



CHEMICAL CHARACTERIZATION OF THE THERMAL FLUID DISCHARGE FROM WELL PRODUCTION TESTS IN THE BERLÍN GEOTHERMAL FIELD, EL SALVADOR

Roberto Enrique Renderos

Geotérmica Salvadoreña S.A. de C.V. (GESAL)
km 11½ Carretera al Puerto La Libertad
Santa Tecla, La Libertad
EL SALVADOR, C.A.
rrenderos@gesal.com.sv

ABSTRACT

An extensive chemical monitoring programme has been developed since the beginning of geothermal production of the Berlín geothermal field in 1992. This monitoring programme has made possible the identification of the main processes taking place in the reservoir. Chemical stabilization of the most recently drilled wells, evidence of mixing and boiling, connection between the reinjection and production zones and other physico-chemical processes have been observed through chemical and isotopic monitoring as well as tracer tests. Production tests have been part of this monitoring programme. Water and steam samples have been collected at different wellhead pressures in order to estimate the main contribution of the different aquifers to the production zone, as well as the chemical composition of the feed zone fluids.

Ratios between conservative constituents of geothermal fluids, calculated thermodynamic data and deep chemical composition of the fluids, have been utilized in the present study. According to the result of this analysis, the origin of the fluids seems to be the same for the whole production zone and the chemical composition of the fluid feeding each production well is the same.

1. INTRODUCTION

El Salvador is located on the southern coast of Central America, where the Cocos plate is subducting beneath the Caribbean plate, forming an east-west tectonic graben. On the southern margin of this graben lies the Quaternary volcanic chain. Tectonics and volcanism in the El Salvador region have provided abundant geothermal activity. Ten geothermal areas have been identified, five of which are high-temperature geothermal fields (180-300°C) (Monterrosa, 1998). The Berlín geothermal field is one of them. It is located in the District of Usulután in the eastern part of the El Salvador Republic approximately 112 km east-southeast of San Salvador, the capital city (Figure 1). The well field occupies a part of the northwestern flank of the Berlín-Tecapa volcanic complex, which rises to an elevation of 1300 m a.s.l. The main geological feature of the area is a major caldera, largely filled with volcanic

material, as well as a 3–4 km wide graben extending NNW-SSE. The geothermal activity at the surface can be linked to the graben faults and the volcanic centre. The elevation of the system ranges between 600 and 900 m a.s.l. on the northern slope of the Berlín – Tecapa volcanic complex. The heat source for the geothermal system is believed to be a cooling magma body or intrusion associated with the young activity of the volcanic complex.

The Berlín geothermal field has been utilized for electricity generation since 1992 when two 5 MWe backpressure power units were installed. From 1997 to 1999, 18 wells (8 producers and 10 injectors) were drilled and a new 56 MWe (2 x 28 MW) unit was constructed. The actual power plant was started on the 23rd April 1999 with the commercial operation of condensation unit No.1; on the 1st of July of the same year, commercial condensation unit No. 2 was started.

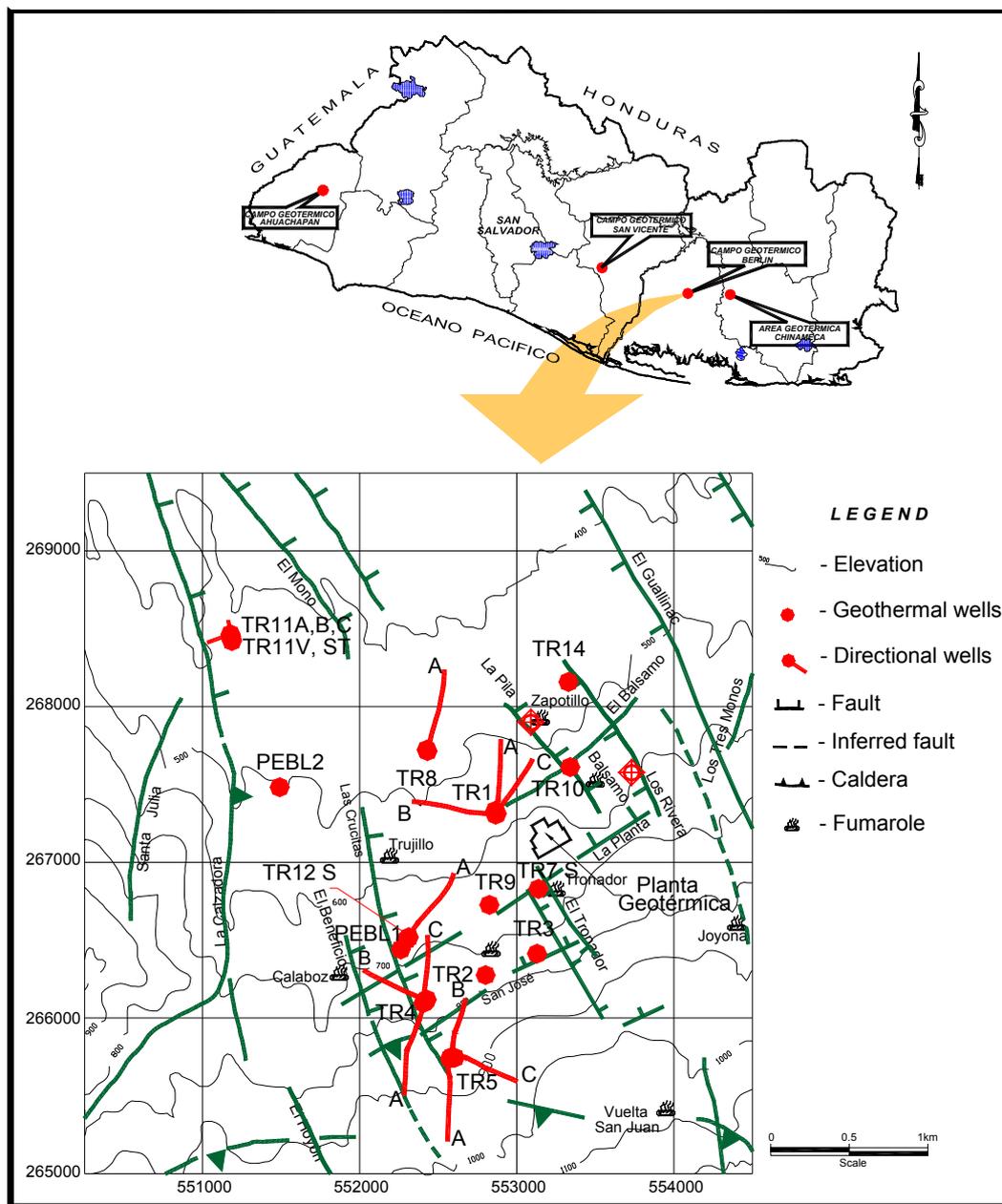


FIGURE 1: Berlín geothermal field

2. EXPLORATION AND UTILIZATION HISTORY

Servicio Geológico Nacional of El Salvador undertook geo-scientific studies of the geothermal area at Berlín in 1953. Interest in the geothermal potential of the area increased in the 1960s, when the Comisión Ejecutiva Hidroeléctrica del Río Lempa (CEL), the National Electricity Company, with the co-operation of the United Nations Development programme, undertook an initial exploration programme that included the drilling of the first deep exploratory well (TR-1). Drilling at Berlín continued from 1976 to 1981, with the drilling of five additional deep wells (TR-2, 3, 4, 5 and 9). All the wells turned out to be good producers, except well TR-4 due to an obstruction at depth. On the basis of these results, CEL decided to install two back-pressured wellhead generation units of 5 MWe (gross) each. These units went into operation in 1992. Wells TR-2 and TR-9 were planned to be used as producers and well TR-1 as a reinjection well for the used fluids, but as limited reinjection capacity didn't allow both power units to be put on line, so well TR-9 was temporarily used as an injection well. Unit I was taken out of production on July 9 1992 due to carryover of corrosion material from well TR-2 to the turbine. From 1993 to 1995 three deep wells, with temperatures 240-270°C, were drilled for reinjection purposes (TR-8, TR-10, TR-14). Both the 5 MWe units have been in operation since February 1995 with wells TR-2 and TR-9 as producers (7.5 MWe) (Montalvo and Axelsson, 2000).

In 1993 Electrosunult (ELC) assessed the feasibility of installing a condensing power plant with a capacity of 50 MWe. In 1994, Geothermal Energy New Zealand Ltd. (GENZL) conducted a geo-scientific survey in Berlín. These studies confirmed the extension of the existing field to the south of the present production area (Rivas, 2000).

From 1997 to 1999 the "First condensing development of Berlín geothermal field" project was carried out. Eight producing and 10 injection wells were drilled. The producing wells are clustered within an area of about 2 km² with depth from about 1900 m to nearly 2400 m, and productive zones are encountered from about 1,550 m depth. Maximum temperatures in the production wells are consistently in the range of about 290 to 305°C. The new power plant with two condensing units of 28 MWe each was then built. Both of them started to operate in November 1999 and utilise the single flash steam power cycle with low-level, direct contact condensers, two stage, steam-jet ejectors for non-condensable gas extraction from the condensers, and mechanical draft cooling towers. The expected production of 56 MWe has almost been attained (50 MWe).

The potential of the Berlín geothermal field has been reassessed by GENZL (PB Power, GENZL Division, 2000) and the result was that the field could sustain 152 ± 42 MWe. In the year 2000, additional geoscientific surveys were carried out by GESAL in the southern part of the geothermal field in order to assess the possibility of installing a third 28 MWe power unit. Four new wells will be drilled, starting next year.

Extensive chemical monitoring has been carried out in order to assess the optimal production management and this report includes an update of the chemical parameters determined in the reservoir fluid and the results of chemical data interpretation from well production tests from 1999 to 2002.

3. GEOLOGICAL AND GEOTHERMAL FEATURES OF THE RESERVOIR

3.1 Geology

The strato-volcano of the Berlín-Tecapa volcanic complex is located inside the system of faults in the southern part of the E-W oriented Central American graben, in the zone of crustal weakness produced by the intersection of the faults of the Central American graben with its conjugate NW-SE and NE-SW (D'Amore and Tenorio, 1999). It is composed of a series of peripheral volcanic cones that expelled andesitic lava and scoria, that emerge around the craters in the southeast part of the caldera of the old Berlín volcano (Correia et al., 1996).

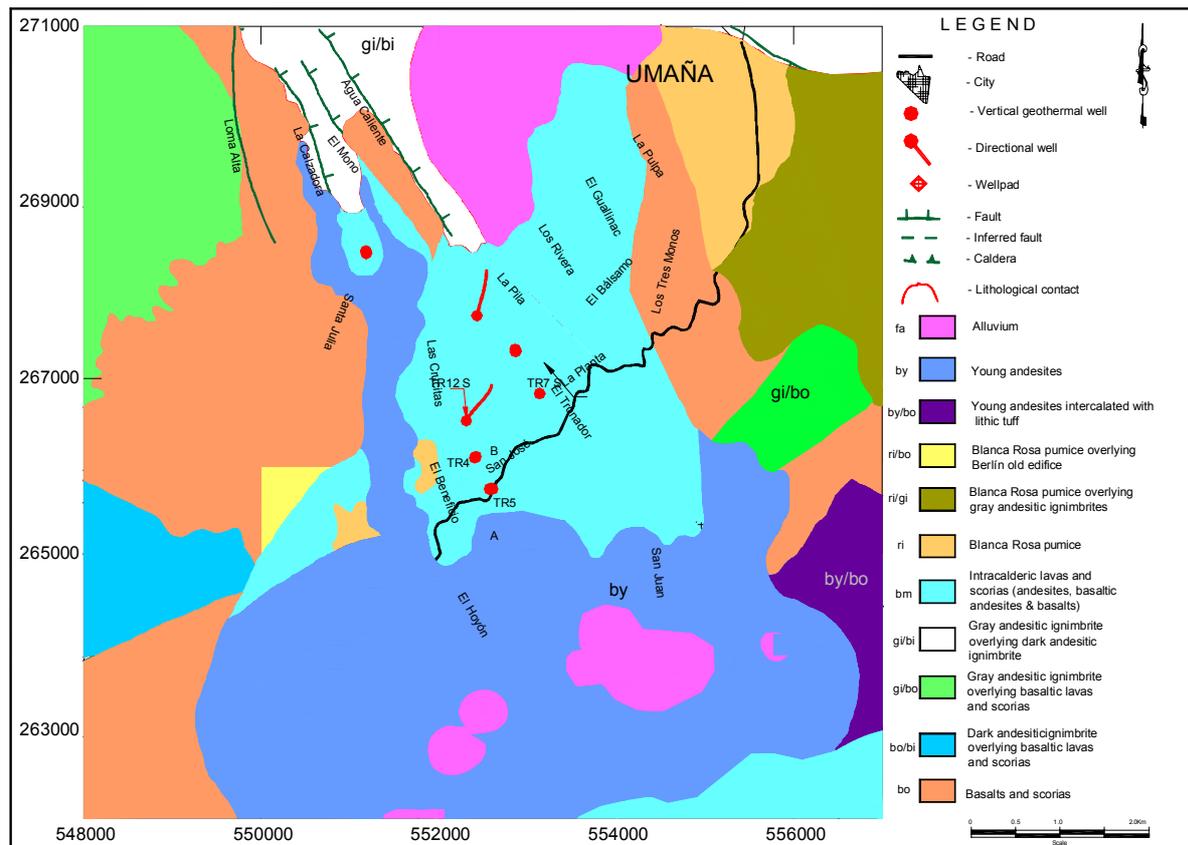


FIGURE 2: Berlín geothermal field structural map

The structure of the graben is related to distensive tectonics, generated by the subduction of the Cocos oceanic plate under the continental Central American-Caribbean plate. Melting of the oceanic plate at depth along the subduction zones produces an andesitic-type magma that rises and accumulates in structurally weak zones of the crust. During the final activity of the Berlín volcano (0.1 Ma), the eruption produced large quantities of ignimbrites and the collapse of the volcanic structure, with the formation of the Berlín caldera (Figure 2). It is evident from the figure that the position of the northern boundary of the caldera is not clear. The heat source, identifiable in an active magmatic chamber, gave rise to the Berlín geothermal system, whose hydrothermal system is related to andesitic volcanism. Geophysical and chemical data indicate that the heat source lies south of the present geothermal field, where the craters are located (Figure 2) (D'Amore and Tenorio, 1999).

