation temperature and initial pressure distribution at -1000 m a.s.l. and Figures 23 and 24 show two temperature cross-sections through the well field from south to north.

Both the temperature and pressure contours in Figures 21 and 22 indicate a flow of geothermal fluid from southwest to the north or northeast. The temperature contours show that the geothermal fluid changes direction to the northwest, oriented to the main reinjection area and well TR-1.

The temperature cross-sections in Figures 23 and 24 show a lateral flow from southwest to northeast, and a change in direction is observed towards the northwest part of the field. The lateral flow was identified in the temperatures profiles while a reversed temperature was observed below the main feed zones in the production wells.

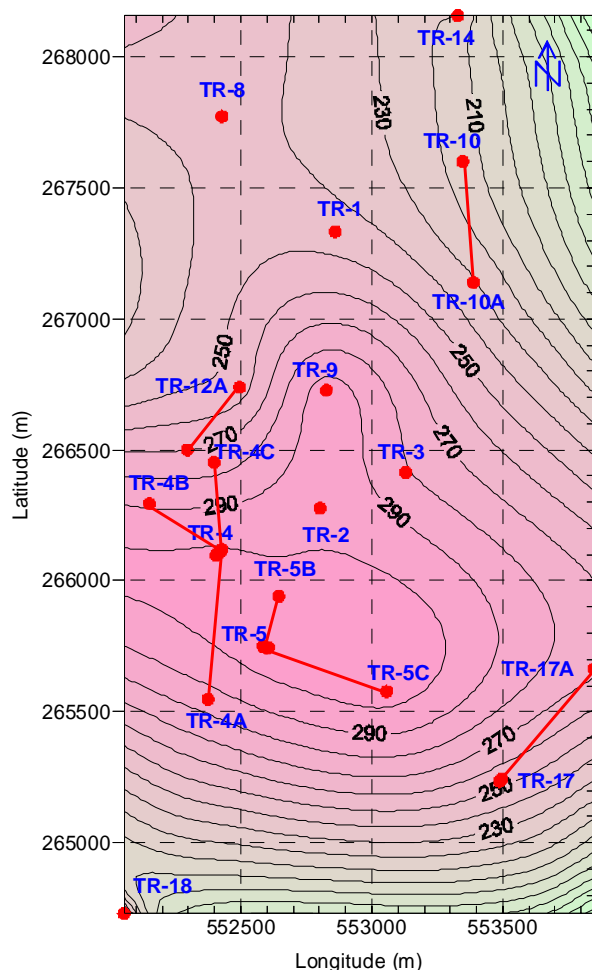


FIGURE 21: Formation temperature contours at -1000 m a.s.l. in the Berlín geothermal field

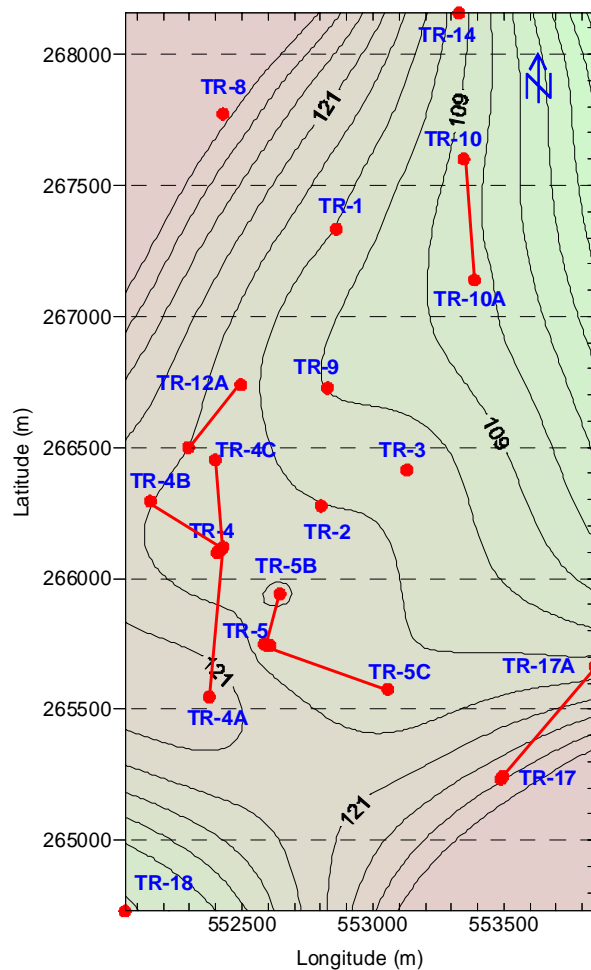


FIGURE 22: Initial pressure contours at -1000 m a.s.l. in the Berlín geothermal field

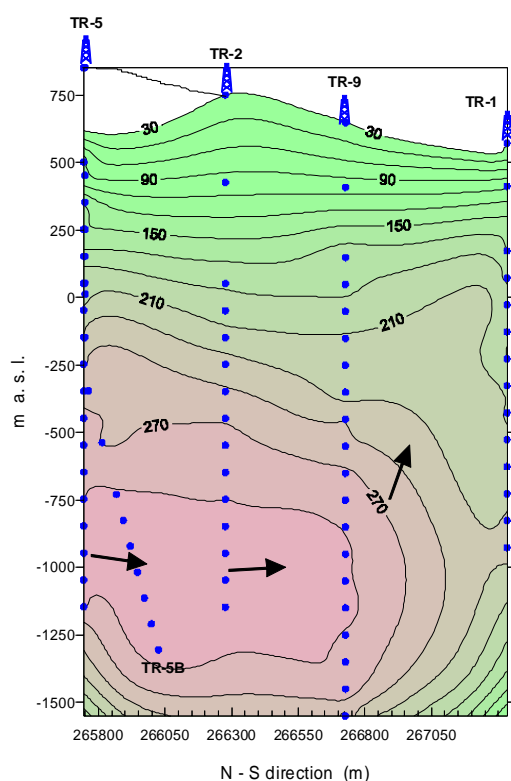


FIGURE 23: A N-S temperature cross-section through wells TR-5, TR-5B, TR-2, TR-9 and TR-1

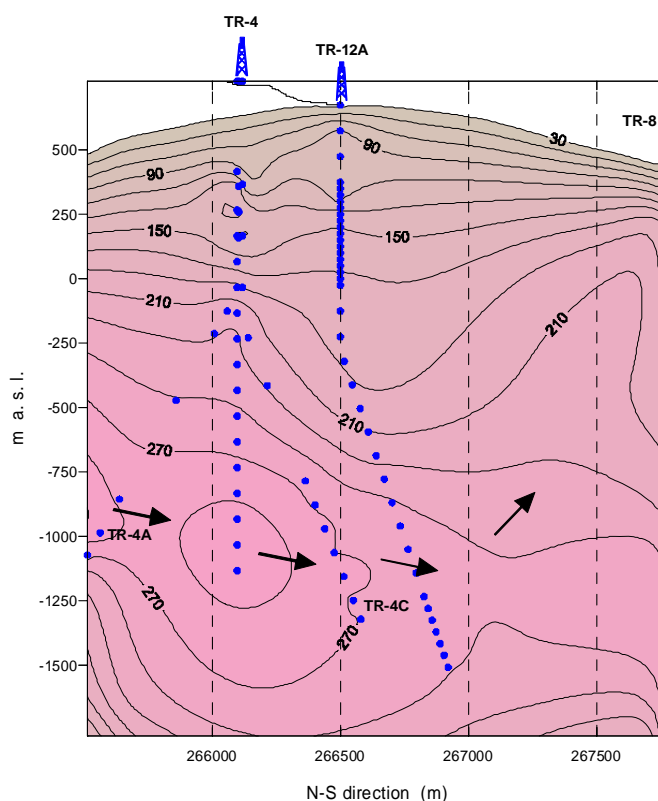


FIGURE 24: A N-S temperature cross-section through wells TR-4A, TR-4, TR-4C, TR-12A and TR-8

## 4. TEMPERATURE AND PRESSURE CHANGES SINCE START OF PRODUCTION

The temperature and pressure changes in the Berlín geothermal field are described in this chapter. The changes are the results of field exploitation since 1992. The temperature changes are mainly results of pressure drawdown, however, reinjection seems to have caused temperature decline in some production wells, mainly due to reinjection into the production zone. The pressure changes in the Berlín geothermal field are associated with different production scenarios during the 13 years of exploitation.

### 4.1 Pressure changes

After 13 years of exploitation in the Berlín geothermal field the drawdown in the reservoir pressure is evident. During the first year of exploitation, when two back-pressure units were in operation, the reservoir pressure was close to 40 bar-g at sea level, with a mass extraction close to 78 kg/s. During that year well TR-2 was used as production well and TR-9 as a reinjection well.

Figure 25 shows the total production and reinjection rates in the Berlín geothermal field and the resulting reservoir pressure decline at sea level from 1992 to 2005. The figure shows the increased production and reinjection rates when the two condensing units started operations in 1999. The total extraction rate was then increased from about 130 kg/s to approximately 430 kg/s. This seems to have resulted in a 12 bar reservoir pressure drop, according to observed pressure in the monitoring wells TR-4 and TR-5.



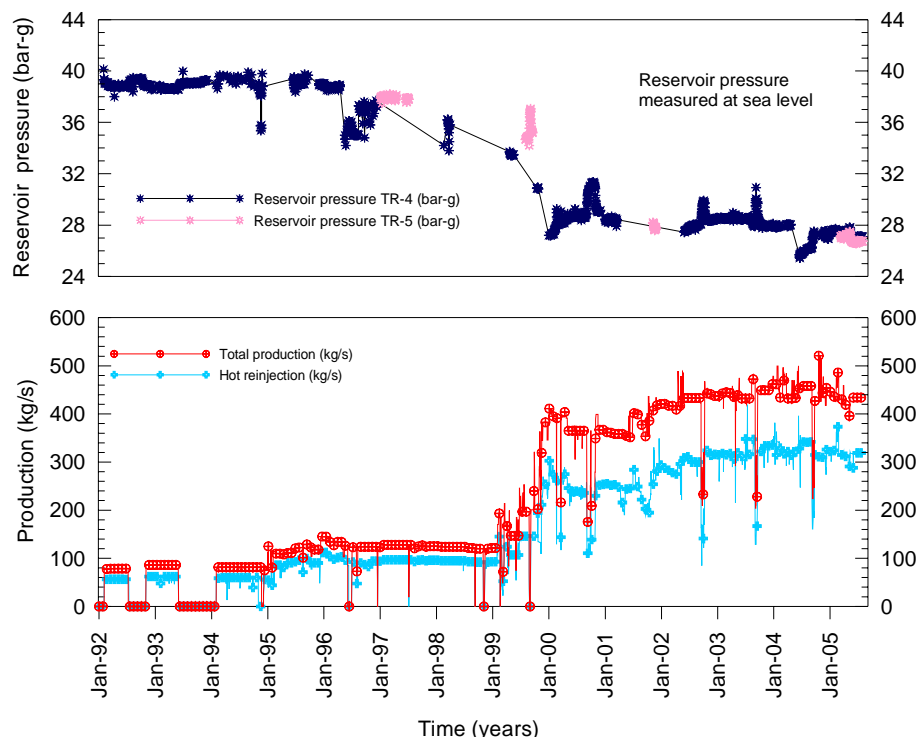


FIGURE 25: Reservoir pressure, total production and reinjection history in the Berlín geothermal field from 1992 until 2005

#### 4.2 Reinjection into Berlín reservoir

Reinjection of separated geothermal water is practiced at many geothermal fields as a means of disposal but also for reservoir pressure support. Reinjection should be considered an essential part of any sustainable, environmentally friendly geothermal utilization but should also be considered an important part of the management of a geothermal resource.