The NNW-SSE fault system is the most important regionally as it is responsible for the formation of the Central American graben and also the active Quaternary volcanic chain of the country. Some of the most recent volcanic edifices such as Cerro Pelón, Laguna de Alegría and Cerro de Alegría, 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.

On the other hand the NW-SE fault system is considered the most recent, active and important geothermally, because this system permits the ascent of fluids from depth to the surface. This system has generated a graben that cuts through the northern part of this caldera. The majority of the hydrothermal manifestations and the geothermal field itself are found inside this structure (Correia et al., 1996).

3.2 Alteration mineralogy

The alteration mineralogy characterizing the Berlín geothermal field is due to the replacement of original glass and minerals by secondary minerals. The primary mineralogy associated with the subsurface lithology distribution is summarized in Table 1.

TABLE 1: Primary mineralogy of Berlín geothermal field

Rock type	Primary minerals identified
Basalt	Labradorite, bytownite, augite, hypersthene and pigeonite
Andesitic-basalt	Labradorite, andesine, augite and hypersthene
Andesites	Andesine, augite and hypersthene
Lithic tuff	Rock fragment, clay and glass
Pumice	Glass

The hydrothermal alteration of the Berlín geothermal field is characterised by a mixture of secondary minerals shown in Table 2. 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, which is associated with permeable zones at high-temperatures (230-260°C).

TABLE 2: Secondary minerals identified in the Berlín geothermal field

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

The mineralogical facies are defined using the empirical relationship between the rock formation temperatures measured in the wells and the alteration temperatures of the secondary minerals (Santos, 1995). Table 3 shows the mineralogical facies as a function of temperatures in the Berlín geothermal field.

TABLE 3: Classification of mineralogical facies of Berlín geothermal field

Facies	Characteristic minerals	Temperature range (°C)	Depth range (m a.s.l.)	Average thickness (m)
Argillic	Clay minerals: Zeolite and smectite type	50-150	150 to 50	400
Phyllic-argillic	Clay mineral type chloritic: Zeolite, quartz, calcite	150-180	100 to -100	400
Phyllic	Drop in clay mineral content and appearance of chlorite traces	180-200	-400 to -700	600
Phyllic-prophyllitic	Chlorite group (type pennite) and epidote traces	200-230	-950 to -1200	300
Prophyllitic	Epidote	230-250	-1200 to ?	?

3.3 Hydrogeochemistry

The average temperature in the liquid-dominated geothermal field of Berlín is close to 300°C in the southern production zone, in wells TR-5, TR-4, and TR-2. The discharged fluids are classified as sodium-chloride type with chloride content from 3000 to 7000 ppm, pH values between 5 and 8 and salinity between 7000 and 20000 ppm. The gas/steam ratio is usually between 0.001 and 0.003 in well steam.

The groundwater of the Berlín geothermal field can be classified into three main groups: (1) neutral sodium-bicarbonate water of shallow meteoric origin, located both in the north and the northwestern parts of the field; (2) sulphate water of surface origin and low pH due to oxidation of H₂S (e.g. spring 83 and Laguna de Alegría); (3) NaCl-type with a high SO₄ concentration, such as springs F-20, F-126, F-128 and F-129.

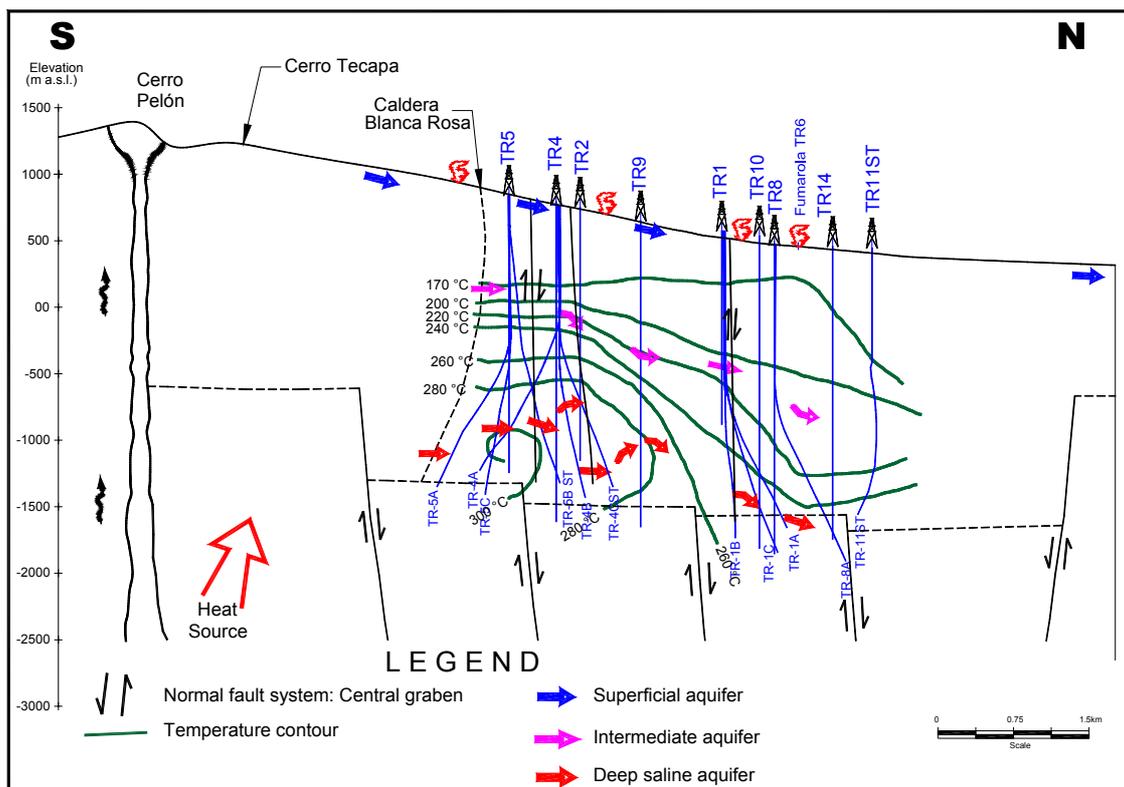


FIGURE 3: Hydrogeochemical conceptual model of the Berlín geothermal field

Using chemical data three types of geothermal aquifers can be identified in the Berlín geothermal field: (1) a low-salinity (1600 ppm) shallow aquifer at depths between 200 and 300 m a.s.l.; (2) intermediate saline aquifers (6600 ppm) at sea level; (3) a deeper saline aquifer (8000-12000 ppm) at a depth of -800 to -1200 m a.s.l. (GESAL, 2000).

Figure 3 shows that the upflow zone is located in the south part of the field, with flow from south to north. During its flow, the fluid cools by boiling and conductive cooling (D’Amore and Tenorio, 1999). The recharge zone is located in the high part of the volcanic complex. Referring to isotope data on rainwater from different altitudes and locations, the recharge of the Berlín geothermal field is at 1350 m a.s.l.

3.4 Reservoir pressure

The most evident change in the Berlín geothermal system during the last 10 years of production has been pressure decline. The reservoir pressures in the Berlín geothermal field have been monitored during different periods in wells TR-4 and TR-5, and presently in well TR-4A in the production zone and TR-10 in the reinjection zone. Wells TR-5 and TR-4 have been used as producing wells since 1999 and 2001, respectively. Unfortunately, the data available from different periods appears not to be fully comparable (Montalvo and Axelsson, 2000).

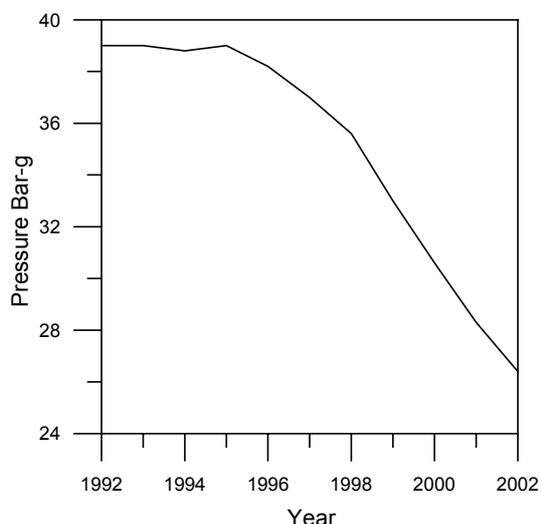


FIGURE 4: Annual average reservoir pressure for Berlín geothermal field

Figure 4 shows the annual average reservoir pressure within the production zone in the Berlín geothermal field where a decline of about 13 bars can be observed.

3.5 Tracer tests

Eleven tracer tests have been carried out in the Berlín geothermal field. The tracers used include iodine-131 (9), ethanol (1) and sodium chloride (1). The tracer tests were carried out to identify hydrothermal connections and geological barriers in different zones of the geothermal field. Only the last tests showed tracer return from injection zone to production zone. The 9th test with Iodine-131 (I-131) in reinjection well TR-12A (Figure 1) lasted from May to August 2000. The results from 93 days of monitoring showed tracer return in production wells TR-4C, TR-5A, TR-5B and TR-9. This is evidence of a connection between the reinjection and production zones with low values of reinjected water returning to the production zone. The tracer percentage recovery was 9.44% for well TR-4C, equivalent to 2.83 kg/s of the total 30 kg/s reinjected in well TR-12A, 2.86% (0.86 kg/s) for well TR-5B, 1.37% (0.41 kg/s) for well TR-9, and 0.24% (0.071 kg/s) for well TR-5A.

4. FLUID CHEMISTRY

4.1 Analytical data

An extensive chemical monitoring programme was carried out during the ten years of production from the Berlín geothermal field. Water and steam samples were collected during normal production of the 9 wells from the wellhead sample point with the aid of a stainless steel Webre mini-separator. Several samples were also collected during production tests in 6 wells over the last three years, but the samples in this case were collected from the two-phase pipeline to the silencer. The sampling technique is the same in both cases, two-phase fluid was separated with the aid of a Webre separator at constant sampling pressure. Samples of the water phase for isotope analysis were collected during production but no reliable isotope data is available for the production tests, probably due to the unsteady conditions of the well during testing.

Chemical analysis was carried out in the laboratory of Geotérmica Salvadoreña S.A. de C.V. in El Salvador, except for some isotopic analysis in 1996 which was carried out in the isotope laboratory of the International Atomic Energy Agency (IAEA) in Vienna. Table 4 lists the analytical methods used for chemical analysis and their capabilities.

TABLE 4: Analytical methods for chemical analysis

Parameter	Method	Detection limit (ppm)
Ca	Atomic absorption spectrophotometry	0.901
SiO ₂	Atomic absorption spectrophotometry	1.458
B	Atomic absorption spectrophotometry and colorimetry	0.3369
K	Atomic absorption spectrophotometry	2.754
Li	Atomic absorption spectrophotometry	0.0246
Mg	Atomic absorption spectrophotometry	0.006
Na	Atomic absorption spectrophotometry	3.621
Cl	Potentiometry and ion chromatography	10.00, 0.043
HCO ₃	Potentiometry	0.39
SO ₄	Colorimetry and ion chromatography	4.87, 0.043
δ ² H, δ ¹⁸ O	Mass spectrometry	-3.62‰ - -118.72‰, -1.17‰ - -15.73‰
CO ₂	Potentiometry	0.41
H ₂ S	Titrimetry	0.01
NCG*	Gas chromatography	0.001 mmol/100 mol

* NCG: He, H₂, Ar, O₂, N₂, CH₄, CO

The groundwater samples are from the year 2001, and reinjection well samples from the year 2002. For the present study, chemical composition of steam and water from geothermal production wells shown in Tables 1 and 2, and for groundwater in Table 3 in Appendix I was used to evaluate the present status of the chemical behaviour of the Berlín geothermal field fluids. Tables 1-6 in Appendix II show the chemical composition of the samples collected during the production tests to study the chemical composition from different feed zones at the level of permeable horizons in the selected wells.

The chloride content of groundwater in the Berlín geothermal field is in the range 2-1150 ppm with temperatures between 37 and 98°C and pH values from 7 to 8; most of the water is bicarbonate type. With reference to the isotopic ratios, groundwater manifestations located in the northwest part of the geothermal field do not have any relation to the Berlín geothermal system (Matus et al., 1999; Magaña 1999).

The chloride concentration of the well discharge water is between 2500 and 8000 ppm. The isotope ratios

for the production well water are found to range from -2.5‰ to -3.8‰ for $\delta^{18}\text{O}$ and from -41‰ to -45‰ for $\delta^2\text{H}$. The range of isotope ratios of reinjection well water is from -2.5‰ to -3.15‰ for $\delta^{18}\text{O}$ and from -43.6‰ to -44.75‰ for $\delta^2\text{H}$.