In the Berlín geothermal field, reinjection has been maintained since the start of production in 1992, when the two back-pressure units were installed. It was planned to use wells TR-2 and TR-9 as producers and reinject the separated water into wells TR-1 and TR-6, drilled in 1991. Well TR-6 was abandoned due to a blow-out at only 150 m depth. Due to the limited reinjection capacity of well TR-1 it was decided to put only one of the power units online and use well TR-9 temporarily as a reinjection well. Between 1993 and 1995, three deep wells were drilled for reinjection purposes (TR-8, TR-10, and TR-14). These wells are located 1-2 km north of the production wells. In February 1995 the second back-pressure unit was connected by using wells TR-2 and TR-9 as producers. Well TR-10 was connected to the reinjection line in 1995, shortly after completion, but was closed in 1998 due to loss of absorption (Montalvo and Axelsson, 2000).

In 1999 the two condensing units were put online, as part of the first condensing development of the Berlín geothermal field. From 1996 to 1999, eleven more reinjection wells were drilled (TR-11, TR-11ST, TR-11A, TR-11B, TR-11C, TR-1A, TR-1B, TR-1C, TR-7, TR-8A, TR-12 and TR-12A). The location of these wells is shown in Figure 1.

Currently, the total production capacity from nine producing wells is close to 507 kg/s, of which 127 kg/s is steam and 380 kg/s separated water at 10.5 bar-g separation pressure. Considering that the two condensing units have a high-pressure steam consumption value of (2 kg/s)/MWe, the actual generation capacity of the Berlín geothermal field is close to 63 MWe, without new wells being drilled. Currently, the installed production capacity of Berlín geothermal power plant is 56 MWe.

The field has 7 or 8 production wells in operation. Due to loss of absorption (injection capacity) in the reinjection wells, the geothermal power plant cannot be operated at full capacity. Since 1999, when the condensing units went online, wells TR-3, TR-4A and TR-12A have been used as reinjection wells in order to complete the reinjection capacity, and produce the 56 MWe required. These wells were drilled as production wells. Reinjection into the production zone has been continued in order to maintain power generation in the range of 50 to 54 MWe. In some reinjection wells (TR-14 and TR-7) there is evidence of absorption loss due to scaling problems. These wells have been chemically stimulated in order to recover the reinjection capacity. Table 2 shows the total production and reinjection capacity in the Berlín geothermal field.

TABLE 2: Production and reinjection capacity in the Berlín geothermal field

Production wells	Separation pressure (bar-g)	Steam (kg/s)	Water (kg/s)	Total flow (kg/s)	Reinjection well	Water (kg/s)
TR-2	10.1	15.0	42.0	57.0	TR-1A	45.0
TR-4	10.6	11.0	25.0	36.0	TR-1B	20.0
TR-4B	10.6	17.0	37.0	54.0	TR-1C	38.0
TR-4C	10.6	16.0	45.0	61.0	TR-7	0.0
TR-5	10.6	4.0	21.0	25.0	TR-8	19.0
TR-5A	10.5	22.0	82.0	104.0	TR-8A	13.0
TR-5B	10.5	10.0	28.0	38.0	TR-10	36.0
TR-5C	10.6	24.0	73.0	97.0	TR-10A	0.0
TR-9	10.1	8.0	27.0	35.0	TR-11ST	28.0
					TR-11A*	0.0
					TR-12	30.0
					TR-14	0.0
					TR-3	20.0
					TR-4A	34.0
					TR-12A	29.0
	<b>Total production</b>	<b>127.0</b>	<b>380.0</b>	<b>507.0</b>	<b>Total reinjection</b>	<b>312.0</b>

\*Cold water reinjection

#### 4.3 Tracer tests in Berlín geothermal field

Tracer tests are used extensively in surface and groundwater hydrology as well as in pollution and nuclear waste storage studies. Tracer tests involve injecting a chemical tracer into a hydrological system and monitoring its recovery through time at various observation points. The results are, subsequently, used to study flow-paths and quantify fluid flow in a hydrological system. The main purpose of conducting tracer tests in geothermal studies is to predict possible cooling of production wells due to long term reinjection of colder fluid, through the study of the hydraulic connections between injection and a production well (Axelsson et al., 2005).

Several tracer test experiments have been carried out in the Berlín geothermal field, using different kinds of tracers. In the analysis of the first eight tracer tests the results indicated no evidence of tracer returns in the production wells in a monitoring period of 36 to 76 days. Based on this analysis the initial conclusion was that no fast flowpaths were detected between the reinjection and the production zones, therefore, a premature thermal breakthrough was not expected.

The 9th test was injection of a tracer into directional well TR-12A, located close to the production zone. The tracer test was conducted during the period from May 16<sup>th</sup> - August 17<sup>th</sup> 2000, but the well has been in continuous reinjection since 1999 to present.

Analysis of the results shows that there exists a connection between the production zone and well TR-12A, since part of the reinjection water is detected in the monitoring wells TR-4C, TR-5A, TR-5B and TR-9. According to calculations, using the program TRMASS (Arason, 1993), the total mass recovery in the production zone was close to 14% (4.3 kg/s) of what was injected into well TR-12A. The separated water injected in well TR-12A is close to 30 kg/s. Table 3 shows the values of mass recovery in the monitoring well (Montalvo et al., 2001).

TABLE 3: Mass recovery in monitoring wells after a tracer test in well TR-12A

Well no.	Recovery (%)	Time arrival (days)	Time of max. concentration (days)	Flow back (kg/s)	Total production (kg/s)	Water production (kg/s)
TR-4C	9.4	1.0	6.0	2.83	46.0	30.0
TR-5B	2.9	3.0	15.0	0.868	37.0	25.0
TR-9	1.7	11.0	23.0	0.513	37.0	30.0
TR-5A	0.2	15.0	23.0	0.071	77.0	57.0

This analysis was possible due to the fact that production well TR-12A was used for reinjection in order to increase the reinjection capacity in 1999. It was planned to use the well for that only for a short period of time. However, after six years of power production the well is still used as a reinjection well.

#### 4.4 Temperature changes

Initially, when the production in the Berlín geothermal field started in 1992, well TR-2 was used as a production well and TR-9 as a reinjection well. In May 1993, reinjection was stopped into well TR-9 and in 1995 the well was integrated into production. In 1999, when the two condensing units were commissioned, six more wells were added to production. After six years of production for the two condensing units, changes in temperature with time have been observed in some of the wells. The following is a discussion about the temperature changes:

*Well TR-2:* The first production well in Berlín geothermal field and has been in operation since 1992. It is shut-in only when the units are off-line for maintenance. The feed zone temperature is 295°C and it has been constant, according to measurements since 1982 (Figure 3). Cooling is, therefore, not observed in this well.

*Well TR-4:* The temperature logs in this well indicate cooling in the main feed zone. In May 2002 the measured temperature was close to 300°C, but in April 2004 the measured temperature was close to 287°C, which means that the temperature has declined between 10 and 13°C in the feed zone. This well is used for reservoir pressure monitoring, but is connected to the power plant when more steam is required. The temperature logs are shown in Figure 4.

*Well TR-4B:* Cooling has not been observed in this well. Figure 6 shows the temperature logs. The temperature in the feed zone is stable, close to 292°C. The well was chemically stimulated in December 2001. Production has been more or less stable since then.

*Well TR-4C:* The temperature changes in this well are evident. Temperature logs, shown in Figure 7, indicate that the temperature has declined about 12°C in the main feed zone. The well was chemically stimulated in March 2004. After stimulation, production characteristics have been stable.

*Well TR-5:* The temperature changes in this well are shown in Figure 8. Based on this information the temperature has declined about 4°C in the main feed zone. Production has also declined the total mass from 34-25 kg/s, and the steam fraction from 23-16%.

*Well TR-5A:* The temperature logs after reparation are shown in Figure 9. During thermal recovery the temperature was close to 298°C after 17.6 days, since stop of circulation. This can be considered the stabilization temperature; therefore, the thermodynamic conditions of this well seem to be stable.

*Well TR-5B:* The temperature logs which were obtained during thermal recovery and production are shown in Figure 10. Based on the observed temperature logs, it is estimated that the temperature has declined between 5 and 9°C. Recently, small changes have been observed in the production rate.

*Well TR-5C:* The temperature logs obtained during thermal recovery and the production period are shown in Figure 11. Based on the logs, it is estimated that the temperature has declined about 7°C, but the production rate has not changed significantly.

*Well TR-9:* Was drilled as a production well. In 1992 due to the limited reinjection capacity of well TR-1, it was decided to use well TR-9 temporarily as a reinjection well, being online from February 1992 to May 1993. Subsequently, the temperature declined about 30°C in the feed zone from 292 to 262°C. In 1995 the well was connected to the back-pressure units and in 1999 it was connected to the condensing plant. Figure 12 shows the temperature measurements carried out during thermal recovery and after the production began in 1995. From 1999 to 2002 a thermal recovery of 23°C, was observed in the well with a maximum measured temperature of 285°C in the feed zone. Since 2002 the temperature has declined about 13°C and the measured temperature at the feed zone is 272°C. This cooling has affected the production rate. The total flow is now close to 35 kg/s, but was initially about 50 kg/s.