The concentration of non-condensable gases from well discharges was in the range of 0.21-0.58% per weight for wells TR-5A and TR-4, respectively, in the year 2002. The pattern for non-condensable gas concentrations is similar for fluids from all wells in that they tend to decline with time during well discharge. Only very few exceptions to this have been observed. In wells TR-2 and TR-9, gas concentration increased up to 0.44 wt % in 1995, and subsequently decreased to 0.34 wt % in 2002.

With reference to the relative abundance of chloride, sulphate and bicarbonate in the water of the geothermal wells, the water was classified as sodium-chloride type (Figure 5) with relatively low sulphate and bicarbonate content, typical of high-temperature systems associated with andesitic and rhyolitic magmatism (Magaña, 1999).

Relative Cl and B contents suggest the addition of these two elements before, during or after the rock dissolution process, or loss of Li. According to Figure 6, relative well water concentrations suggest an ageing geothermal system with a homogenous fluid source at depth.

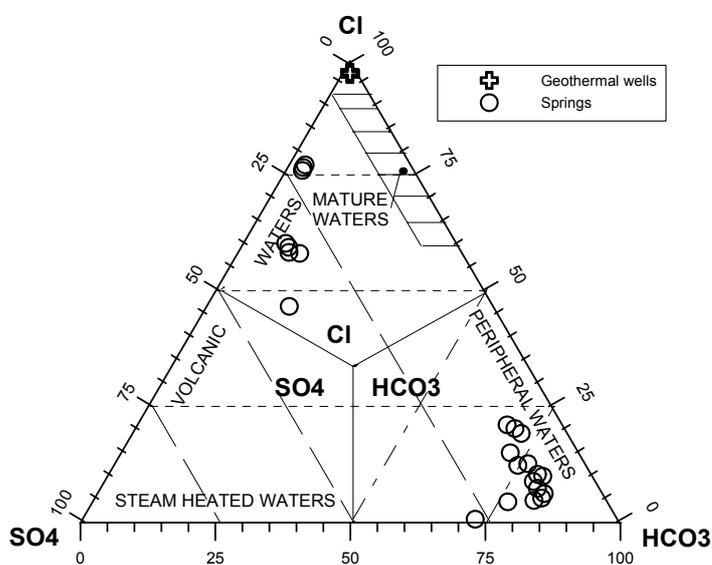


FIGURE 5: The Cl-SO₄-HCO₃ diagram for selected Berlin waters

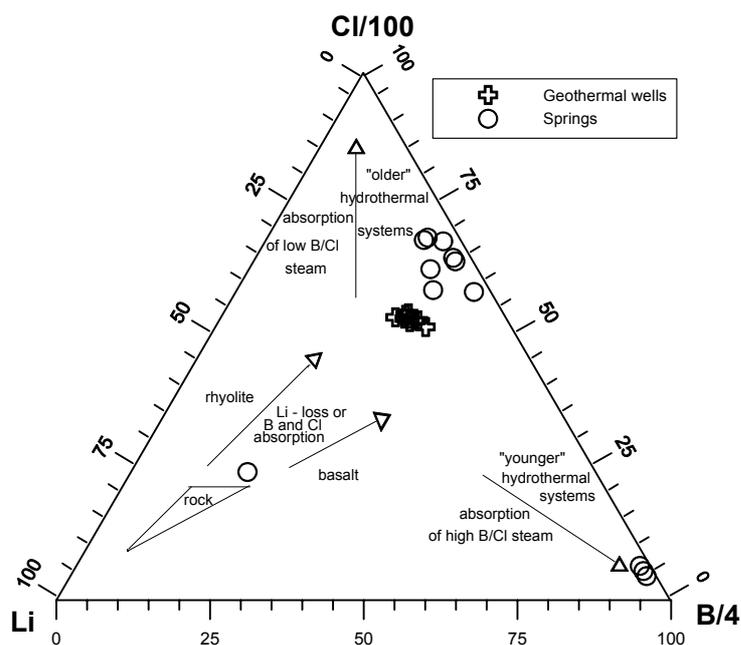


FIGURE 6: The Cl-Li-B diagram for selected Berlin waters

4.2 Isotope composition

Physical properties of geothermal systems like temperature, and physicochemical processes such as water-rock interaction, mixing and steam separation, have a large influence on isotope ratios. As isotopes are able to retain their physical and chemical characteristics, they are suitable as tracers for the origin of water and regional flow directions. Stable isotopes such as ^{18}O and ^2H have distinct roles in defining the hydrological conditions and evaluating the processes that affect fluids. Isotopes are also useful in characterizing boiling and in monitoring the flow of injected fluids (Tenorio et al., 1997).

Since 1996, the laboratory of stable isotopes at Geotérmica Salvadoreña S.A. de C.V has collected monthly rainfall samples at different elevations. This monitoring has been useful in determining the local meteoric water line described by:

$$\delta^2\text{H} = 7.92 \delta^{18}\text{O} + 9.51 \tag{1}$$

with a correlation of 0.992 (Matus et al., 1999). Figure 7 shows the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ ratios of deep geothermal water, ground water and reinjection water (Arnórrsson and D'Amore, 2000). Isotope ratios for production and reinjection wells are similar, although small shifts are observed in well TR-4, TR-5 and TR-5A fluids. The recharge of the Berlín geothermal field is located at 1350 m a.s.l. with reference to isotope data comparison between rainwater from different altitudes and locations, and thermal water. The upflow area is located in the southern part near well TR-5.

The linear relationship between chloride and $\delta^{18}\text{O}$ is evidence of ascending hot water mixed with cold water (Figure 8).

Figure 9 shows the relationship between chloride and $\delta^2\text{H}$ in the well discharge. For well TR-2 dilution with meteoric water is possible due to

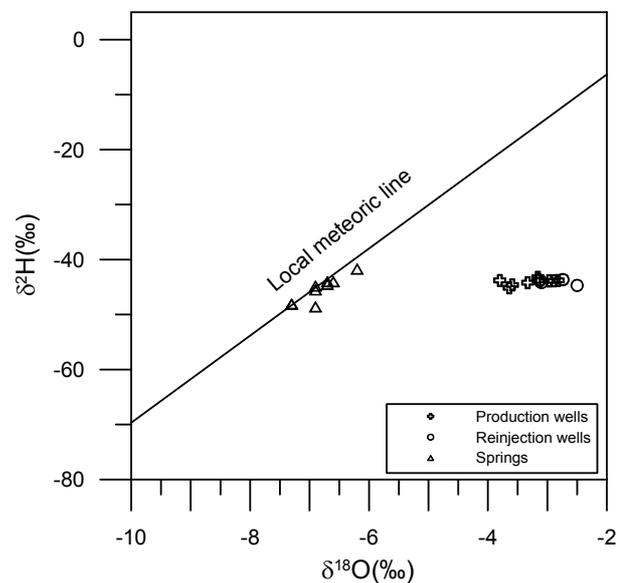


FIGURE 7: $\delta^{18}\text{O}$ vs. $\delta^2\text{H}$ for Berlín waters

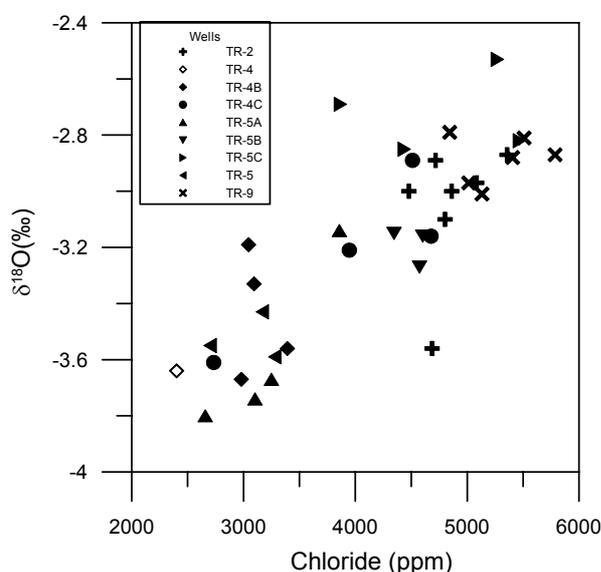


FIGURE 8: Chloride vs. $\delta^{18}\text{O}$ for Berlín well waters

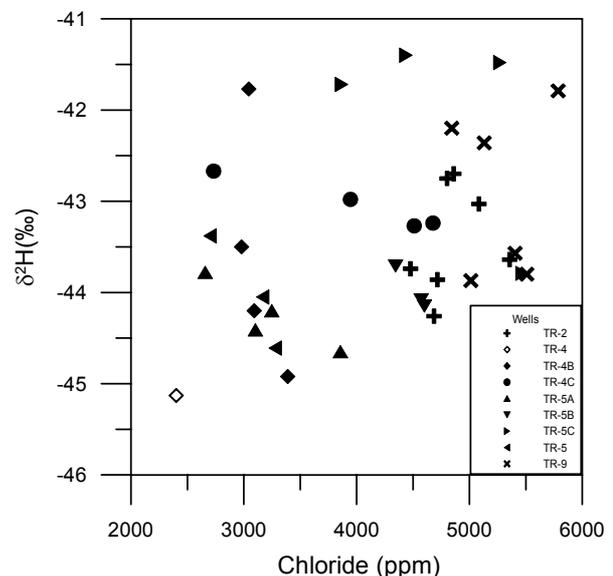


FIGURE 9: Chloride vs. $\delta^2\text{H}$ for Berlín well waters

depletion in $\delta^2\text{H}$. Values for well TR-5 fluid seem to be getting more negative and increasing in chloride content with time. Values for wells TR-4C and TR-5C fluids are more positive and chloride content has increased over the last three years due to boiling. Isotope ratios in well TR-4B fluids vary greatly during this period, probably because of variable sampling conditions.

In general, the isotope ratios of production wells are approaching a common value with time. Previous publications (Matus et al., 1999; Montalvo and Axelsson, 2000) confirm three main groups of geothermal water according to isotope composition. Recent isotopic data shows that it is not possible to distinguish between new and old production wells or reinjection wells.

4.3 Geothermometers

Three solute geothermometers: Quartz (Fournier and Potter, 1982), Na/K (Arnórsson et al., 1983) and Na-K-Ca (Fournier and Truesdell, 1973), and three gas geothermometers CO_2 , H_2S (Arnórsson et al., 1998; D'Amore and Arnórsson, 2000) and H_2 -Ar (Giggenbach, 1991) were used for estimation of sub-surface temperatures.

Solute geothermometers assume the attainment of chemical equilibrium in geothermal systems. Gas geothermometers are considered to correspond to equilibrium between the respective gases and specific mineral buffers. In Table 5, there is a summary of the results for temperatures of the selected well fluids in the year 2002. In general, gas geothermometers underestimate the temperature values. The H_2S temperatures tend to be lower than measured temperatures. The Na-K-Ca geothermometer yields systematically higher values than the quartz geothermometer. Using solute geothermometry, higher values were obtained for well TR-5 than those for the other wells, in agreement with measured temperatures.

TABLE 5: Results of solute and gas geothermometers for wells in the Berlin area

Well no.	Qtz (°C)	Na/K (°C)	Na-K-Ca (°C)	CO_2 (°C)	H_2S (°C)	H_2 -Ar (°C)	T_{meas} (°C)	Enth. _{mea} (kJ/kg)
TR-2	268	289	277	250	236	253	295	1349
TR-4	274	271	289	269	246	260	298	1309
TR-4B	262	259	266	270	235	252	285	1581
TR-4C	268	285	278	263	238	268	295	1403
TR-5A	274	289	290	231	220	252	295	1433
TR-5B	259	284	279	248	229	256	285	1355
TR-5C	276	280	273	248	232	254	285	1288
TR-5	274	299	295	243	237	256	305	1340
TR-9	257	265	270	250	229	258	285	1344

Figure 10 shows the Na-K-Mg triangular diagram (Giggenbach, 1988). It can be used to classify water as fully equilibrated with rock at given temperatures, partially equilibrated, or immature when the rock is dissolved but no chemical equilibrium has been reached. According to this classification, discharged water from Berlin geothermal wells can be classified as close to fully equilibrated water. This is evidence that the well discharge water is of single origin water according to chemical composition.

4.4 Mineral saturation

The state of saturation for anhydrite, calcite and amorphous silica in the aquifers for selected wells has been evaluated using the WATCH speciation program (Arnórsson et al., 1982; Bjarnason, 1994). The

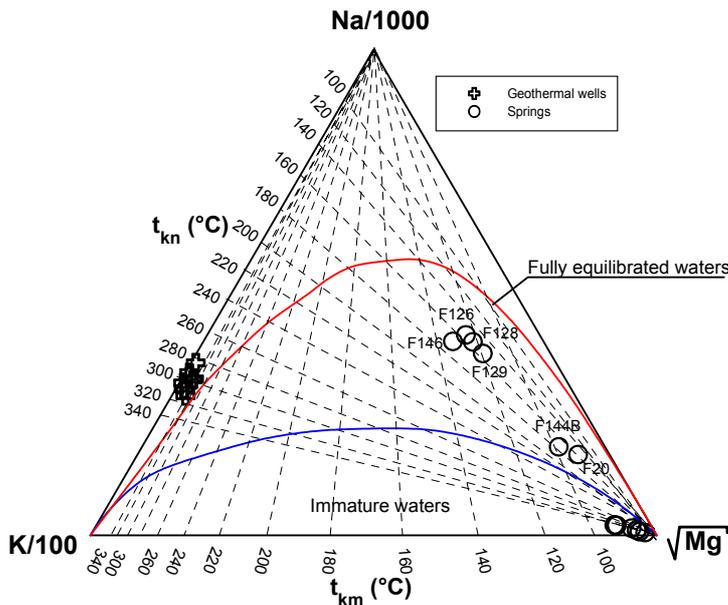


FIGURE 10: The Na-K-Mg triangular diagram for Berlin selected waters

results are presented in Figure 11. The state of saturation was estimated using measured temperature as a reference temperature and one single step adiabatic boiling in the temperature range 100-300°C. In 2002, all well water was oversaturated with respect to amorphous silica at temperatures lower than 160°C and undersaturated at higher temperatures than 180°C. Undersaturation with respect to calcite and anhydrite was observed. Boiling seems to be the reason for supersaturation with respect to amorphous silica.