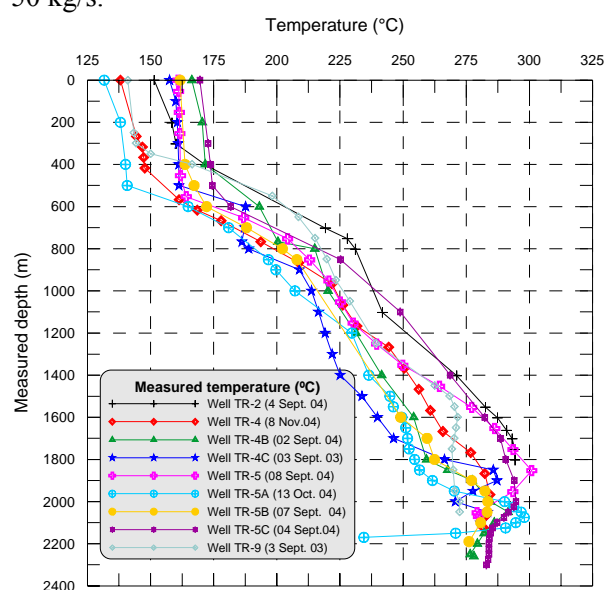


FIGURE 26: Measured temperature profiles in the Berlin production wells from 2003 to 2004

Appendix IV shows the values of temperatures from recent logs in the production wells in operation in Berlín geothermal field, and Figure 26 shows the temperature profiles in the production wells.

In Sections 4.2 and 4.3, reinjection into the production zone and its effect on the neighbouring production wells were discussed, specifically the effects due to reinjection into well TR-12A, having established the connection between directional well TR-12A and the production zone. The data shows that the wells TR-4, TR-4C, TR-5, TR-5B, TR-5C and TR-9 have all suffered temperature decline during the last years, but the most drastic changes are seen in wells TR-4, TR-4C and TR-9, with a cooling of 10, 12 and 13°C, respectively.

The temperature decline in the wells is in agreement with the tracer test analysis made by Montalvo et al., (2001). A hydraulic connection between wells TR-3 and TR-4A has not yet been demonstrated, but the effect is clearly seen. Reinjection in the production zone will be reduced with the aim of minimizing the premature temperature decline in the production zone.

## 5. ANALYSIS OF WELL TESTS

Well testing methods have been used for decades to evaluate groundwater and petroleum reservoirs. These methods have also been successfully applied to geothermal reservoirs, especially for single-phase reservoirs (Grant et al., 1982; Kjaran and Eliasson, 1983). Well tests give information on the

hydrogeological conditions of the well/reservoir system; one can deduce the reservoir permeability thickness product ( $kh$ ) and the storativity ( $C_i h$ ) in the drainage volume of the well.

During a well test, the flowrate or injection rate is changed. This will create a time-dependent pressure change in the reservoir, which is either monitored in the production well itself (single well test) or in an observation well (interference test). Generally, these pressure transient testing techniques include pressure drawdown, build-up, productivity, injectivity, fall-off, and interference. For pressure transient testing analysis, several simplifying assumptions (Grant et al., 1982) are made, such as:

- 1) The reservoir aquifer is horizontal with constant thickness;
- 2) It has a uniform and homogeneous permeability;
- 3) It is impermeable at the top and bottom;
- 4) The fluid is of uniform and constant compressibility;
- 5) The temperature is everywhere the same and constant.

Although some of these assumptions may not be true, the reservoir parameters may be estimated, and can give a basis for comparison. In this section the three methods are utilized in the analysis of data from well TR-4C. These methods are also described in detail in Lee (1982) and Grant et al. (1982).

### 5.1 Semi-logarithmic analysis

Initially, the reservoir is assumed at rest ( $P_i$ ). At time zero ( $t = 0$ ) the production well begins discharge at a constant rate  $q$  ( $\text{m}^3/\text{s}$ ). The pressure in the reservoir, as a function of time ( $t$ ) and radial distance ( $r$ ) from the production well is given by assuming infinitely small well radius and that Darcy's law is valid:

$$P(r, t) = P_i + \frac{q\mu}{4\pi kh} E_i \left( -\frac{\mu C_i r^2}{4kt} \right) \quad (2)$$

where  $P_i$  = Initial pressure (Pa);  
 $C_i$  = Total compressibility (1/Pa);  
 $\mu$  = Dynamic viscosity (kg/ms);  
 $E_i(x)$  = The so-called exponential integral.

$$E_i(-x) = -\int_x^\infty \frac{e^{-u}}{u} du \quad (3)$$

for  $x < 0.01$  we can use

$$E_i(-x) \approx 0.5772 + \ln(x) \quad (4)$$

Equation 2 is sometimes called the Theis solution. If  $t > 100 \mu C_i r^2 / 4k$  then this equation can be written for the distance  $r$  as:

$$P_i - P(r, t) = \frac{2.303q\mu}{4\pi kh} \left[ \log(t) + \log\left(\frac{4k}{\mu C_i r^2}\right) + \frac{\gamma}{2.303} \right] \quad (5)$$

$$P_i - P(r, t) = \frac{2.303q\mu}{4\pi kh} \left[ \log\left(\frac{4k}{\mu C_i r^2}\right) + \frac{\gamma}{2.303} \right] + \frac{2.303q\mu}{4\pi kh} \log(t) \quad (6)$$

Equation 6 can be simplified to the form  $\Delta P = A + m \log(t)$  which is a straight line with slope  $m$ , when pressure changes are plotted on a semi-logarithmic scale against time, where:

$$\Delta P = P_i - P(r, t); \quad A = \frac{2.303q\mu}{4\pi kh} \left[ \log\left(\frac{4k}{\mu C_i r^2}\right) + \frac{\gamma}{2.303} \right] \quad \text{and} \quad m = \frac{2.303q\mu}{4\pi kh} \quad (7)$$

The transmissivity ( $T$ ) can be calculated from:

$$T = \frac{kh}{\mu} = \frac{2.303q}{4\pi m} \quad (8)$$

If the temperature is known, we can find the dynamic viscosity ( $\mu$ ) from steam tables, thus the permeability thickness ( $kh$ ) can be estimated by:

$$kh = \frac{2.303q\mu}{4\pi m} \quad (9)$$

Using the value of the drawdown  $\Delta P$  on the semi-logarithmic straight line, at some selected time ( $t$ ) the storativity ( $C_i h$ ) can be estimated by:

$$S = C_i h = 2.25 \left( \frac{kh}{\mu} \right) \left( \frac{t}{r^2} \right) 10^{-\frac{\Delta P}{m}} \quad (10)$$

## 5.2 Horner method

The theoretical pressure response curve for a varying production rate can be derived by adjusting the Theis solution. If a production rate stops at time ( $t_p$ ), that is the start of the build-up test, the pressure change after time  $\Delta t$  is:

$$\Delta P_{ws} = \Delta P_{+q} + \Delta P_{-q} \quad (11)$$

$$\Delta P_{ws}(r, \Delta t) = \frac{2.303q\mu}{4\pi kh} \left[ \log\left(\frac{4k(\Delta t + t_p)}{\mu C_i r^2}\right) - \frac{\gamma - 2s}{2.303} \right] - \frac{2.303q\mu}{4\pi kh} \left[ \log\left(\frac{4k\Delta t}{\mu C_i r^2}\right) - \frac{\gamma - 2s}{2.303} \right] \quad (12)$$

$$P_{ws}(r, \Delta t) = \frac{2.303q\mu}{4\pi kh} \left[ \log\left(\frac{4k}{\mu C_i r^2}\right) + \log(\Delta t + t_p) - \log\left(\frac{4k}{\mu C_i r^2}\right) - \log(\Delta t) \right] \quad (13)$$

Equation 13 can be simplified by combining the logarithmic terms, thus:

$$\Delta P_{ws} = \frac{2.303q\mu}{4\pi kh} \log\left(\frac{t_p + \Delta t}{\Delta t}\right) \quad (14)$$

Here,  $t_p$  is the duration of production and  $\Delta t$  is the elapsed time after shut-in. The expression  $(t_p + \Delta t)/\Delta t$  is called the Horner time. It should be noted that when the shut-in time  $\Delta t$  approaches infinity, the Horner time  $(t_p + \Delta t)/\Delta t$  approaches 1. Plotting  $\Delta P_{ws}$  versus  $(t_p + \Delta t)/\Delta t$  on semi-logarithmic graph, gives according to Equation 14 a straight line with the slope:



$$m = \frac{2.303q\mu}{4\pi kh} \quad \text{so} \quad kh = \frac{2.303q\mu}{4\pi m} \quad (15)$$

The storativity can then be estimated by Equation 10.

### 5.3 Dimensionless variables and type curve method

Well test analysis often makes use of dimensionless variables. The importance of dimensionless variables is that they simplify the reservoir models by embodying reservoir parameters such as flow rate ( $q$ ) and permeability ( $k$ ), thereby reducing the total number of unknowns. They have the additional advantage of providing a model solution that is independent of any particular system. It is an inherent assumption in the definition that permeability, viscosity, compressibility, porosity and thickness are all constant.

The  $P_D$ ,  $t_D$  and  $r_D$  are dimensionless variables and are defined as:

$$P_D = \frac{2\pi kh}{q\mu} [P_i - P(r, t)] \quad t_D = \frac{kt}{C_t \mu r_w^2} \quad \text{and} \quad r_D = \frac{r}{r_w} \quad (16)$$

A dimensionless solution, associated with a specific reservoir model, is plotted on a log ( $P_D$ ) versus log ( $t_D$ ) graph called a type curve. Generally, the procedure for the type curve method is as follows:

1. Plot the data on a log ( $P_D$ ) versus log ( $t_D$ ) graph;
2. The plot and the type curve must be in the same scale;
3. Slide the curves together until they match;
4. Any convenient match point can be chosen;
5. The pressure and time values are read from both graphs ( $\Delta P_D$ ,  $P_{DM}$ ,  $\Delta t_M$ ,  $t_{DM}$ );
6. The transmissivity is evaluated as:

$$T = \frac{kh}{\mu} = \frac{q}{2\pi} \left( \frac{P_D}{\Delta P} \right)_M \quad (17)$$

7. And the storativity can be estimated by:

$$S = C_t h = \frac{kh}{\mu r_w^2} \left( \frac{\Delta t}{t_D} \right)_M \quad (18)$$

### 5.4 Well test analysis in well TR-4C

The pressure data from well TR-4C were analyzed using semi-logarithmic, Horner plot, and type curve methods. The data were collected by using Kuster tools which, due to their mechanical characteristics, have a relatively high degree of uncertainty. The data used for the analysis come from a build-up test when the well was shut-in after production, and a fall-off test after the injection was stopped. Both tests were carried out during 12<sup>th</sup> and 13<sup>th</sup> of May 2004. Figure 27 shows the data from the tests.

The pressure was measured during the build-up test at a depth of 2000 m using the Kuster tool. The production rate before the build-up started was 29 kg/s. The duration of build-up was 7 hours (420 minutes). After build-up and prior to the injection/fall-off test, the Kuster tool was lowered to a depth of 2000 m where the pressure was again measured. The injection rate prior to the fall-off period was 20 l/s, with a duration of 1.25 hour (75 minutes), while the duration of fall-off was 13 hours (780 minutes) (Romero, 2004). Figure 28 shows the plots of the different methods utilized in the analysis. After these pressure tests the well was chemically stimulated.