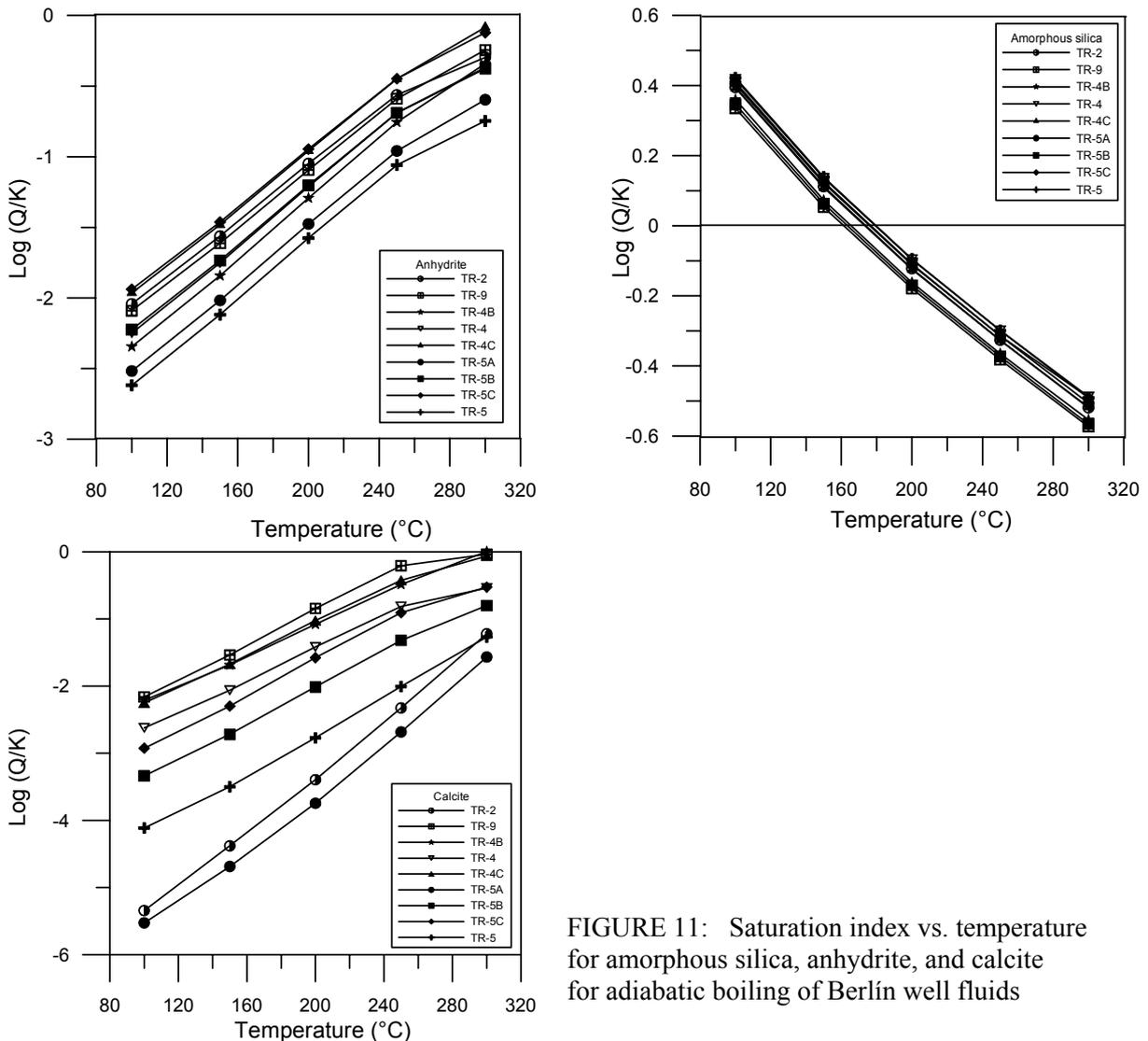


FIGURE 11: Saturation index vs. temperature for amorphous silica, anhydrite, and calcite for adiabatic boiling of Berlin well fluids

4.5 The chloride-enthalpy mixing model

Figure 12 shows the chloride-enthalpy diagram (Fournier, 1981; Arnórsson, 2000), which indicates the main processes occurring in the geothermal system at present conditions in the Berlín geothermal system.

At initial conditions, before production from the geothermal field started, water in well TR-5 was formed by mixing of a parent water with chloride content of 4000 ppm and meteoric water. Direct boiling with steam losses from TR-5 water produced a concentrated brine that progressively affected the water in wells TR-2, TR-9 and, particularly, well TR-3 (D'Amore and Tenorio, 1999).

At the present conditions, boiling and mixing seem to be the predominant processes. Steam loss produces loss of heat and causes the chloride content to increase in the liquid phase. Wells TR-2, TR-4C, TR-5C, and TR-9 are the most representative of this. Most of the geothermal well water plots in the mixing zone.

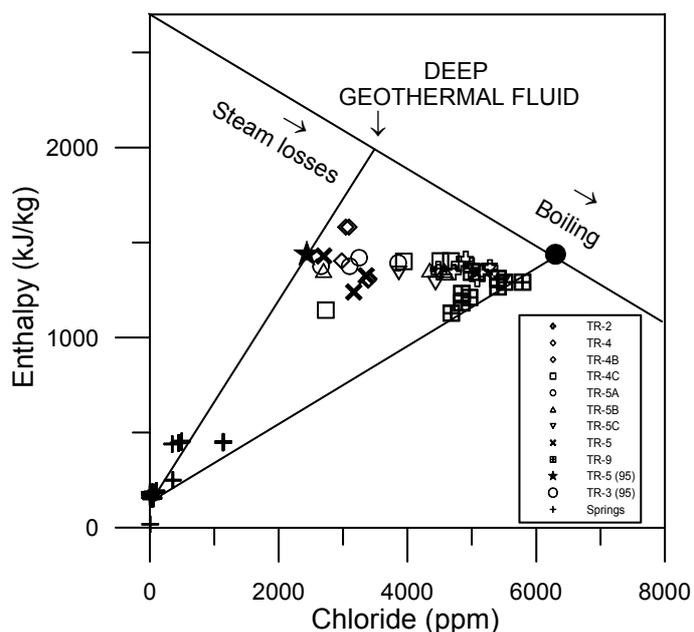


FIGURE 12: Chloride-enthalpy mixing model for the Berlín geothermal well fluids

5. PRODUCTION TESTS

Chemical samples, collected during production tests at different wellhead pressures, have the main objective of trying to identify the chemical composition of the possible different feed zones in a production well. Water and gas samples were collected from the two-phase pipeline after every change in wellhead pressure. Results of chemical analysis are shown in Appendix II and evaluation parameters for the production tests in Appendix III.

The components analysed and parameters determined for each selected well include: chloride and steam fraction at reservoir conditions, the ratios Cl/B, Na/K (Mercado, 1970; Fournier 1981) and Cl/SO₄, quartz (Fournier and Potter, 1982), Na/K (Arnórsson et al., 1983), and Na-K-Ca (Fournier and Truesdell, 1973) geothermometers and measured temperatures, see Appendix IV, (Stefánsson and Steingrímsson, 1990). For wells where downhole chemical data is available, some correlations were tested in an attempt to identify possible feed zones. The WATCH speciation program (Arnórsson et al., 1982, Bjarnason, 1994) was used in order to determine the chemical speciation and steam fraction of the deep fluid. The production wells with available chemical data for the present study are TR-2, TR-4B, TR-4C, TR-5C, TR-5 and TR-9.

5.1 Well TR-2

The maximum measured temperature in well TR-2 is 293 °C at 1700-1800 m depth (-948 to -1048 m a.s.l.) and the maximum chloride content 6238, 7600 and 6268 ppm at 1400, 1750 and 1900 m, respectively (Figure 13). These could be the main feed zones of the well according to downhole data from 1990 (Correia et al., 1996). This information is in agreement with temperature measurements that confirm a permeable zone between 1400 and 1700 m depth.

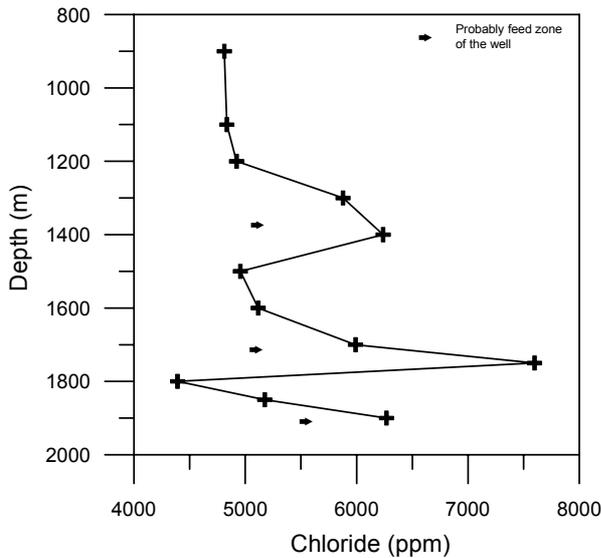


FIGURE 13: Chloride content vs. depth for downhole samples from well TR-2
Berlín geothermal field

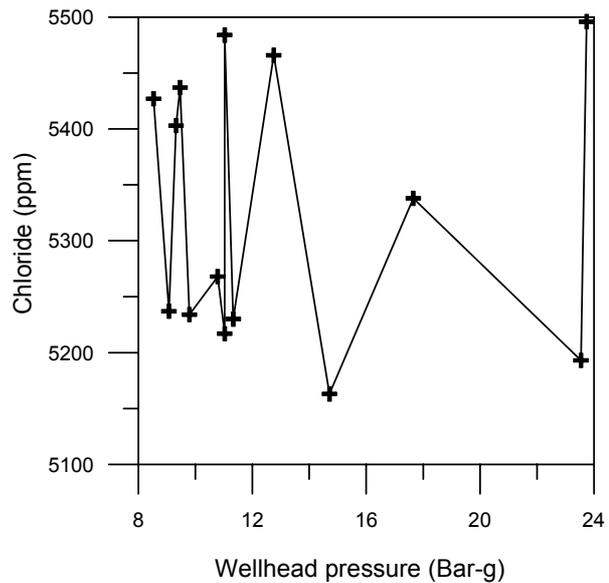


FIGURE 14: Chloride content at reservoir conditions vs. wellhead pressure for production tests in well TR-2

The chloride concentration of the reservoir water during production tests (Figure 14) was between 5163 and 5839 ppm which is higher than that estimated during normal operation of the well (4717 ppm) at 11 bar-g approximately. Quartz temperatures were higher than Na-K-Ca temperatures but not consistently higher than Na/K temperatures. Quartz geotemperatures are often lower than measured temperatures.

There are large variations in the chemical composition of samples from the production test of 19.2.2000, probably due to inadequate stabilization time before collection of samples. But good correlation is observed for data from production tests in 1.5.2000 and 28.4.2001 where Cl/B ratio is in the range 48.8-51.7 for the first date and 52.3-54.4 for the second date. For production tests from 27.10.2000, the Cl/B ratio varies greatly, probably due to water of different origins but this is not consistent with the rest of the production tests. The Na/K ratios are relatively constant in spite of changes in wellhead pressure. There are only variations between different dates for different tests.

The steam fraction at reservoir conditions seems to be constant during each test according to data from 1.5.2000 and 27.10.2000, but there are differences between the two tests. For the test from 28.4.2001, the steam fraction decreases as the wellhead pressure increases, suggesting that water phase only feeds the well.

5.2 Well TR-4B

According to analytical results for a downhole sample collected in February 2002, the maximum concentration of chloride in well TR-4B is 2785 ppm at 2000 m depth (Figure 15). Results of temperature measurements were used to identify a permeable zone between 1900 and 2100 m depth.

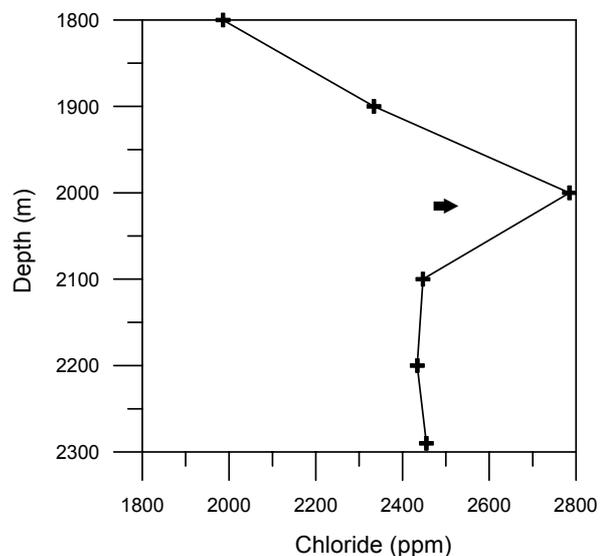


FIGURE 15: Chloride content vs. depth for downhole samples from well TR-4B
Berlín geothermal field

Downhole chemical data is consistent with chemical

data from the production test. The Cl/B ratio is apparently constant with values from 43.1 to 44.3 suggesting that all water is of the same origin. A similar tendency was observed with Na/K ratios. Anomalous values were observed in the production test on 19.2.2000. Partially equilibrated water, according to the Na-K-Mg ternary diagram, was observed as well as temperatures of 240°C for the K-Mg geothermometer, and temperatures of 260°C, and 310°C for the Na/K geothermometer. The quartz geothermometer temperature is higher than measured temperature and Na-K-Ca and Na/K temperatures.