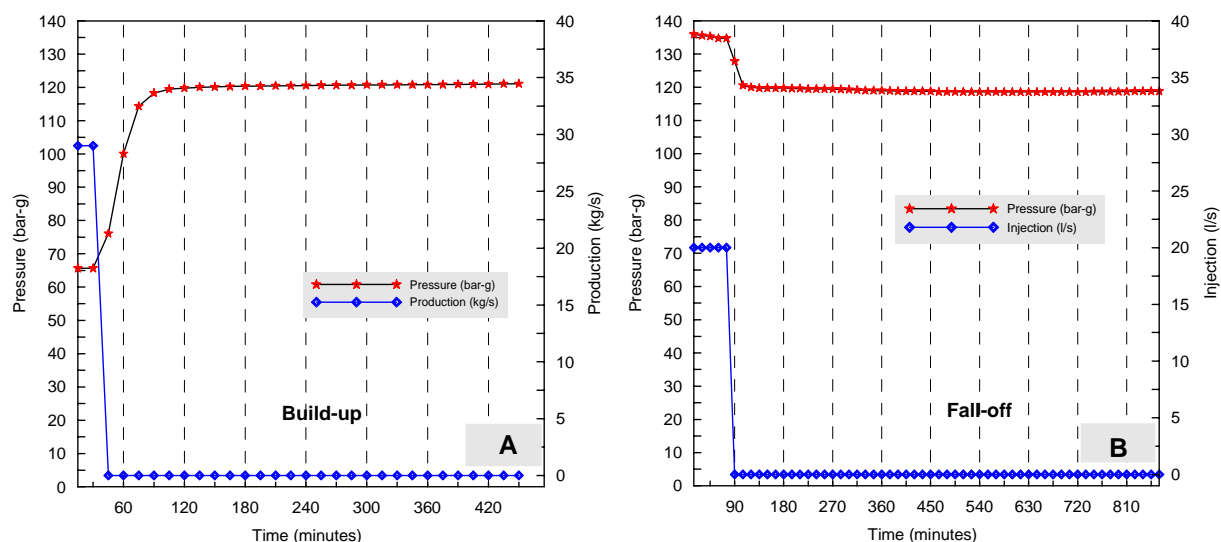


FIGURE 27: Well tests in well TR-4C; a) Build-up; and b) Fall-off

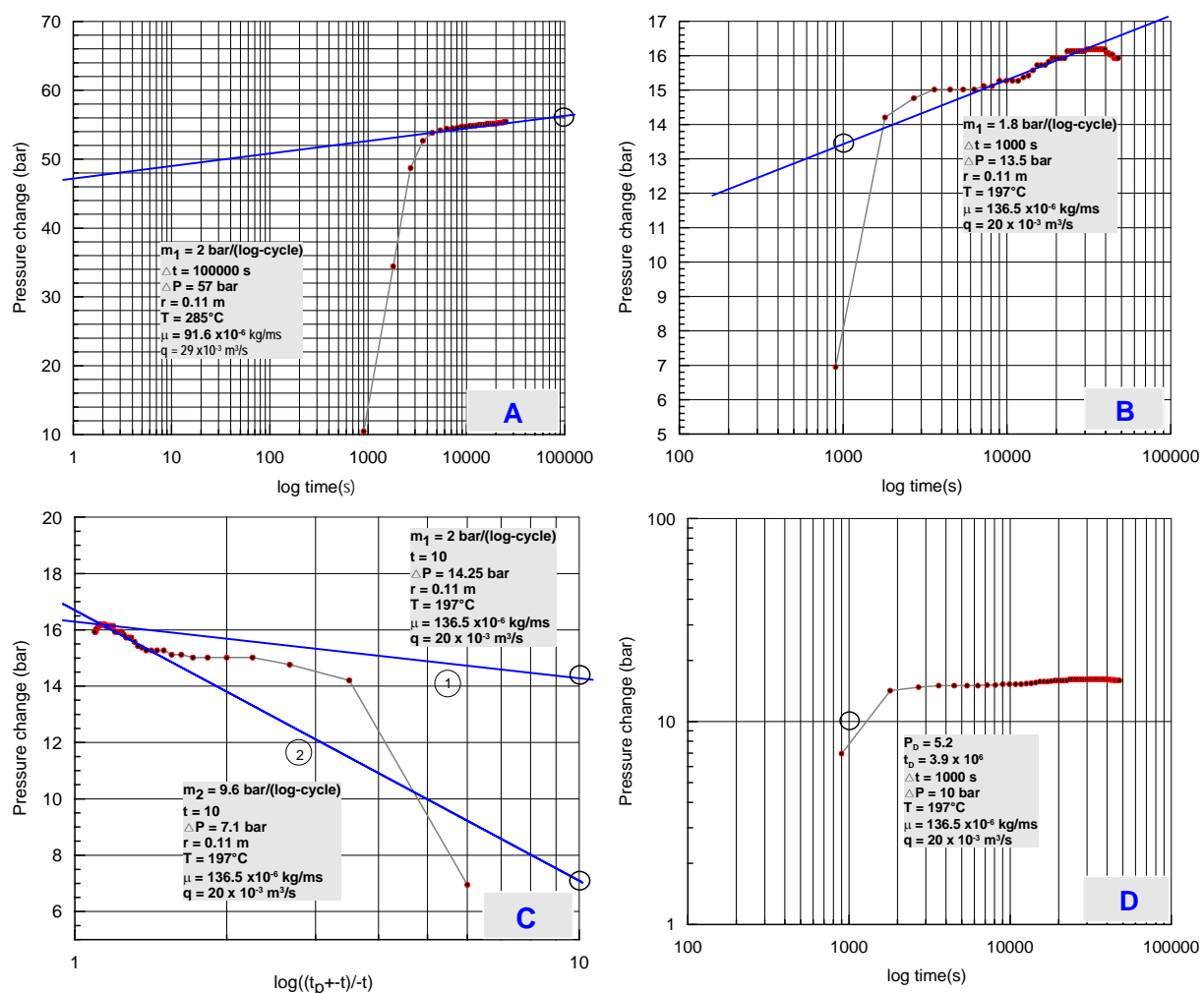


FIGURE 28: Analysis of tests in well TR-4C; a) Semi-log plot for build-up; b) Semi-log for fall-off; c) Horner plot for fall-off; and d) Type curve plot for fall-off

The results of the build-up and fall-off test analysis are presented in Table 4. Only the semilog method was applied for the build-up test. The transmissivity is estimated  $2.7 \times 10^{-8} \text{ m}^3/\text{Pa s}$ . By assuming reservoir temperature of  $280^\circ\text{C}$  and viscosity  $91.6 \times 10^{-8} \text{ kg/ms}$  permeability thickness of about 2.5 Dm is obtained. Due to relatively high pressure change the obtained storativity is also very high and is considered unrealistic.

TABLE 4: Parameter estimates for well test analysis in well TR-4C  
(skin factor estimated by using  $C_i h = 6.8 \times 10^{-11} \text{ Pa}^{-1}$  and  $h = 1000 \text{ m}$ )

Method of analysis	Transmissivity, $kh/\mu$ ( $10^{-8} \text{ m}^3/\text{Pa-s}$ )	Permeability thickness, $kh$ (Dm)	Storativity $C_i h e^{-2s}$ (m/Pa)	Skin factor, $s$
<b>Build-up</b>				
Semi-log	2.7	2.5	$1.6 \times 10^{-29}$	
<b>Fall-off</b>				
Semi-log	2.0	2.8	$1.2 \times 10^{-10}$	+ 3.2
Horner	1.8 (1) 0.38 (2)	2.5 (1) 0.52 (2)		
Type curve	1.7	2.3	$3.6 \times 10^{-10}$	+ 2.6

The three methods mentioned above were applied for the build-up test, as shown in Table 4. The semilog method gives permeability thickness about 2.8 Dm and storativity about  $1.2 \times 10^{-10} \text{ m/Pa}$ . In this test the temperature is considered  $197^\circ\text{C}$ . The storativity is surely affected by skin so the storativity can be assumed to be  $C_i h e^{-2s}$ . By assuming reservoir storativity ( $C_i h$ ) about  $6.8 \times 10^{-8} \text{ m/Pa}$ , the skin factor is estimated about +3.2. The reservoir storativity is estimated by using reservoir thickness ( $h$ ) 1000 m, 10% porosity ( $\phi$ ) and total compressibility ( $C_t h$ )  $6.8 \times 10^{-11} \text{ m/Pa}$ , where  $C_t h = C_w \phi + C_r (1 - \phi)$  and  $C_w = 5 \times 10^{-11} \text{ Pa}^{-1}$  and  $C_r = 2 \times 10^{-10} \text{ Pa}^{-1}$  are typical values for compressibility of water and rock, respectively. The type curve method gives permeability thickness about 2.3 Dm and skin related storativity about  $3.6 \times 10^{-10} \text{ m/Pa}$  for the build-up test. By applying same method as above the skin factor is estimated +2.6. Two straight lines are shown for the Horner plot analysis in Figure 28. They give permeability thickness about 2.5 and 0.52 Dm. The former value resembles the other methods better.

The well test analysis shows that the permeability thickness is between 2 and 3 mD. The skin factor is likely in the range of +2.5 - +3.2 presenting damaged well. The productivity index for the well is around 0.7 kg/s/bar. This means that well TR-4C is a poor production/injection well, but is located in a highly permeable formation.

## 6. SIMPLE LUMPED PARAMETER MODELLING

The pressure response of a geothermal reservoir to exploitation depends on the characteristics of the fluid recharge. The recharge in a reservoir, in particular, depends on differences in fluid pressure, permeability, temperature and the geometry of the reservoir and surrounding formations. To understand the response, it is necessary to know the exploitation characteristics of the geothermal system, consisting of the reservoir and the surrounding recharge aquifers.

The response of a geothermal reservoir to exploitation can be analysed by using lumped-parameter reservoir models. Lumped-parameter models provide an estimate of the reservoir and aquifer parameters that fit data measured over an entire period of monitoring. This is analogous to methods used for system analysis in electrical and mechanical engineering. In this chapter, a lumped parameter model (Axelsson, 1989) is applied for the interpretation of pressure and production data from the Berlín geothermal field.

## 6.1 The LUMPFIT program

The lumpfit models consist of a few capacitors or tanks that are connected by resistors. The program LUMFIT, which employs a non-linear, iterative, least square procedure, is used (Axelsson and Arason, 1992). The tanks simulate the storage of different parts of the reservoir in question, whereas the

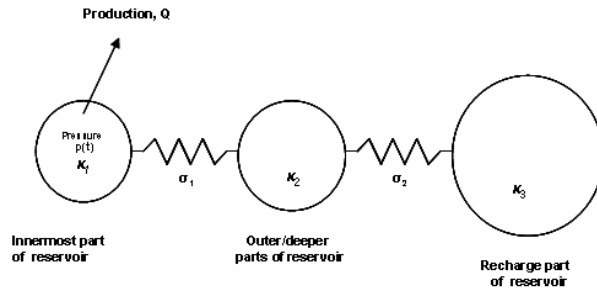


FIGURE 29: A closed lumped parameter models (Axelsson, 1989)

resistors simulate the permeability (Figure 29). A tank in lumped model has the mass storage coefficient  $\kappa$ . The tank response to a load of liquid mass  $m$  gives a pressure increase given by  $p = m/\kappa$ . The mass conductance of a resistor in a lumped model is  $\sigma$  when it transfers  $q = \sigma\Delta p$  units of liquid mass per unit time at the impressed pressure differential  $\Delta p$ . The pressures in the tank simulate the pressures in different parts of the reservoir, whereas production from the reservoir is simulated by withdrawal of water from only one of the tanks (Axelsson, 1989).

Lumped models can be either open or closed. Open models are connected by a resistor to an infinitely large imaginary reservoir, which maintains a constant pressure. On the other hand, closed lumped models are isolated from any external reservoir. Actual reservoirs are most generally represented by two- or three-tank closed or open lumped parameter models (Axelsson, 1989). The pressure response,  $p$ , of a single-tank open model for a constant production,  $Q$ , at time  $t = 0$  is given by the following equation:

$$p(t) = -\left(\frac{Q}{\sigma_1}\right) \left(1 - e^{-\left(\frac{\sigma_1}{\kappa_1}t\right)}\right) \quad (19)$$

The pressure response ( $p$ ) of a more general open model with  $N$  tanks, to a constant production ( $Q$ ), at times  $t = 0$ , is given by

$$p(t) = -\sum_{j=1}^N Q \frac{A_j}{L_j} * \left(1 - e^{-(L_j t)}\right) \quad (20)$$

The pressure response of an equivalent  $N$ -tank closed model is given by the equation

$$p(t) = -\sum_{j=1}^{N-1} Q \frac{A_j}{L_j} * \left(1 - e^{-(L_j t)}\right) + QBt \quad (21)$$

The coefficients  $A_j$ ,  $L_j$  and  $B$  are functions of the storage coefficients of the tanks ( $\kappa_j$ ) and the conductance coefficients of resistors ( $\sigma_j$ ) of the model, estimated by the LUMPFIT program.

## 6.2 The Berlín production history

The total production rate from the Berlín geothermal field is presented in Figure 30. At the beginning of commercial exploitation in February 1992, the pressures values measured at sea level were in the range of 39–40 bar-g, and the average fluid production rate was 90 kg/s. Since October 1999, the average total mass extraction has been more or less constant at around 440 kg/s. The lowest production rate during the year occurs in the month of September each year due to maintenance stops of one of the condensing units. The reinjection in the Berlín geothermal field is close to 312 kg/s, of which 83 kg/s are reinjected into the production zone into wells TR-3, TR-4A and TR-12A. The net extraction rate from the production zone has, therefore, been about 360 kg/s.

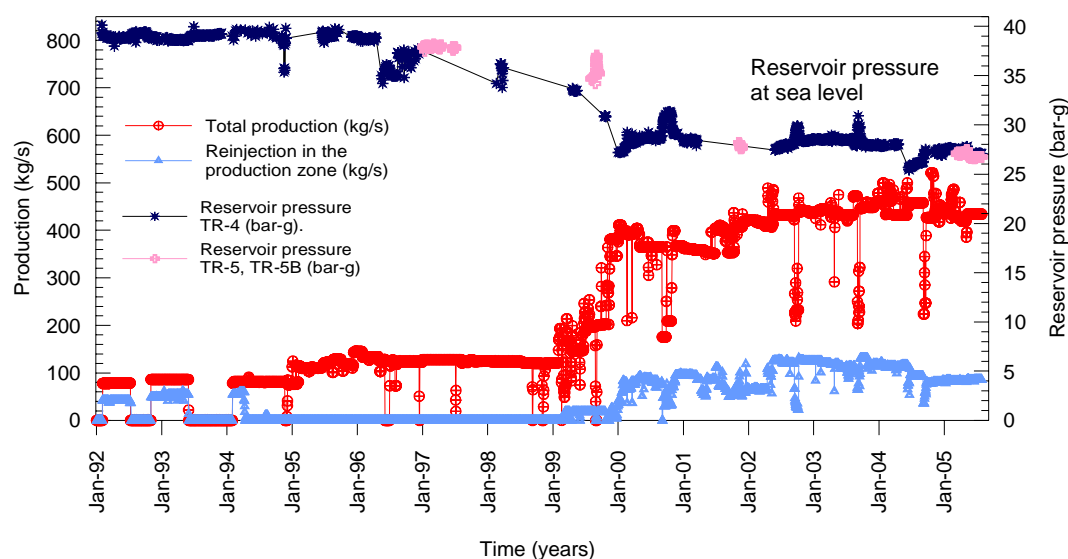


FIGURE 30: Reservoir pressure at sea level and total mass extraction

The monitoring of the production response of the Berlín geothermal reservoir has been limited in some periods, due to the unavailability of monitoring wells, and in some cases due to problems with the available pressure tools. Wells TR-4, TR-5 and TR-5B have been utilized as monitoring wells during the last years. The pressure has always been measured at sea level.

### 6.3 Lumped-parameter models used for Berlín reservoir

The main objective of reservoir evaluation was to estimate the long-term production potential of the Berlín geothermal reservoir. The lumped parameter model was used to simulate the observed pressure decline (drawdown). The net production (total production minus reinjection in the production zone) rate and observed reservoir pressure from February 1992 until July 2005 were utilized as an input file in the LUMPFIT program. The modelling results are presented in Table 5. The Table summarizes the estimated parameters obtained from the best fit of the lumped parameter model, using two-tank closed and two-tank open models. Both models yield similar acceptable fits, providing a coefficient of determination of 93.4% and standard deviation of 1.26 bars. Figure 31 shows the match between the observed and calculated reservoir pressures.

TABLE 5: Parameters of best fit for two-tank closed and two tank open models

Parameter	2-tank closed	2-tank open
$\kappa_1$ (ms <sup>2</sup> )	2128.65	1275
$\kappa_2$ (ms <sup>2</sup> )	$5.30 \times 10^5$	$2.83 \times 10^4$
$\sigma_1$ (10 <sup>-5</sup> ms)	28.11	39.92
$\sigma_2$ (10 <sup>-5</sup> ms)		65.64
Coefficient of determination (%)	93.10	93.44
Standard deviation (bars)	1.29	1.26

### 6.4 Reservoir properties

The lumped parameter models were used for estimating the reservoir properties of the Berlín geothermal field. It is assumed that the Berlín reservoir is liquid-dominated and the storage is dominated by the liquid and formation compressibility. The volume of the different tanks can be estimated as:

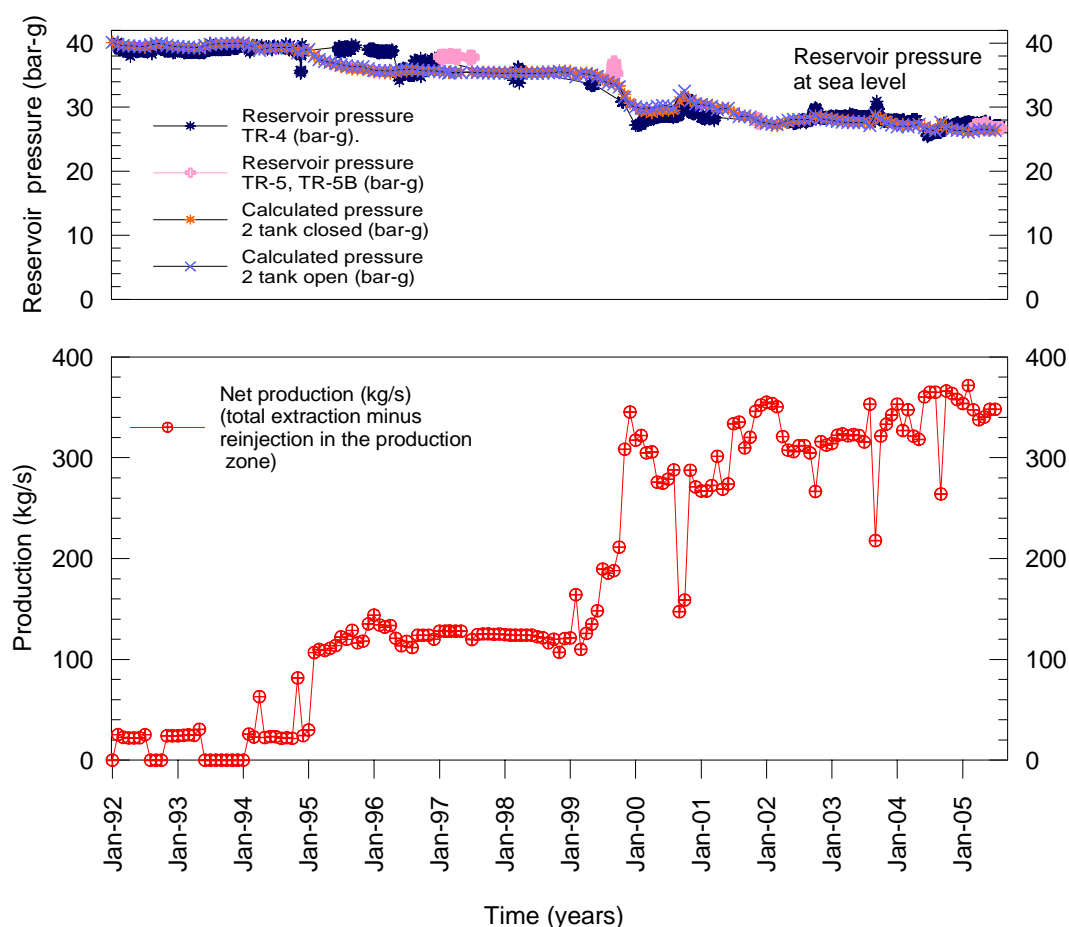


FIGURE 31: Observed reservoir pressure at sea level in 1992-2005 and calculated pressure

$$V = \frac{\kappa}{\rho_w * c_t} \quad (22)$$

where  $\rho_w$  is the liquid density and  $c_t$  is the total compressibility ( $c_t = \phi c_w + (1 - \phi) c_r$ ). It is also assumed that the average reservoir temperature is  $T = 295^\circ\text{C}$ ; liquid compressibility is  $c_w = 2.3 \times 10^{-9} \text{ Pa}^{-1}$ ; rock compressibility is  $c_r = 2 \times 10^{-11} \text{ Pa}^{-1}$ ; fluid density is  $\rho_w = 745 \text{ kg/m}^3$ , and that the porosity is  $\phi = 10\%$ .