Chloride content at reservoir conditions shows small variations with wellhead pressure during production tests; values from 3260 ppm to 3357 ppm suggest water of the same origin. The CO₂ partial pressures support this. Steam fraction in the reservoir calculated for wellhead pressures between 5.6 and 8.6 bar-g seems to be constant. Values from 0.1957 to 0.1626 were observed when wellhead pressure increased.

5.3 Well TR-4C

No chemical data for a downhole samples is available for well TR-4C, but using results of temperature measurements, permeable zones between 1750 and 2100 m depth were identified. The chloride content at reservoir conditions was constant during each production test, but differences were observed between different tests. Data from 19.2.2000 shows a chloride content in the range 3929 to 4053 ppm. The origin of the water seems to be the same at wellhead pressures between 5.4 and 17.3 bar-g. At wellhead pressure of 9.61 bar-g, low values for Cl/B and Cl/SO₄ were observed compared to the rest of the data, but these values were not consistent with the steam fraction value in the reservoir, which was constant for each test but different between different tests. Chloride content increased during the tests, in agreement with data available from normal production of well TR-4C.

Na/K geothermometer temperatures were higher than Na-K-Ca and quartz temperatures but similar to measured temperatures for the production test of 19.2.2000. Geothermometer temperatures proved similar in the production test of 15.5.2000 but were lower than measured temperatures.

5.4 Well TR-5C

Temperature data for well TR-5C were used to identify the main feed zone at 2000 m depth. Chloride content at reservoir conditions during the production test was in the range 4940-5776 ppm. There is an inverse relationship between chloride content and wellhead pressure (Figure 16). The higher the wellhead pressure, the lower the chloride content. This relationship is not due to differences in steam fractions within the reservoir since those were constant during the production test.

The Cl/B ratio is constant between 49 and 53.2, when wellhead pressure changed. The higher value was observed at 7.4 bar-g. Cl/SO₄ ratios were different for the two production tests, higher values were observed for the production test of 25.3.2001 than for the others. The highest at 5.8 bar-g suggested a high temperature depth or direct fluid movement within the well. Na/K ratios were constant for each production test suggesting that

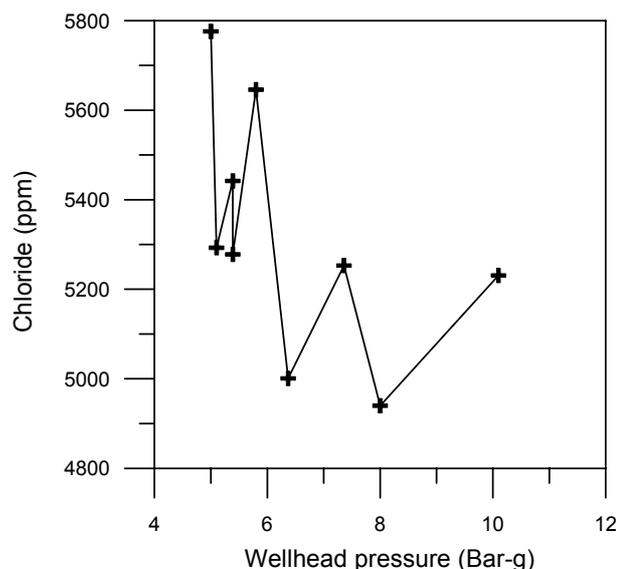


FIGURE 16: Chloride content at reservoir conditions vs. wellhead pressure for production tests in well TR-5C

the same fluid entered the well during each production test.

On 18.3.2000, Na-K-Ca temperatures were higher than Na/K, and quartz temperatures. Measured temperature was lower than Na-K-Ca and equal to Na/K temperature. On 25.3.2001, quartz geotemperatures were higher than Na/K and Na-K-Ca temperatures. Measured temperatures were similar to Na/K temperatures.

5.5 Well TR-5

No recent data for downhole chemistry is available, Figure 17 shows data from 1987, where relatively higher chloride content at the upper levels was observed but does not follow temperature profiles which registered highest values at 1800 m depth (-1000 m a.s.l.). An inversion in the chloride content was observed at 1900 m depth (-1060 m a.s.l.), which was also seen in temperature logs. This could indicate the main feed zone of the well.

Constant values for Cl/B and Na/K ratios, 43.3-46.3 and 4.1-4.9 respectively, were observed in the production tests. This is probably due to water of the same origin and chemical composition feeding the well. No changes in steam fraction at reservoir conditions were observed when wellhead pressure increased, a constant value of 0.0407 was obtained for the production tests of 18.3.2000 and 15.5.2000. Calculated chloride content at reservoir conditions was in the range 3084-3266.

Na/K geotemperatures were higher than Na-K-Ca and quartz temperatures. Measured temperature was lower than Na/K and higher than quartz temperature.

Calculated chloride content for production tests was relatively low at reservoir conditions for all production wells in the Berlin geothermal system. This is in agreement with values obtained for samples collected during the normal operation of the well.

5.6 Well TR-9

According to results for downhole samples from 1991 (Figure 18), chloride content showed a possible feed zone at -1700 m depth, in agreement with temperature data sharing a maximum temperature of 290°C. In most cases, measured temperature was close to quartz temperature and

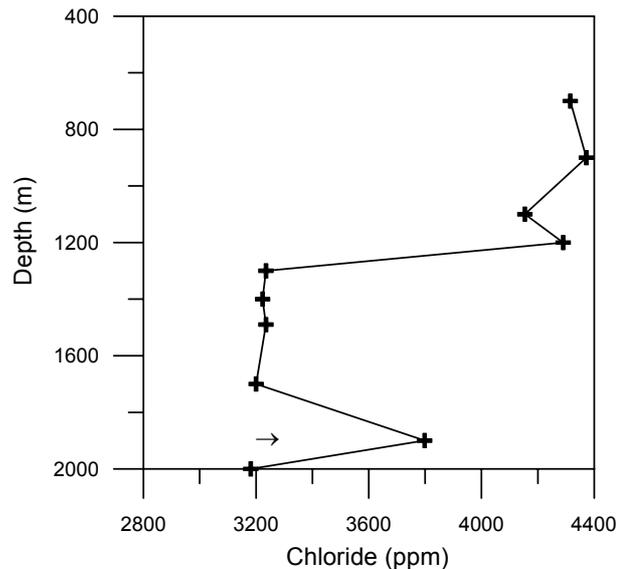


FIGURE 17: Chloride content vs. depth for downhole samples from well TR-5 Berlin geothermal field

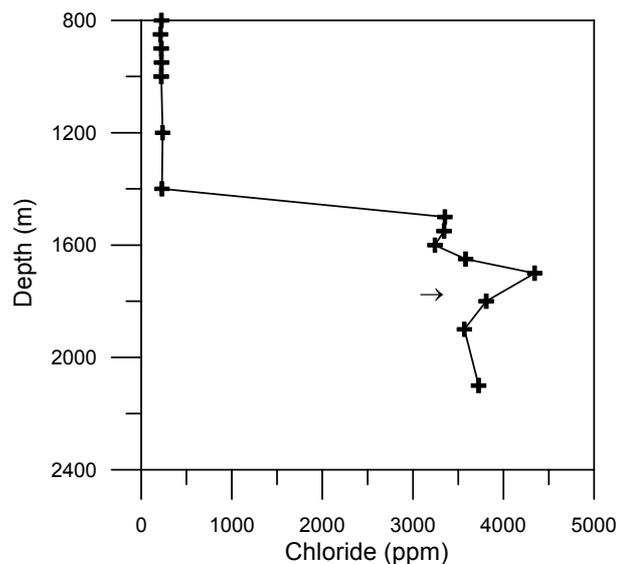


FIGURE 18: Chloride content vs. depth for downhole samples from well TR-9 Berlin geothermal field

higher than Na/K and Na-K-Ca temperatures.

Calculated values for chloride content at reservoir conditions during production tests were in the range 5100-5571 ppm. Cl/B, Na/K and Cl/SO₄ ratios in the range 51.6-60.0, 4.7-5.0 and 876-967, respectively, indicating that fluid of a single origin is feeding the well.

For the production test of 19.2.2000, calculated steam fraction at reservoir conditions was zero. This is evidence of boiling and liquid-dominant fluid feeding the well with increased wellhead pressure.

6. CONCLUSIONS

The solute geothermometers most often yielded temperatures comparable to those measured in the aquifer of the wells selected for the present study. All the gas geothermometers gave too low values. In order to improve them, it is necessary to obtain appropriate calibration that takes into account the composition of the mineral in the buffers with which these gases tend to equilibrate.

$\delta^2\text{H}$ ratios are relatively constant but there is a trend toward lower negative values for $\delta^{18}\text{O}$ for fluids from the production zone and lower negative values for reinjection well fluids. The isotope ratios of production well fluids in the Berlín geothermal field are very similar.

As there are no changes in the concentration of chloride and carbon dioxide in the total discharge despite changes in the discharge enthalpy as well as in the chemical composition at different sampling pressures, the excess enthalpy could be due to the heat flow from the rock to the fluid moving through the aquifer to wells TR-4B, TR-4C, and TR-5A.

Boiling seems to be the predominant process controlling the chemistry of the system, as is most clearly shown by TR-2, TR-4C, TR-5C and TR-9 well fluids.

Comparison between solute thermometers and those measured at the depth level of the permeable horizons as well as results of the production tests, suggest that the deep aquifer constitutes the main feed zones for the wells in the Berlín geothermal system. The Cl/B ratio varies between 42.6 and 52.5, and is very similar for all the wells. These values suggest that the origin of the fluids feeding the wells is the same. Observed differences are due to different processes as well as thermodynamic and geological conditions around the wells, that cause changes in physico-chemical characteristics.

Data obtained from chemical analysis during some of the production tests was not reliable. Lack of adequate stabilization time during sampling seems to be the main reason for this. This aspect should be considered if production tests continue to be part of the chemical monitoring of the Berlín geothermal field.

Isotope ratios could be useful in trying to identify the possible origin of feeding zones. Unfortunately this data was not available for the present study, but should be included in future studies.

A future chemical monitoring programme for the Berlín geothermal field should include downhole sampling as well as production tests. Data obtained from downhole chemistry could give more reliable information than production tests, about the high-activity hydrothermal zones in producing aquifers. No evidence of different feeding zones was obtained during the present study for production tests. The feeding fluids had the same chemical properties when all the evaluation parameters, included in this report, were considered.

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APPENDIX I: Chemical composition of geothermal fluids in the Berlín system

TABLE 1: Gas composition Berlín production well fluids (in mmol/100 moles)

Well	Year	H ₂	Ar	N ₂	CH ₄	CO	H ₂ S	CO ₂	NH ₃	Total	Weight %
TR-2	1993						19	110		129.00	0.30
TR-2	1994						13.7	105		118.70	0.28
TR-2	1995	1.23		3.92	0.32		8.58	169	0.12	182.90	0.44
TR-2	1996	1.95		2.49	0.28		11.19	122	0.08	138.18	0.32
TR-2	1997	1.33		2.49	0.3		11.16	117	0.11	132.85	0.31
TR-2	1998	1.46		1.2	0.29	0.01	16.42	114	0.09	133.00	0.31
TR-2	1999	1.41	0.155	2.63	0.27	0.01	12.02	122	0.09	138.59	0.33
TR-2	2000	1.44	0.148	3.30	0.25	0.05	11.00	114		130.41	0.31
TR-2	2001	1.42	0.126	2.79	0.26	0.00	12.47	113		130.21	0.31
TR-2	2002	1.86	0.142	4.42	0.42	0.00	16.38	124		147.64	0.34
TR-4	2002	2.39	0.146	9.19	0.45	0.00	23.93	213		248.72	0.58
TR-4B	1999	1.89	0.325	7.19	0.29	0.11	17.12	254	0.017	281.25	0.67
TR-4B	2000	2.01	0.184	4.19	0.27	0.10	14.38	237		258.28	0.61
TR-4B	2001	1.62	0.152	2.82	0.26	0.00	11.47	133		149.52	0.35
TR-4B	2002	1.80	0.142	1.62	0.32	0.00	16.31	221		241.18	0.57
TR-4C	1999	1.84	2.53	23.0	0.40	0.16	15.18	277	0.070	320.27	0.75
TR-4C	2000	1.49	0.190	3.94	0.27	0.10	12.12	154		172.21	0.41
TR-4C	2001	4.22	0.329	1.33	0.25	0.10	22.71	137		166.20	0.38
TR-4C	2002	2.97	0.141	10.6	0.47	0.00	17.74	178		210.40	0.49
TR-5A	1999	1.45	0.349	7.33	0.29	0.11	13.54	139	0.112	162.83	0.38
TR-5A	2000	1.27	0.204	2.37	0.25	0.09	11.00	108		123.63	0.29
TR-5A	2001	2.99	0.498	2.96	0.27	0.00	18.22	85.3		110.20	0.25
TR-5A	2002	1.12	0.088	3.98	0.26	0.00	9.29	74.7		89.44	0.21
TR-5B	1999	1.41	0.168	3.28	0.27	0.10	15.07	134	0.103	154.40	0.36
TR-5B	2000	1.58	0.174	3.87	0.27	0.10	11.95	124		141.73	0.33
TR-5B	2001	1.61	0.131	2.32	0.26	0.10	11.68	114		130.06	0.31
TR-5B	2002	1.85	0.129	7.50	0.40	0.00	13.12	116		139.30	0.32
TR-5C	1999	1.54	0.688	10.5	0.30	0.12	15.79	101	0.386	130.49	0.30
TR-5C	2000	1.27	0.145	2.98	0.27	0.10	11.63	96.2		112.61	0.26
TR-5C	2001	1.87	0.200	1.81	0.26	0.10	10.40	96.9		111.57	0.26
TR-5C	2002	1.71	0.126	2.88	0.34	0.00	14.63	116		135.83	0.32
TR-5	1999	1.59	0.142	2.64	0.27	0.10	12.68	134	0.185	151.51	0.36
TR-5	2000	1.46	0.167	3.67	0.26	0.10	12.87	126		144.72	0.34
TR-5	2001	3.36	0.429	5.41	0.28	0.11	11.07	145		165.46	0.39
TR-5	2002	1.76	0.124	5.72	0.37	0.00	18.24	135		161.70	0.38
TR-9	1993						17.28	102		119.48	0.28
TR-9	1994						12.85	107		119.95	0.29
TR-9	1995	1.5		2.95	0.31		13.57	178	0.14	196.94	0.47
TR-9	1996	1.61		2.65	0.32		13.34	125	0.01	143.38	0.34
TR-9	1997	1.82		3.55	0.34		12.32	184	0.15	202.59	0.48
TR-9	1998	1.93	0.14	1.61	0.27	0.10	16.24	194		214.38	0.51
TR-9	1999	1.79	0.13	2.77	0.24	0.09	12.60	198		215.92	0.51
TR-9	2000	1.73	0.145	3.43	0.24	0.09	12.01	115		133.20	0.31
TR-9	2001	1.62	0.125	2.10	0.26	0.00	13.01	119		136.64	0.32
TR-9	2002	2.06	0.14	4.33	0.40	0.00	12.92	122		142.18	0.33