Table 6 shows the calculated results considering a radial flow (2-D) model and assuming reservoir thickness of  $h = 1000 \text{ m}$ . The surface area estimated by the two models assuming a confined system, are  $6.9$  and  $11.5 \text{ km}^2$ . Compared with the present exploitation surface area, which is about  $6 \text{ km}^2$ , the results can be considered realistic. The estimated permeability of the Berlín reservoir according to the two models is  $17$  and  $22 \text{ mD}$ . These values are considered realistic but should only be interpreted as rough estimates due to the different assumptions.

TABLE 6: Estimated reservoir properties

Model type	Reservoir volume ( $\text{km}^3$ )		Area ( $\text{km}^2$ )		Permeability (mD)	
	Confined system	Free surface	Confined system	Free surface	Confined system	Free surface
					(2-D) Radial flow	
Two-tank closed	11.5	52	11.5	52	23	4
Two-tank open	6.9	2.8	6.9	2.8	17	6



The area estimated by the two models using the unconfined model, is 2.8 and 52 km<sup>2</sup>. This indicates that a free surface reservoir characterized by expanding boiling zone can be extended in areas much larger than the actual production area.

## 6.5 Future prediction

One of the main purposes of simulating a reservoir is to bring off predictions on pressure changes for a given future production scenarios. The best fitting lumped models are considered suitable for predicting the pressure changes in the actual reservoir due to future production. The net production rates (total production minus reinjection in the production zone) were simulated for the Berlin reservoir until the year 2027. First we assumed that the present net production (434 kg/s minus the 83 kg/s reinjected into the production zone) would continue until January 2007.

Then we assume that the third condensing unit will be online increasing electricity generation up to 100 MWe, and operate at full load for 20 years. The total estimated production rates for 100 MWe generation are around 750 kg/s. Assuming that only 20 kg/s of separated water is reinjected in the production zone (into well TR-3), the net extraction is estimated to be 730 kg/s.

Figure 32 shows the results with two-tanks open and two-tanks closed models. The open two-tank model, which can be considered an optimistic case, shows additional pressure drawdown of about 16 bar-g for 20 years at sea level. The two-tank closed model, which, on the other hand, should be considered as a pessimistic case, shows 26 bar-g pressure drawdown over the same time period.

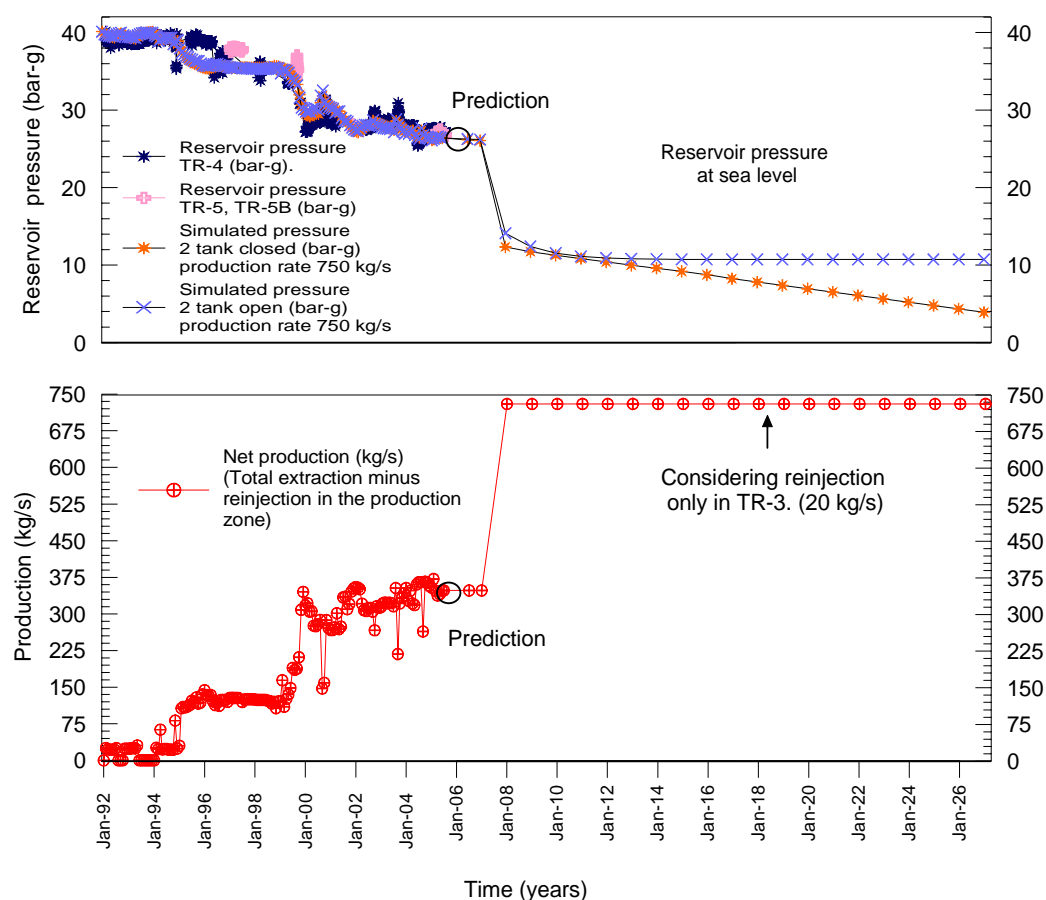


FIGURE 32: Prediction for Berlin reservoir for the next 20 years using two-tanks closed and two-tanks open models

## 7. CONCLUSIONS AND RECOMMENDATIONS

The estimated formation temperatures and initial pressures in Berlín geothermal field shown in the contour maps in Figures 21 and 22 are in concordance with the actual conceptual model accepted for the Berlín reservoir, which establishes that the geothermal fluid is moving from an upflow zone in the southwest part of the field toward the north and northeast, with a change in direction past the production zone to the northwest.

The connection between well TR-12A and other wells in the production zone has been demonstrated by tracer tests made in the year 2001 by Montalvo et al. According to their results it is clear that the connection contributes to temperature decline in neighbouring production wells. This is also confirmed in the measured temperatures in some of the production wells, especially in wells TR-4, TR-9 and TR-4C.

In order to minimize the temperature decline in the production zone, it is necessary to evaluate the reinjection into well TR-12A, and establish the minimum flow which can be injected without cooling the neighbouring wells. It is also necessary to establish the connection between wells TR-3 and TR-4A and the actual production wells for the purpose of evaluating whether this reinjection is affecting the reservoir fluid temperature or not, evident mainly because these reinjection wells are located in the production zone.

Reinjection into the production zone must, however, be suspended as soon as possible when sufficient reinjection capacity outside the production zone has been obtained.

The skin factor estimated using well test analysis for well TR-4C was in the range of +2.5 to 3.2, which indicates that this well was damaged during drilling due to the infiltration of drilling mud into the formation. Therefore, it is a good practice after well completion to carry out a chemical stimulation, to reduce damage and guarantee improved production from the well.

The estimation of reservoir parameters using the results from the LUMPFIT parameter models for Berlín production history are considered acceptable. This evaluation estimates a reservoir area between 6.9 and 11.5 km<sup>2</sup> and a permeability between 17 and 23 mD, based on different assumptions, such as a reservoir thickness of 1000 m, and an average reservoir temperature of 295°C.

Pressure decline in the reservoir is predicted until year 2027 assuming present net production until January 2007 when the third condensing unit will be put online (total production minus reinjection in the production zone). The three units will then be operated at full capacity for 20 years. These results can be used only as a reference as lumped parameter models only consider pressure changes in the reservoir provoked by the production but not changes in other parameters such as temperature, permeability, boiling and storativity, which can also change with the passing of time.

The availability of a monitoring well is very important because it provides the possibility of having permanent reservoir pressure monitoring. In the past this monitoring has been interrupted and the reservoir pressure has not been monitored for long periods. This information is relevant for the management of the field and for predicting the future behaviour of the Berlín reservoir.

Finally, all aspects considered in this report should be taken as a particular interpretation of the author, resulting from the information, knowledge and practices acquired in the UNU Geothermal Training Programme 2005, Iceland.

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# APPENDIX I: General information of wells drilled in the Berlín geothermal field

TABLE 1: General information on the wells drilled in the Berlín geothermal field since 1968 until 2005

Well		Drilling finished	Location		Elevation (m a.s.l)	Measured depth (m)	Casing (m) 9 5/8"	Slotted liner (m)		
			Latitude	Longitude				9 5/8"	7 5/8"	7"
TR-1	R/A (V)	29 July 1968	267333.00	552860.00	573.30	1458	0 a 326		0 a 750	
TR-1A	R (D)	27 November 1998	267333.00	552872.79	573.30	2328.90	773 a 1555			1449.8 - 2328.9
TR-1B	R (D)	26 January 1999	267313.05	552872.79	573.30	2421.60	781.8 - 1509			1474.5 - 2421.6
TR-1C	R (D)	16 April 1999	267313.05	552872.79	573.30	2495.00	814 - 1648			1608.4 - 2474
TR-2	P (V)	02 June 1978	266276.07	552802.45	752.00	1900.00	0 - 746.1		713.1 - 1900	
TR-3	R/P	30 October 1979	266413.35	553129.65	760.00	2300.00	0 a 1511.2		1474 a 2296.2	
TR-4	P (V)	08 July 1980	266097.57	552405.42	767.30	2150.00	0 a 1302.7		1300 a 2150	
TR-4A	R/P (D)	04 December 1997	266104.14	552413.25	767.30	2027.00	0 - 1571.45			1420 - 2027
TR-4B	P (D)	30 March 1998	266111.47	552420.04	767.30	2288.00	0 - 1746.5			1686 - 2288
TR-4C	P (D)	24 August 1998	266118.80	552426.84	767.30	2179.00	0 - 1488.45			1447 - 2179
TR-5	P (V)	04 July 1981	265744.28	552606.00	852.80	2086.00	0 - 1267		1242 - 2079	
TR-5A	P (D)	29 August 1998	265739.82	552575.38	852.80	2321.10	0 - 1600.48			1415.33 - 2321.1
TR-5B	P (D)	31 December 1998	265749.53	552585.00	852.80	2208.00	0 - 1594.55			1532.84 - 2205.5
TR-5C	P (D)	23 March 1999	265745.24	552594.63	852.80	2336.60	0 - 1568.26			1491.6 - 2336.6
TR-7	R (V)	04 October 1999	266829.09	553137.79	657.00	747.70		313 - 747.7		
TR-8	R (V)	31 May 1994	267772.80	552426.79	466.10	2322.50	0 - 1486.2		1462.4 - 2322.5	
TR-8A	R (D)	26 May 1999	267773.91	552431.65	466.10	2590.00	741.25 - 1754			1715.06 - 2590
TR-9	P (V)	28 December 1980	266726.33	552825.98	649.20	2298.00	0 - 1442.7		1277 - 2286	
TR-10	R (V)	05 May 1995	267611.81	553340.36	537.10	2329.00	0 - 1484		1446 - 2329	
TR-10A	R (D)	24 September 2002	267600.2	553346.5	537.10	2326.50	648.8 - 1447.6			
TR-11	R/A	16 October 1997	268449.89	551181.09	445.40	2500.70	0 - 1341			
TR-11ST	R (D)	27 November 1997	268449.89	551181.09	445.40	2042.70	0 - 1341			1307.4 - 2042.7
TR-11A	R (V)	14 January 1998	268435.18	551184.04	445.40	490.66		346.9 - 490.66		
TR-11B	R/A	11 February 1998	268420.42	551186.98	445.40	614.00	0 - 433.37			
TR-11C	R/A	29 March 1998	268464.60	551178.16	445.40	800.00	0 - 594.93			
TR-12	R (V)	18 August 1999	266518.7	552312.2	675.00	728.60		250 - 728.5		
TR-12A	R (D)	04 July 1999	266500.12	552295.54	675.00	2326.00	664.58 - 1484.5			1475 - 2326
TR-14	R (V)	28 February 1994	268158.20	553328.70	457.00	2125.30	0 - 1190.9		1137.9 - 2125.3	
TR-14S	R	07 May 1999			457.00	137.00	0 - 70		68.4 - 137	
TR-14S BIS	R	25 April 2000			457.00	137.00	0 - 65.3		53 - 137.15	
TR-17	P (V)	01 December 2003	265243.37	553496.56	1080.00	2600.00	0 - 1353			1319 - 2586
Tr-17A	P (D)	22 June 2004	265234.07	553488.98	1080.00	2690.00	951 - 1747			1710 - 2687
TR-17B	P (D)	03 January 2005	265224	553481	1080.00	1845.00				1845.00
TR-18	P (V)	25 February 2004	264729	552053	995.00	2660.00	895 - 1819			1773 - 2536
TR-18A	P (D)	30 July 2004			995.00	1085.00				1085.00