TABLE 2: Chemical and isotopic composition of Berlin geothermal well waters

Well	Year	Na	K	Ca	Mg	Li	Cl	SO ₄	HCO ₃	SiO ₂	B	pH	S.P. (bar-g)	Enthalpy (kJ/kg)	δ ² H (‰)	δ ¹⁸ O (‰)
TR-2	1992	3375	765	68	0.09		6900	4.4	12.9	856	145	6.72	7.8	1352		
TR-2	1993	3923	825	76	0.08		6842	5.6	9.51	781	133	6.42	7.6	1339		
TR-2	1994	3755	865	90	0.078		6933	4	14.6	901	118	6.8	8.0	1378		
TR-2	1995	4170	970	23	0.161	15.2	7460	13.5	7.8	889	132	6.0	2.4	1345		
TR-2	1996	3980	868	64	0.043	16.7	6756	7.2	27.1	699	128	6.82	7.8	1369	-44.26	-3.56
TR-2	1997	3600	803	94	0.071	15.2	6599	3.5	7.1	916	117	6.2	9.7	1413	-42.7	-3.00
TR-2	1998	3623	812	76	0.107	14.6	6676	5.4	11.9	927	143	6.7	9.2	1388	-42.75	-3.10
TR-2	1999	3553	731	118	0.054	14.4	6459	6.1	8.51	733	125	6.52	10.79	1308	-43.03	-2.97
TR-2	2000	3072	693	83	0.062	11.5	5683	1.5	9.5	718	93	6.30	10.00	1360	-43.74	-3.00
TR-2	2001	3299	612	80	0.0326	10.6	5780	7.6	1.0	575	119	6.43	11.7	1344	-43.64	-2.87
TR-2	2002	3378	688	87	0.053	14.9	6328	15.4	0.37	728	117	5.24	12.0	1344	-43.86	-2.89
TR-4	2002	2490	526	31	0.005	9.9	4666	21.7	6.6	784	93	6.96	10.8	1309	-45.13	-3.64
TR-4B	1998	2205	575	50	0.04	10.1	4068	14.6	40.7	998	104	7.37	2.26	1085	-41.56	-3.31
TR-4B	1999	2145	488	31	0.043	8.5	3861	12.1	44.0	718	94	7.21	9.51	1302	-44.92	-3.56
TR-4B	2000	2192	469	28	0.011	7.8	3946	3.3	28.7	756	82	7.0	9.48	1403	-43.5	-3.67
TR-4B	2001	2256	468	30	0.043	7.2	4084	2.0	15.1	632	79	7.07	8.24	1581	-41.77	-3.19
TR-4B	2002	2259	374	25	0.001	6.7	4081	17.8	12.1	683	88	6.95	9.80	1581	-44.2	-3.33
TR-4C	1999	2237	489	26	0.107	7.7	3812	5.8	10	723	99	6.50	8.8	1144	-42.67	-3.61
TR-4C	2000	2890	593	51	0.026	9.9	5347	5.0	16.1	747	103	6.93	10.79	1401	-42.98	-3.21
TR-4C	2001	3334	706	81	0.007	11.7	6138	15.1	3.8	664	127	6.18	10.35	1403	-43.27	-2.89
TR-4C	2002	3421	693	77	0.013	13.5	6326	20.8	10.7	736	115	6.78	11.0	1403	-43.24	-3.16
TR-5A	1999	2028	456	18	0.065	8.3	3655	10.7	4.2	791	82	6.01	9.38	1375	-43.78	-3.8
TR-5A	2000	2309	515	25	0.046	8.9	4226	5.8	6.0	824	72	6.10	10.30	1375	-44.41	-3.74
TR-5A	2001	2820	603	30	0.025	12.0	5092	6.5	2.9	924	114	6.28	11.0	1393	-44.65	-3.14
TR-5A	2002	2272	489	21	0.26	8.7	4273	14.1	0.9	750	86	5.66	11.8	1420	-44.2	-3.67
TR-5B	1999	2242	533	38	0.08	11.3	4134	8.9	10.0	677	87	6.31	9.86	1354	-43.52	-3.26
TR-5B	2000	3006	590	59	0.036	10.8	5410	4.1	9.5	750	106	6.52	10.25	1354	-44.08	-3.27
TR-5B	2001	3375	685	66	0.001	10.9	5960	8.9	3.3	697	121	6.46	11.9	1340	-44.15	-3.16
TR-5B	2002	2982	614	62	0.037	12.6	5647	12.6	3.8	656	107	6.46	11.5	1355	-43.71	-3.15
TR-5C	1999	3006	595	101	0.12	12.9	5336	11.4	16.8	607	109	6.9	5.88	1339	-41.72	-2.69
TR-5C	2000	3300	652	103	0.087	13.0	5874	8.6	7.4	668	123	5.05	9.51	1285	-41.395	-2.85
TR-5C	2001	4075	728	139	0.029	14.8	6970	10.8	3.2	671	136	6.15	9.61	1354	-41.48	-2.53
TR-5C	2002	3803	761	128	0.154	18.2	7059	15.0	5.3	747	122	6.54	12.3	1288	-43.79	-2.82
TR-5V	1999	1525	373	14	0.030	7.1	2807	5.6	5.7	580	69	6.3	8.9	1498		
TR-5V	2000	2065	475	22	0.057	8.2	3833	4.2	9.6	730	86	6.5	10.0	1429	-43.38	-3.55
TR-5V	2001	2588	547	25	0.001	9.5	4526	8.1	4.6	656	93	6.1	9.46	1240	-44.05	-3.43
TR-5V	2002	2466	563	25	0.022	10.6	4604	10.4	1.8	780	90	6.37	11.3	1325	-44.61	-3.59
TR-9	1993	4025	770	83	0.09		6914	4.3	7.9	854	132	6.5	7.6	909		
TR-9	1994	3405	825	72	0.08		6199	7.2	8.9	703	119	6.6	8	1232		
TR-9	1995	3545	750	94	0.22	14.1	6106	7.9	27.9	459	116	7	2.6	1211		
TR-9	1996	3645	735	110	0.14	14.9	6587	9.2	30.1	645	127	7.1	10.8	1266		
TR-9	1997	4005	819	115	0.06	15.7	6803	15.9	27.5	659	132	7.01	19.6	1291	-41.79	-2.87
TR-9	1998	3818	838	120	0.06	15.7	7126	7	25.6	853	150	7.13	17.3	1291	-43.8	-2.81
TR-9	1999	3289	661	141	0.050	13.2	5540	5.8	19.3	606	123	6.93	13.7	1128	-42.36	-3.01
TR-9	2000	3449	733	122	0.211	12.6	6282	5.4	24.4	771	108	6.75	10.0	1183	-42.2	-2.79
TR-9	2001	3361	718	120	0.062	13.3	6121	18.9	9.0	674	126	5.28	11.08	1311	-43.57	-2.88
TR-9	2002	3644	714	134	0.006	14.9	6526	13.9	9.3	632	120	6.52	10.9	1344	-43.87	-2.97
TR-1A	2002	3525	731	83	0.091	14.7	5999	18.3	1.59	844	118	6.5			-43.87	-3.13
TR-1C	2002	3579	736	86	0.095	15.0	5815	16.8	3.84	845	121	6.5			-43.72	-3.13
TR-3	2002	3489	684	99	0.060	11.6	6405	14.2	1.89	827	124	5.6			-44.70	-2.50
TR-8A	2002	3964	777	118	0.079	18.4	7627	14.3	5.06	808	138	6.6			-43.63	-2.74
TR-11st	2002	3558	741	82	0.091	15.3	6267	17.5	4.39	840	118	6.7			-44.19	-3.10
TR-14	2002	3948	810	116	0.065	18.5	7626	18.2	6.1	822	138	6.5			-43.66	-2.74

TABLE 3: Chemical and isotopic composition of groundwater in the Berlín area (in ppm)

Sample	Na	K	Ca	Mg	Li	Cl	SO ₄	HCO ₃	SiO ₂	B	δ ¹⁸ O (‰)	δ ² H (‰)
F-1	34.2	11.1	31.9	32.5	0.13	6.9	14.7	361	121	0.18	-6.9	-44.9
F-5	27.1	8.8	27.2	28.0	0.11	6.5	12.9	301	115	0.16	-6.8	-48.7
F-12	77.3	19.2	40.8	24.5	0.10	100	35.7	303	155	1.8	-6.6	-43.8
F-16	52.7	13.4	33.8	21.4	0.12	25.3	34.1	329	152	0.65	-6.8	-44.1
F-20	293	10.2	83.0	1.6	0.29	362	263	107	120	5.7	-6.3	-41.9
F-80	50.2	14.9	13.8	5.2	0.10	4.6	53	147	165	1.9	-6.8	-45.5
F-126	706	22.6	135	0.7	0.35	1149	266	25.3	123	13.9	-5.6	-38.5
F-128	704	22.4	133	0.8	0.34	1146	273	25.0	128	14.2	-5.5	-40.8
F-129	710	23	137	0.9	0.35	1141	280	25.9	130	14.4	-5.5	-40.4
F-144	339	13.6	73.5	0.001		501	245	55	179	6.8	-6.2	-42.1
F-144B	331	14.7	70.9	1.7		493	244	63	163	5.7	-6.2	-42.3
F-145	335	13.5	58.7	0.16		450	230	63	175	7.4	-6.1	-41.6
F-146	333	8.0	63.1	3.9		352	172	61	132	4.2	-6.2	-41.5
P-4	44.9	14.7	54.0	29.1	0.01	44	34.9	300	120	0.72	-6.7	-44.5
P-5	52.9	16.7	42.6	21.3	0.01	57	42.9	272	135	0.70	-6.1	-40.0
P-7	54.1	16.9	36.5	26.2	0.01	49.2	33.9	301	132	0.88	-7.4	-48.2

APPENDIX II: Chemical composition of geothermal fluids during production tests in the Berlín geothermal field0

TABLE 1: Chemical composition during production tests in well TR-2 (water concentrations in ppm)

Well	Time	Date	Na	K	Ca	Mg	Li	Cl	SO ₄	HCO ₃	SiO ₂	B	pH	H ₂	Ar	N ₂	(mmol / 100 moles)				Enthalpy (kJ/kg)	S.P. (bar-g)	
																	CH ₄	CO	SH ₂	CO ₂			
TR-2	13:55	19.2.2000	3960	831	107	0.056	16.69	7423	4.5	12.0	936	123	6.6	1.21	1.05	3.21	0.27	0.1	10.1	111	1336	7.1	10.8
TR-2	14:40	19.2.2000	3896	862	104	0.071	16.30	7316	6.1	9.9	961	144	6.6	1.44	1.46	3.62	0.27	0.1	11.0	103	1336	6.7	14.7
TR-2	17:30	19.2.2000	4024	904	104	0.621	13.76	7353	5.1	10.8	981	115	6.7	1.29	1.71	2.50	0.26	0.1	11.2	101	1336	5.1	23.5
TR-2	10:55	1.5.2000	3852	766	83	0.115	12.35	7358	4.6	9.6	890	151	6.7	1.32	0.12	1.22	0.25	0.1	11.0	97	1344	7.4	9.1
TR-2	11:47	1.5.2000	3834	769	105	0.087	12.16	7320	4.3	10.5	879	149	6.9	1.05	0.10	0.07	0.25	0.1	10.0	96	1344	7.8	9.8
TR-2	12:50	1.5.2000	4158	764	108	0.078	11.76	7338	5.5	12.5	860	149	6.7	1.24	0.10	1.18	0.26	0.1	10.4	94	1344	7.3	11.0
TR-2	13:40	1.5.2000	4048	863	99	0.107	16.43	7395	3.5	9.4	877	143	6.7	1.22	0.12	1.63	0.23	0.1	9.7	92	1344	6.8	11.3
TR-2	10:02	27.10.2000	4242	839	125	0.315	15.03	7645	26.1	13.4	899	122	6.3	2.03	0.15	2.02	0.26	0.1	13.4	107	1360	6.8	9.3
TR-2	10:40	27.10.2000	4187	824	113	0.099	15.06	7756	8.2	15.5	905	120	6.5	1.96	0.14	2.08	0.26	0.1	13.0	71	1360	6.1	9.5
TR-2	12:30	27.10.2000	4120	851	121	0.094	15.03	7887	8.6	35.4	907	109	6.6	1.94	0.14	2.31	0.26	0.1	13.3	74	1360	5.5	11.0
TR-2	14:18	27.10.2000	4137	913	96	0.093	16.37	8010	6.7	17.2	996	135	6.6	2.06	0.16	2.82	0.26	0.1	13.2	80	1360	4.7	23.7
TR-2	07:55	28.4.2001	4137	883	104	0.055	16.79	7720	7.7	4.5	898	143	6.5	1.80	0.14	2.63	0.23	0.1	16.0	146	1349	6.4	8.5
TR-2	08:50	28.4.2001	4293	861	114	0.102	16.82	7796	6.7	4.4	887	143	6.6	1.82	0.17	2.85	0.26	0.1	19.8	241	1322	6.2	12.8
TR-2	10:10	28.4.2001	4089	891	95	0.143	16.28	7650	5.0	2.2	892	146	6.8	1.74	0.18	4.25	0.24	0.1	10.1	217	1296	5.8	17.7