OBSERVATIONS:      D      Directional well      P      Production well      P/R      Production/ injection well  
                                  V      Vertical well      R      Injection well      R/A      Abandoned injection well

## APPENDIX II: Estimated initial pressure profiles for Berlín wells

Figures 1-8 show measured pressure profiles and the estimated initial pressure profiles in Berlín wells.

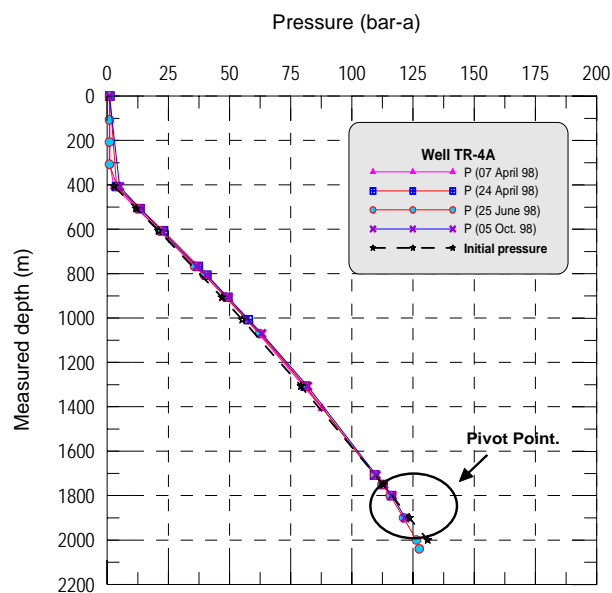


FIGURE 1: Pressure profiles and estimated initial pressure in well TR-4A

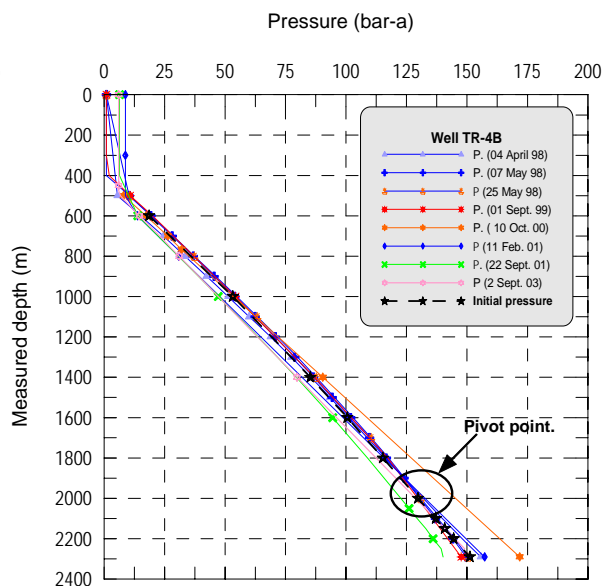


FIGURE 2: Pressure profiles and estimated initial pressure in well TR-4B

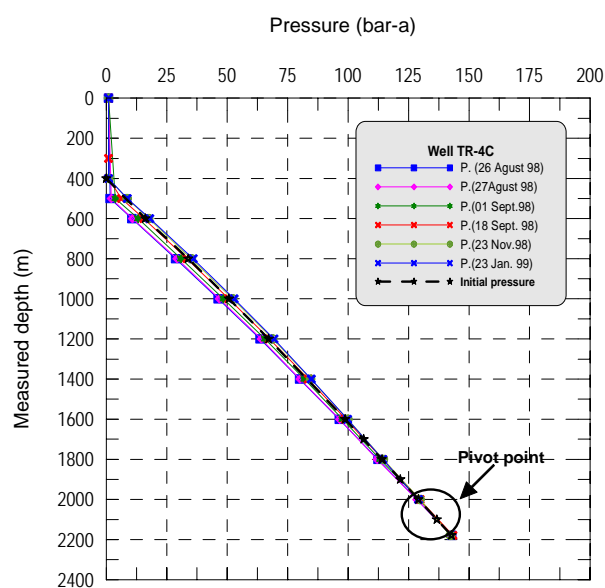


FIGURE 3: Pressure profiles and estimated initial pressure in well TR-4C

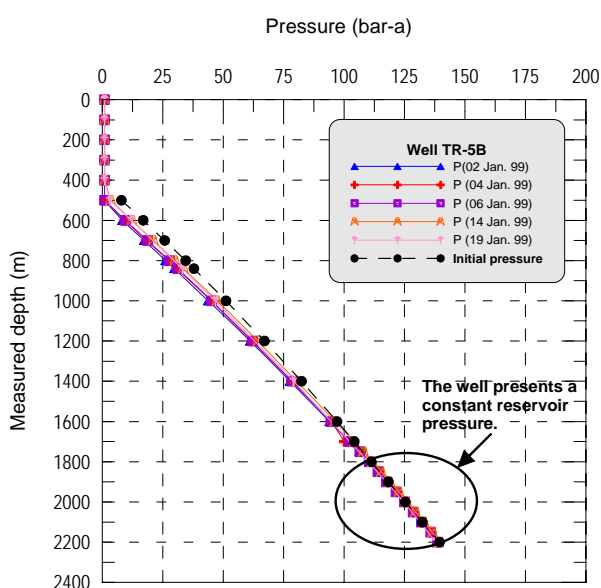


FIGURE 4: Pressure profiles and estimated initial pressure in well TR-5B



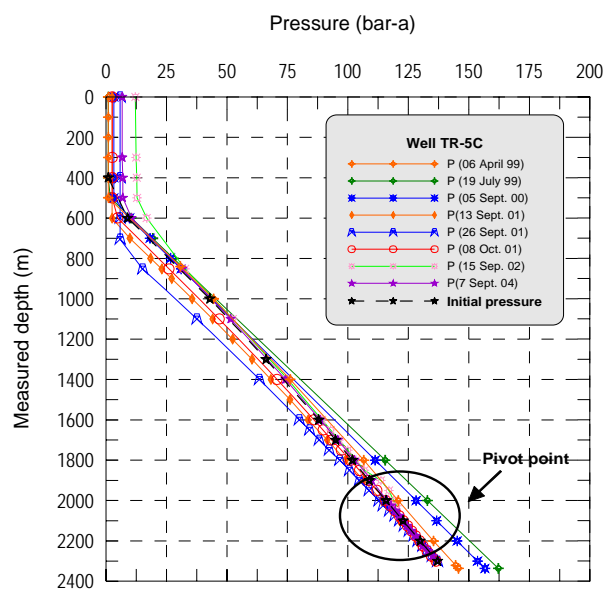


FIGURE 5: Pressure profiles and estimated initial pressure in well TR-5C

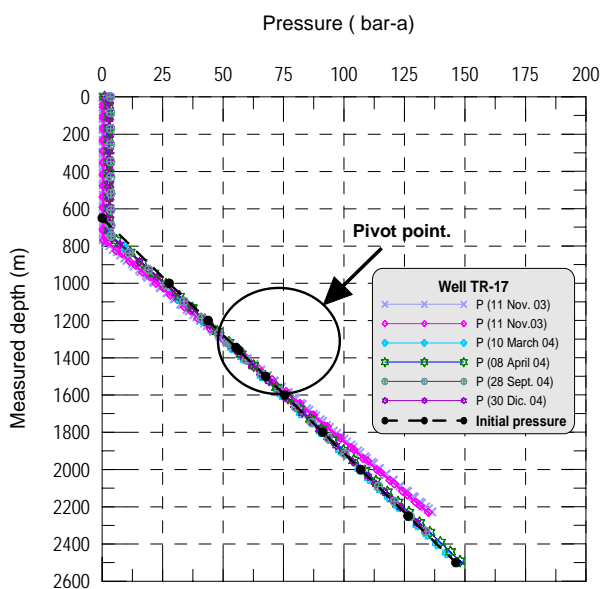


FIGURE 6: Pressure profiles and estimated initial pressure in well TR-17

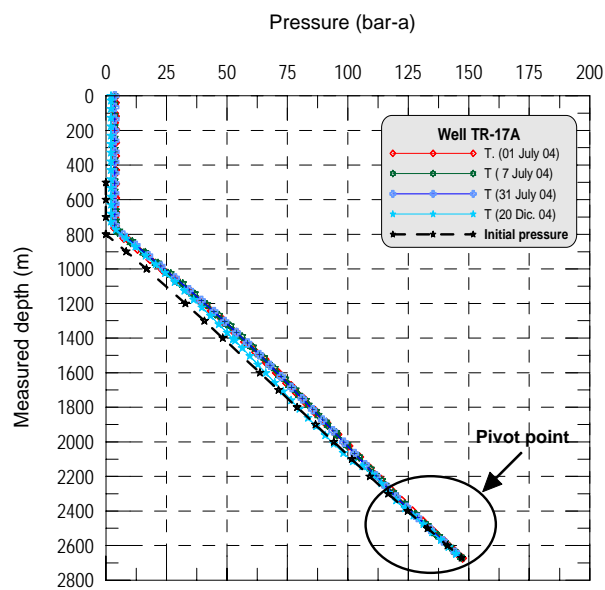


FIGURE 7: Pressure profiles and estimated initial pressure in well TR-17A

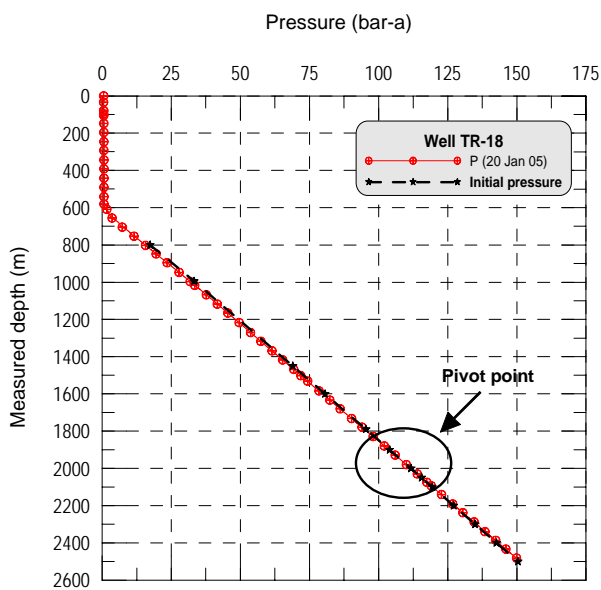


FIGURE 8: Pressure profiles and estimated initial pressure in well TR-18

### APPENDIX III: Estimated formation temperatures and initial pressures of the Berlín wells

TABLE 1: Estimated formation temperatures and initial pressures in the older Berlín wells (Monterrosa, 1993)

[illegible]

TABLE 2: Estimated formation temperatures and initial pressures of the more recent Berlín wells (this analysis)

TR-4A			TR-4B			TR-4C			TR-5B		
Measured depth (m)	Temp. (°C)	Press. (bar a)	Measured depth (m)	Temp. (°C)	Press. (bar a)	Measured depth (m)	Temp. (°C)	Press. (bar a)	Measured depth (m)	Temp. (°C)	Press. (bar a)
407.0	137.0	2.9	600.0	134.0	18.6	400.0	102.0	0.9	400.0	99.3	0.9
507.0	153.0	11.9	1000.0	225.0	53.2	600.0	130.0	16.2	500.0	149.7	7.9
607.0	135.0	21.0	1400.0	252.0	85.3	800.0	187.0	33.9	600.0	147.2	16.9
907.0	221.0	47.0	1600.0	277.0	100.5	1000.0	221.0	50.7	700.0	169.9	25.8
1007.0	227.0	55.2	1800.0	289.0	115.2	1200.0	229.0	67.1	800.0	189.4	34.5
1307.0	251.0	79.2	2000.0	292.0	129.7	1600.0	265.0	98.7	840.0	200.9	37.9
1750.0	286.0	112.8	2100.0	286.0	137.1	1700.0	267.0	106.4	1000.0	227.7	51.2
1900.0	301.0	123.5	2150.0	282.0	140.8	1800.0	275.0	114.0	1200.0	254.1	67.1
2000.0	274.0	131.0	2200.0	284.0	144.5	1900.0	270.0	121.6	1400.0	268.9	82.4
			2290.0	285.0	151.2	2000.0	280.0	129.1	1600.0	291.9	97.1
						2100.0	270.0	136.7	1700.0	297.6	104.2
						2179.0	271.0	142.7	1800.0	300.2	111.3
									1900.0	301.8	118.3
									2000.0	302.4	125.3
									2100.0	301.3	132.3
									2200.0	295.8	139.5
TR-5C			TR-17			TR-17A			TR-18		
Measured depth (m)	Temp. (°C)	Press. (bar a)	Measured depth (m)	Temp. (°C)	Press. (bar a)	Measured depth (m)	Temp. (°C)	Press. (bar a)	Measured depth (m)	Temp. (°C)	Press. (bar a)
400	97	0.94	650	165	0.94	500	145.36	0.94	800	199.6	17.35
600	150.2	8.91	1000	218	27.66	600	145.59	0.94	995	243.4	33.25
1000	236	42.9	1200	243	43.82	700	145.77	0.94	1450	256	68.98
1300	272	66.15	1345	245	55.33	800	170.3	0.94	1600	258	80.64
1600	297	87.92	1360	248.65	56.52	900	199.87	8.36	1790	258	95.42
1700	301	94.92	1500	248.15	67.57	1000	212.25	16.74	1900	259	104
1800	303	101.88	1600	250.07	75.46	1200	247.53	32.85	2000	263	111.7
1900	304	108.83	1800	253.1	91.19	1300	257.63	40.7	2050	264	115.6
2000	303	115.8	2000	256	106.87	1400	260.49	48.32	2100	264	119.4