TABLE 2: Chemical composition during production tests in well TR-4B (water concentration in ppm)

Well	Time	Date	Na	K	Ca	Mg	Li	Cl	SO ₄	HCO ₃	SiO ₂	B	pH	H ₂	Ar	N ₂	(mmol / 100 moles)				Enthalpy (kJ/kg)	P Mx (bar-g)	WHP (bar-g)
																	CH ₄	CO	SH ₂	CO ₂			
TR-4B	13:00	2/19/00	2687	600	40	1.181	11.35	5037	12.5	42.3	1018	117	7.5	1.42	1.38	2.05	0.26	0.10	11.1	148	1320	1.52	6.37
TR-4B	13:55	2/19/00	2767	366	38	0.6	10.93	4911	9.00	42.6	988	118	7.6	1.57	1.90	2.87	0.27	0.11	11.8	157	1320	1.42	5.39
TR-4B	6:44	4/1/01	2678	482	44	0.030	8.71	4712	22.6	22.0	965	108	7.4	2.88	0.16	3.08	0.26	0.10	20.6	172	1559	4.9	5.59
TR-4B	7:37	4/1/01	2852	534	39	0.016	8.58	4643	18.9	19.9	960	105	7.3	2.82	0.15	2.36	0.27	0.10	23.6	191	1543	4.9	6.18
TR-4B	8:33	4/1/01	2830	540	34	0.001	8.44	4596	18.9	20.3	966	107	7.3	2.99	0.14	2.39	0.27	0.10	13.8	190	1532	4.70	6.47
TR-4B	9:24	4/1/01	2371	512	37	0.001	9.21	4460	18.6	23.3	1014	101	7.3	2.30	0.16	2.42	0.27	0.10	12.7	198	1509	8.63	8.63

TABLE 3: Chemical composition during production tests in well TR-4C (water concentration in ppm)

Well	Time	Date	Na	K	Ca	Mg	Li	Cl	SO ₄	HCO ₃	SiO ₂	B	pH	H ₂	Ar	N ₂	CH ₄	CO	SH ₂	CO ₂	Enthalpy (kJ/kg)	P Mx WHP (bar-g)	
																						Enthalpy (kJ/kg)	P Mx
TR-4C	2:50	2/19/00	3401	775	61	0.076	13.80	6166	7.9	17.94	927	114	7.0	1.33	4.66	4.11	0.28	0.11	12.5	143.1	1484	2.35	5.39
TR-4C	3:38	2/19/00	3355	753	60	0.037	13.69	6105	8.1	26.42	807	129	7.4	1.32	4.57	4.05	0.27	0.11	11.4	127.6	1484	2.25	8.33
TR-4C	4:20	2/19/00	3402	742	60	0.040	13.51	6206	10.7	22.70	968	132	7.0	1.41	5.21	4.64	0.29	0.11	10.4	137.8	1484	2.30	9.61
TR-4C	5:00	2/19/00	3271	715	54	0.048	13.08	6115	8.0	17.98	927	122	7.1	1.27	4.70	4.09	0.26	0.10	11.1	129.4	1484	1.67	17.26
TR-4C	8:23	5/15/00	3710	790	72	0.138	13.92	6707	7.9	16.72	905	114	7.2	1.42	0.22	6.54	0.25	0.10	9.4	99.1	1367	3.04	8.43
TR-4C	8:28	5/15/00	3542	695	69	0.086	13.64	6692	11.5	32.95	835	144	7.4	1.40	0.21	5.57	0.25	0.10	9.8	104.0	1367	2.75	9.22
TR-4C	9:32	5/15/00	3556	682	63	0.050	13.51	6688	11.2	20.62	754	140	7.2	1.38	0.20	5.44	0.25	0.09	8.7	104.6	1367	2.53	9.42
TR-4C	15:20	4/1/01	3637	786	105	0.030	13.30	7515	17.7	5.25	934	147	7.1	2.08	0.19	3.15	0.27	0.11	18.0	97.5	1424	6.4	7.75
TR-4C	16:30	4/1/01	3598	783	97	0.030	13.05	7273	17.8	8.37	903	152	7.1	3.01	0.22	6.35	0.27	0.10	17.7	107.9	1405	5.9	9.79

TABLE 4: Chemical composition during production tests in well TR-5C (water concentration in ppm)

Well	Time	Date	Na	K	Ca	Mg	Li	Cl	SO ₄	HCO ₃	SiO ₂	B	pH	H ₂	Ar	N ₂	CH ₄	CO	SH ₂	CO ₂	Enthalpy (kJ/kg)	P Mx WHP (bar-g)	
																						Enthalpy (kJ/kg)	P Mx
TR-5C	7:40	3/18/00	4218	839	36	0.428	18.92	7717	15.1	12.1	776	146	6.6	1.38	0.18	3.77	0.26	0.10	11.6	77.0	1339	4.1	5.4
TR-5C	8:15	3/18/00	3925	899	38	0.340	18.81	7484	13.3	10.7	868	144	6.6	1.35	0.18	3.99	0.27	0.10	12.7	76.8	1339	4.1	5.4
TR-5C	9:40	3/18/00	4049	879	35	0.330	18.94	7115	11.1	8.0	873	143	6.5	1.44	0.21	6.06	0.27	0.10	11.1	80.7	1339	3.9	6.4
TR-5C	10:00	3/18/00	4054	865	34	0.092	18.72	7487	13.8	7.1	824	141	6.4	1.29	0.16	3.02	0.27	0.10	12.5	79.5	1339	3.8	7.4
TR-5C	10:50	3/18/00	3970	868	34	0.099	18.72	7469	10.9	7.4	838	148	6.6	1.30	0.16	3.38	0.26	0.10	10.5	79.3	1339	3.7	10.1
TR-5C	5:50	3/25/01	4456	874	151	0.250	18.68	8232	9.0	1.6	968	168	6.3	2.06	0.16	4.30	0.24	0.09	18.5	67.8	1300	3.80	5.00
TR-5C	7:00	3/25/01	4321	865	134	0.220	17.81	7985	9.7	1.3	924	165	6.2	1.02	0.17	3.38	0.24	0.09	9.6	70.6	1300	3.70	5.10
TR-5C	8:30	3/25/01	4131	850	133	0.199	17.4	8075	6.5	1.4	924	165	6.3	1.80	0.15	2.86	0.25	0.10	10.0	66.2	1300	3.60	5.80
TR-5C	9:30	3/25/01	4027	839	130	0.171	17.2	7093	6.8	2.2	916	140	6.3	1.49	0.17	3.85	0.25	0.10	8.0	67.6	1300	3.40	8.00

TABLE 5: Chemical composition during production tests in well TR-5 (water concentration in ppm)

Well	Time	Date	Na	K	Ca	Mg	Li	Cl	SO ₄	HCO ₃	SiO ₂	B	pH	(mmol / 100 moles)							Enthalpy (kJ/kg)	P Mx (bar-g)	WHP
														H ₂	Ar	N ₂	CH ₄	CO	SH ₂	CO ₂			
TR-5	12:58	3/18/00	2709	663	25	0.074	12.11	4818	12.5	11.0	857	111	6.6	1.38	0.14	3.56	0.26	0.10	14.1	102.2	1429	5.6	6.9
TR-5	2:38	3/18/00	2678	654	25	0.150	11.83	4827	6.7	9.1	895	107	6.5	1.71	0.21	7.18	0.27	0.10	15.0	106.4	1429	5.6	7.2
TR-5	2:30	3/18/00	2635	664	23	0.039	11.77	4771	10.4	10.0	889	109	6.6	1.79	0.23	8.42	0.27	0.11	14.3	106.0	1429	5.6	7.5
TR-5	4:40	3/18/00	2693	653	27	0.121	11.75	4770	11.1	9.9	888	109	6.6	1.25	0.14	2.55	0.26	0.10	14.4	103.9	1429	5.6	7.8
TR-5	5:30	3/18/00	2736	654	25	0.214	11.99	4723	10.9	10.9	872	109	6.7	1.39	0.15	3.47	0.27	0.10	11.7	103.2	1429	5.5	8.5
TR-5	6:25	3/18/00	2748	668	25	0.074	11.95	4714	12.5	13.9	850	103	7.0	1.28	0.13	1.35	0.28	0.11	12.1	112.0	1429	5.3	9.2
TR-5	15:15	5/15/00	2702	548	28	0.085	11.13	4978	9.0	4.9	994	109	6.1	1.10	0.11	0.72	0.25	0.10	10.8	102.1	1429	5.1	7.0
TR-5	15:30	5/15/00	2583	538	27	0.041	11.23	4649	5.2	9.0	969	100	6.6	1.27	0.13	2.72	0.25	0.09	10.9	101.6	1429	4.95	7.2
TR-5	16:15	5/15/00	2557	563	25	0.060	11.44	4931	5.4	8.5	932	95	6.6	1.62	0.17	5.32	0.28	0.11	12.9	109.0	1429	4.9	7.5

TABLE 6: Chemical composition during production tests in well TR-9 (water concentration in ppm)

Well	Time	Date	Na	K	Ca	Mg	Li	Cl	SO ₄	HCO ₃	SiO ₂	B	pH	(mmol / 100 moles)							Enthalpy (kJ/kg)	P Mx (bar-g)	WHP
														H ₂	Ar	N ₂	CH ₄	CO	SH ₂	CO ₂			
TR-9	8:00	2/19/00	4158	861	156	0.056	16.07	7532	8.6	25.5	871	137	7.2	1.83	1.67	3.09	0.27	0.10	10.0	107.0	1183	5.54	6.72
TR-9	8:48	2/19/00	4069	833	160	0.512	18.20	7539	8.4	27.0	794	146	7.2	1.65	1.36	2.44	0.26	0.10	10.2	107.2	1183	5.51	7.65
TR-9	9:21	2/19/00	4071	817	155	0.372	18.93	7650	8.4	26.2	869	140	7.2	1.59	1.18	2.17	0.27	0.10	11.3	108.5	1183	5.10	9.22
TR-9	10:01	2/19/00	3996	800	149	0.445	17.88	7547	7.8	27.4	853	126	7.2	1.63	1.36	2.52	0.26	0.10	8.9	105.7	1183	4.60	11.28
TR-9	10:55	2/19/00	3924	780	139	0.117	17.44	7328	8.4	34.0	852	130	7.4	1.58	1.59	2.99	0.26	0.10	9.1	104.7	1183	3.33	17.65
TR-9	8:10	4/28/01	4283	850	133	0.009	16.27	7532	13.0	12.93	884	135	7.1	2.85	0.14	3.30	0.24	0.09	9.6	72.6	1311	5.59	6.10
TR-9	9:05	4/28/01	4003	823	118	0.001	16.70	7792	10.7	11.71	854	134	7.1	2.11	0.13	1.76	0.26	0.10	11.4	115.7	1311	4.95	8.53
TR-9	10:30	4/28/01	4006	845	113	0.004	16.73	7368	11.7	11.84	854	136	7.2	2.14	0.16	1.91	0.26	0.10	10.5	82.0	1311	4.41	11.77

APPENDIX III: Evaluation parameters for production tests in the Berlín geothermal field

TABLE 1: Evaluation parameters for production tests in well TR-2

Well	Time	Date	NaK	Quartz	NaKCa	Cl reservoir	Steam fraction	pCO ₂ (bar-g)	WHP (bar-g)	Cl/B	Cl/SO ₄	Na/K
			T (°C)									
TR-2	13:55	2/19/00	289	298	281	5268	0.0185	0.759	10.8	60.2	1649.6	4.8
TR-2	14:40	2/19/00	295	302	285	5163	0.0185	0.711	14.7	50.8	1199.3	4.5
TR-2	17:30	2/19/00	296	306	287	5193	0	1.37	23.5	63.9	1441.8	4.5
TR-2	10:55	5/1/00	284	289	279	5237	0.0185	0.658	9.1	48.8	1599.6	5.0
TR-2	11:47	5/1/00	284	288	277	5234	0.0185	0.642	9.8	49.0	1702.3	5.0
TR-2	12:50	5/1/00	275	284	271	5217	0.0185	0.637	11.0	49.4	1334.2	5.4
TR-2	13:40	5/1/00	291	286	284	5230	0.0185	0.634	11.3	51.7	2112.9	4.7
TR-2	10:02	10/27/00	282	290	275	5403	0.0296	0.581	9.3	62.7	292.9	5.1
TR-2	10:40	10/27/00	282	290	277	5437	0.0296	0.393	9.5	64.7	945.9	5.1
TR-2	12:30	10/27/00	288	289	279	5484	0.0296	0.422	11.0	72.4	917.1	4.8
TR-2	14:18	10/27/00	295	303	287	5496	0.0296	0.458	23.7	59.2	1195.5	4.5
TR-2	7:55	4/28/01	291	289	284	5427	0.022	0.935	8.5	53.9	1002.6	4.7
TR-2	8:50	4/28/01	294	287	278	5466	0.0033	2.81	12.8	54.4	1163.6	5.0
TR-2	10:10	4/28/01	293	287	286	5338	0	3.01	17.7	52.3	1530.0	4.6

TABLE 2: Evaluation parameters for production tests in well TR-4B

Well	Time	Date	NaK	Quartz	NaKCa	Cl reservoir	Steam fraction	pCO ₂ (bar-g)	WHP (bar-g)	Cl/B	Cl/SO ₄	Na/K
			T (°C)									
TR-4B	13:00	2/19/00	292	301	289	3354	0.0376	0.721	6.4	43.2	403.0	4.5
TR-4B	13:55	2/19/00	235	295	250	3260	0.0376	0.44	5.4	41.8	545.7	7.6
TR-4B	6:44	4/1/01	268	303	270	3357	0.1957	0.245	5.6	43.6	208.5	5.6
TR-4B	7:37	4/1/01	273	303	276	3309	0.1851	0.283	6.2	44.1	245.7	5.3
TR-4B	8:33	4/1/01	274	303	279	3265	0.1778	0.289	6.5	43.1	243.2	5.2
TR-4B	9:24	4/1/01	288	325	284	3339	0.1626	0.293	8.6	44.3	239.8	4.6

TABLE 3: Evaluation parameters for production tests in well TR-4C

Well	Time	Date	NaK	Quartz	NaKCa	Cl reservoir	Steam fraction	pCO ₂ (bar-g)	WHP (bar-g)	Cl/B	Cl/SO ₄	Na/K
			T (°C)									
TR-4C	2:50	2/19/00	297	283	291	4037	0.1156	0.368	5.4	54.1	780.5	4.4
TR-4C	3:38	2/19/00	296	263	290	3987	0.1156	0.33	8.3	47.4	753.7	4.5
TR-4C	4:20	2/19/00	293	289	288	4053	0.1156	0.356	9.6	47.1	580.0	4.6
TR-4C	5:00	2/19/00	293	280	288	3929	0.1156	0.342	17.3	50.0	764.4	4.6
TR-4C	8:23	5/15/00	290	282	285	4469	0.0345	0.552	8.4	58.7	849.0	4.7
TR-4C	8:28	5/15/00	282	270	278	4431	0.0345	0.585	9.2	46.5	581.9	5.1
TR-4C	9:32	5/15/00	279	257	277	4406	0.0345	0.594	9.4	47.9	597.1	5.2
TR-4C	15:20	4/1/01	293	296	281	5289	0.074	0.301	7.8	51.2	424.6	4.6
TR-4C	16:30	4/1/01	293	288	282	5067	0.0608	0.386	9.8	47.7	408.6	4.6

TABLE 4: Evaluation parameters for production tests in well TR-5C

Well	Time	Date	NaK	Quartz	NaKCa	Cl reservoir	Steam fraction	pCO ₂ (bar-g)	WHP (bar-g)	Cl/B	Cl/SO ₄	Na/K
			T (°C)									
TR-5C	7:40	3/18/00	280	268	293	5442	0.0501	0.278	5.4	52.8	512.4	5.0
TR-5C	8:15	3/18/00	295	284	302	5278	0.0501	0.278	5.4	52.0	564.0	4.4
TR-5C	9:40	3/18/00	289	284	300	5001	0.0501	0.294	6.4	49.8	641.0	4.6
TR-5C	10:00	3/18/00	287	276	299	5253	0.0501	0.29	7.4	53.2	544.1	4.7
TR-5C	10:50	3/18/00	290	278	300	5231	0.0501	0.29	10.1	50.4	683.3	4.6
TR-5C	5:50	3/25/01	278	302	274	5776	0.0243	0.39	5.0	49.0	914.7	5.1
TR-5C	7:00	3/25/01	280	293	276	5293	0.0243	0.408	5.1	48.3	823.2	5.0
TR-5C	8:30	3/25/01	284	293	277	5646	0.0243	0.384	5.8	49.1	1242.3	4.9
TR-5C	9:30	3/25/01	285	291	278	4940	0.0243	0.395	8.0	50.7	1043.1	4.8

TABLE 5: Evaluation parameters for production tests in well TR-5

Well	Time	Date	NaK	Quartz	NaKCa	Cl reservoir	Steam fraction	pCO ₂ (bar-g)	WHP (bar-g)	Cl/B	Cl/SO ₄	Na/K
			T (°C)									
TR-5	12:58	3/18/00	309	275	303	3229	0.0407	0.547	6.9	43.3	385.4	4.1
TR-5	2:38	3/18/00	309	281	303	3231	0.0407	0.571	7.2	44.9	720.4	4.1
TR-5	2:30	3/18/00	312	280	306	3193	0.0407	0.569	7.5	43.8	458.8	4.0
TR-5	4:40	3/18/00	308	280	302	3193	0.0407	0.557	7.8	43.7	429.7	4.1
TR-5	5:30	3/18/00	306	277	302	3156	0.0407	0.554	8.5	43.4	433.3	4.2
TR-5	6:25	3/18/00	307	273	303	3149	0.0407	0.605	9.2	45.7	377.1	4.1
TR-5	15:15	5/15/00	289	305	285	3450	0.0407	0.512	7.0	45.7	553.1	4.9
TR-5	15:30	5/15/00	292	292	287	3084	0.0407	0.553	7.2	46.3	894.0	4.8
TR-5	16:15	5/15/00	298	285	292	3266	0.0407	0.697	7.5	51.9	913.1	4.5

TABLE 6: Evaluation parameters for production tests in well TR-9

Well	Time	Date	NaK	Quartz	NaKCa	Cl reservoir	Steam fraction	pCO ₂ (bar-g)	WHP (bar-g)	Cl/B	Cl/SO ₄	Na/K
			T (°C)									
TR-9	8:00	2/19/00	284	288	276	5434	0	1.47	6.7	54.9	875.8	4.8
TR-9	8:48	2/19/00	283	274	274	5436	0	1.48	7.6	51.6	897.5	4.9
TR-9	9:21	2/19/00	281	287	273	5484	0	1.52	9.2	54.8	910.7	5.0
TR-9	10:01	2/19/00	280	284	273	5410	0	1.48	11.3	60.0	967.6	5.0
TR-9	10:55	2/19/00	280	279	273	5100	0	1.57	17.7	56.5	872.4	5.0
TR-9	8:10	4/28/01	279	290	275	5436	0.0316	0.335	6.1	55.8	579.4	5.0
TR-9	9:05	4/28/01	284	284	278	5571	0.0316	0.545	8.5	58.1	728.2	4.9
TR-9	10:30	4/28/01	286	282	281	5223	0.0316	0.394	11.8	54.0	629.7	4.7

APPENDIX IV: Measured temperature profiles for the Berlin wells in 2001

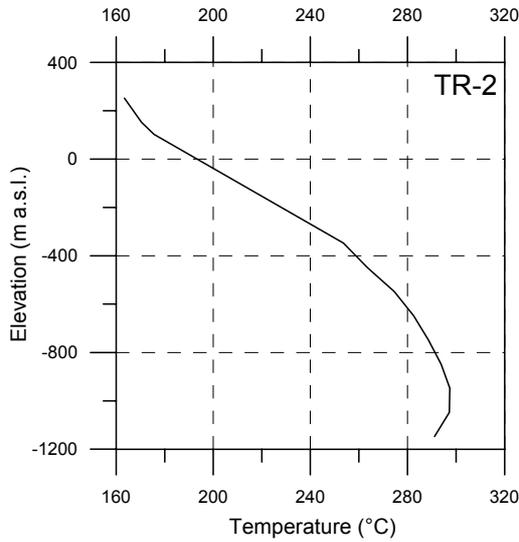


FIGURE 1: Temperature profile from well TR-2 (well elevation 752 m a.s.l.)

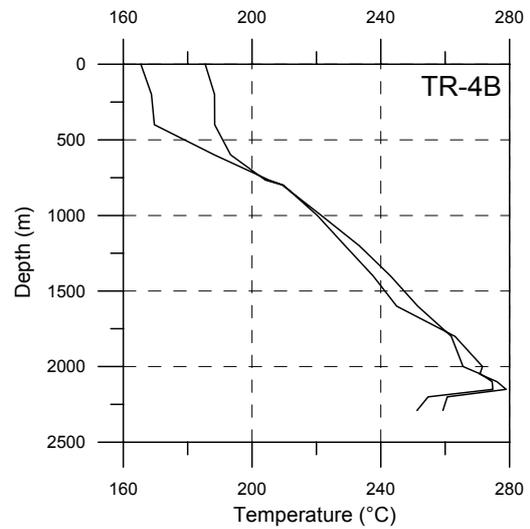


FIGURE 2: Temperature profiles from well TR-4B (well elevation 763 m a.s.l.)

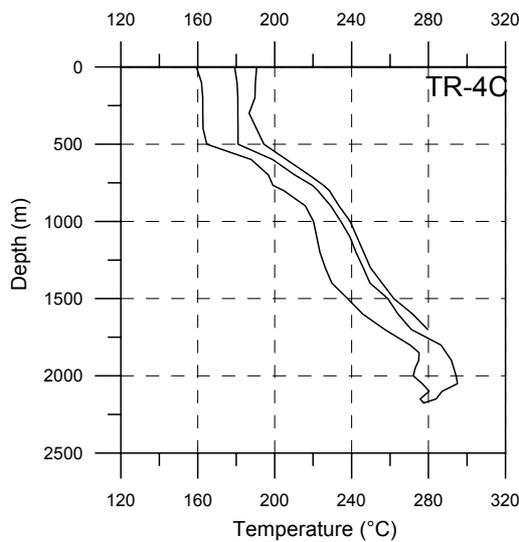


FIGURE 3: Temperature profiles from well TR-4C (well elevation 767 m a.s.l.)

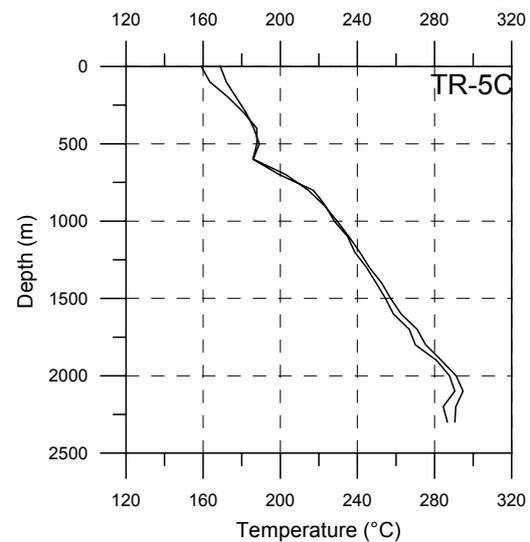


FIGURE 4: Temperature profiles from well TR-5C (well elevation 840 m a.s.l.)

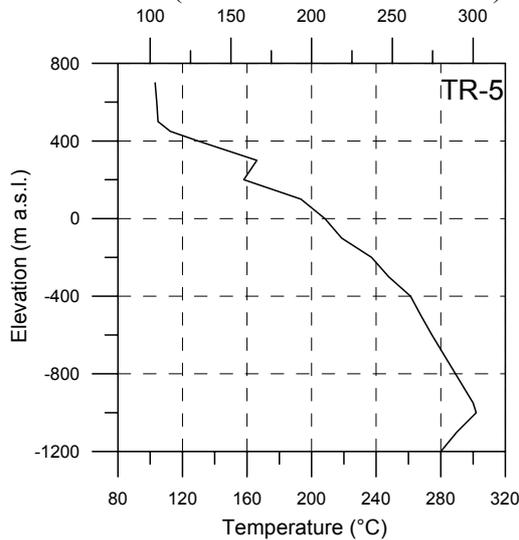


FIGURE 5: Temperature profile from well TR-5 (well elevation 840 m a.s.l.)

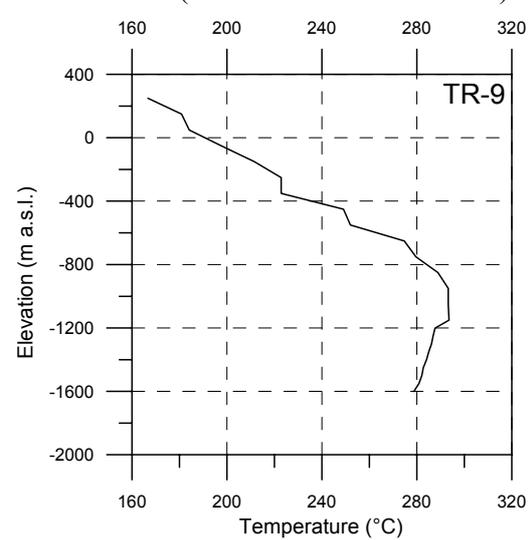


FIGURE 6: Temperature profile from well TR-9 (well elevation 649 m a.s.l.)