2100	302	122.82	2250	254	126.52	1600	263.28	63.66	2200	264	127.2
2200	300	129.88	2500	254	146.26	1700	262.63	71.34	2300	264	134.9
2300	294	137.07				1800	265.04	79.01	2400	264	142.7
						1900	268.54	86.61	2500	263	150.4
						2000	273.34	94.17			
						2100	278.67	101.64			
						2200	278.48	109.1			
						2300	271.67	116.65			
						2400	230.9	124.71			
						2500	228.56	132.92			
						2600	227.82	141.17			
						2670	223.61	146.99			

**APPENDIX IV: Measured temperatures in production wells  
in the Berlín geothermal field from 2003 to 2004.**

TR-2		TR-4		TR-4B		TR-4C		TR-5		TR-5A		TR-5B		TR-5C		TR-9	
Measured depth (m)	Temp. (°C)	Measured depth (m)	Temp. (°C)	Measured depth (m)	Temp. (°C)	Measured depth (m)	Temp. (°C)	Measured depth (m)	Temp. (°C)	Measured depth (m)	Temp. (°C)	Measured depth (m)	Temp. (°C)	Measured depth (m)	Temp. (°C)	Measured depth (m)	Temp. (°C)
0.0	151.4	0.0	138.1	0.0	166.4	0.0	157.5	0.0	160.9	0.0	131.7	0.0	161.7	0.0	169.6	0.0	141.0
202.0	158.4	267.0	144.4	200.0	170.5	100.0	160.0	53.0	161.2	200.0	138.1	400.0	163.7	300.0	172.7	249.0	143.4
302.0	160.1	317.0	146.8	400.0	171.6	200.0	160.6	153.0	161.4	400.0	140.1	500.0	167.2	400.0	173.7	299.0	144.3
402.0	171.8	367.0	147.3	600.0	193.1	300.0	160.9	253.0	161.6	500.0	140.8	600.0	172.2	500.0	174.5	349.0	150.1
702.0	219.2	417.0	147.7	767.0	200.4	400.0	161.2	453.0	161.9	600.0	164.9	700.0	188.0	600.0	181.8	399.0	166.4
752.0	228.0	567.0	161.3	800.0	215.0	500.0	161.2	553.0	164.1	700.0	180.9	800.0	202.2	852.0	225.2	549.0	198.2
802.0	231.1	617.0	168.5	1000.0	220.3	600.0	187.6	653.0	186.9	852.0	196.7	852.0	207.9	1100.0	248.8	649.0	208.6
1102.0	241.8	667.0	177.9	1200.0	231.3	700.0	187.2	753.0	204.3	900.0	199.6	1000.0	218.05	1400.0	268.6	749.0	215.1
1402.0	271.2	767.0	193.6	1400.0	241.5	767.0	186.2	853.0	212.9	1000.0	207.2	1200.0	229.61	1600.0	282.3	849.0	219.7
1552.0	282.6	867.0	208.7	1600.0	254.2	800.0	188.9	953.0	220.6	1200.0	229.7	1400.0	238.22	1700.0	288.5	949.0	223.3
1602.0	287.3	967.0	221.9	1800.0	259.3	900.0	208.9	1053.0	225.2	1400.0	236.4	1600.0	249.0	1800.0	290.6	1049.0	228.9
1662.0	291.0	1067.0	226.1	1850.0	267.6	1000.0	213.7	1153.0	230.2	1500.0	244.7	1700.0	259.5	1900.0	294.0	1249.0	239.2
1702.0	293.2	1167.0	231.7	1900.0	277.4	1100.0	216.5	1253.0	239.5	1550.0	246.1	1800.0	262.4	2000.0	294.7	1449.0	262.5
1752.0	294.2	1267.0	244.2	2000.0	284.6	1200.0	219.1	1353.0	249.9	1600.0	249.5	1900.0	277.1	2025.0	293.8	1499.0	268.4
1802.0	294.3	1367.0	250.4	2050.0	291.5	1300.0	222.0	1453.0	264.4	1650.0	251.0	1950.0	282.4	2050.0	291.6	1549.0	270.3
		1467.0	256.2	2100.0	286.0	1400.0	225.1	1553.0	277.1	1700.0	251.8	2000.0	283.5	2075.0	289.9	1599.0	271.6
		1567.0	260.8	2150.0	282.0	1500.0	233.7	1653.0	286.3	1750.0	252.4	2050.0	283.2	2100.0	287.1	1649.0	270.9
		1667.0	265.7	2200.0	279.4	1600.0	239.8	1753.0	293.5	1800.0	254.5	2100.0	280.7	2125.0	285.4	1699.0	270.2
		1767.0	276.8	2250.0	276.6	1700.0	246.2	1853.0	300.9	1850.0	256.5	2190.0	276.1	2150.0	284.6	1749.0	269.3
		1867.0	282.4	2260.0	278.0	1800.0	266.3	1953.0	293.4	1900.0	261.6			2175.0	284.1	1849.0	269.8
		1967.0	284.4			1850.0	285.7	2053.0	279.3	1950.0	270.2			2200.0	284.0	1949.0	270.4
		2067.0	282.8			1900.0	287.1	2070.0	279.8	2000.0	290.1			2225.0	284.0	1999.0	272.3
		2125.0	281.9			1950.0	277.6			2025.0	293.8			2250.0	284.0	2049.0	272.3
						2000.0	270.7			2050.0	296.7			2275.0	283.6		
						2050.0	283.4			2075.0	298.0			2300.0	283.0		
						2100.0	280.6			2100.0	294.6						
										2125.0	290.5						
										2150.0	270.8						
										2170.0	234.4						
										2175.0							