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ASSESSMENT OF CHEMICAL AND PHYSICAL RESERVOIR PARAMETERS DURING SIX YEARS OF PRODUCTION-REINJECTION AT BERLIN GEOTHERMAL FIELD (EL SALVADOR)

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ABSTRACT

Berlin geothermal field is a liquid-dominated system with temperatures in the range 270-305°C according to the chemistry and measured temperatures from 5 deep wells (depth of 1900-2300 m). Well enthalpy varies between 1200 and 1400 kJ/kg (18-30% steam quality), showing a power potential from 5 to 12 MW_e. The geothermal fluids are of typical sodium-chloride composition with 3000 to 6000 mg/kg of reservoir chloride and silica content ranging from 600 to 900 mg/kg, and 0.25-0.50% by weight of non-condensable gases in the steam separated at 8 bara.

Commercial production began in February 1992 with start-up of well TR-2 using a 5 MW_e backpressure turbine. Well TR-9 began production with a second backpressure turbine in January 1995. These two wells generate a total of close to 8 MW_e. The total water extracted, around 100 kg/s, is being reinjected.

Chemistry of the fluid from wells TR-2 and TR-9 indicates some changes with time, specially for well TR-9, with a cooling in the silica geothermometer from 284°C to 200°C after 2 years of injection, and recovery, after 3 years of production, from 200°C to 285°C. Well TR-2 probably shows some effects of reinjection, with an increase in the reservoir chloride from 4000 to 5000 mg/kg in the first year, and a decrease in the non-condensable gases from 0.36 to 0.10 % in weight. From tracer tests (I^{131} as tracer) we have deduced that some connection exists between wells TR-2 and TR-9. Evaluations of mineral saturation indicate that calcite and quartz are close to equilibrium. A minimum separation pressure of 8–10 bara is required due to the higher content of silica in the separated water. According to geochemical and physical data the main process affecting the reservoir is boiling, due mainly to the drawdown pressure of about 6 barg. There is no influence of reinjection in the production area, according to the isotope and production characteristics.

1. INTRODUCTION

The Berlin geothermal field is located in the eastern part of El Salvador, approximately 112 km ESE of the capital, San Salvador (Fig. 1). The main geological feature of the area is a large caldera, filled for the most part with volcanic materials, as well as a 3 - 4 km wide graben extending NNW-SSE. The geothermal activity at the surface can be linked with 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 Berlin-Tecapa volcanic complex, which rises to an elevation of 1300 m a.s.l. The heat source, due to an active magmatic chamber, has generated the Berlín geothermal system, with a hydrothermal system related to andesitic volcanism. The aim of this study is to evaluate the evolution of the field under exploitation using geochemical and physical data.

2. THE BERLIN CONCEPTUAL MODEL

A conceptual model of the Berlin geothermal field was developed by CEL and others during the early nineties. This model has been refined as more information has emerged.The main tectonic structures are annular faults formed by caldera collapses and the NW-SE graben. The heat source of the geothermal system resides within the Berlin caldera and an upflow of the geothermal fluid is proposed underneath the Tecapa volcano to the south of the well field. From the upflow zone fluid flows laterally towards the north or northwest and enters the well field close to well TR-5, where the top of the geothermal aquifer lies at about 2 km depth (elevation -1000 m a.s.l.). The highest temperature measured in the wells is 305°C. This defines the minimum temperature of the upflow but geothermometers based on fumarole gases indicate recharge temperatures as high as 350°C. Overlying the geothermal reservoir are two shallower aquifers. A groundwater aquifer close to the surface is recharged by local rain in the area and a deeper aquifer of an intermediate temperature (150 to 200°C) is found around sea-level and is about 300 m in thickness. This aquifer is often referred to as the intermediate aquifer. It is not known whether there is a hydrological connection between the intermediate aquifer and the hot geothermal aquifer. The geothermal fluid, consequently, flows through the main reservoir, along the NNW-SSE graben, towards an outflow zone north of the Berlin field. This is clearly demonstrated by decreasing reservoir temperature, and pressure, towards the north. The highest permeability is found in the area where the production wells are located, and is believed to be caused by the intersection of the NNW-SSE graben and the caldera rim faults. Permeability appears to be considerably lower in the area where the injection wells have been drilled. This model is shown in Fig. 2.

3.GEOTHERMAL DEVELOPMENTS AT BERLIN FIELD

Geothermal exploration of the Berlin field started in the 1960s and the first deep exploratory well (TR-1) was drilled in 1968 to a depth of 1458 m. Drilling at Berlin continued during 1978 – 1981 with the addition of five deep wells (TR-2, 3, 4, 5 and 9). All the wells turned out to be good producers except TR-4, due to an obstruction at depth.

A feasibility study was carried out in order to assess the power potential of the field (100 MW_e). Further development was suspended at the field because of the civil war. During 1990 - 1992 CEL installed two 5 MW_e wellhead units. It was planned to use wells TR-2 and TR-9 as producers and reinject the spent fluids into well TR-1 and a new well (TR-6) drilled in 1991. Drilling of TR-6 had to be abandoned due to a blow-out at 150 m depth and the well was filled with cement. Because of the limited reinjection capacity of well TR-1 it was decided to put only one of the power units on line and use well TR-9 temporarily as an injection well. Unit I was taken off line because of a carryover of corrosion material from well TR-2 to the turbine on 9 July 1992. Power generation at Berlín was suspended for about six months while the second unit was prepared for production. During 1993-95 three deep wells were drilled for reinjection purposes (TR-8, TR-10, TR-14), located 1-2 km north of the production wells in the NNW-SSE graben. They all encountered temperatures of 240-270°C. A reinjection line to wells TR-14 and 8 was completed in 1994 and since February 1995 both the 5 MW_e units have been in operation using wells TR-2 and TR-9 as producers (7.5 MW_e). Well TR-10 was connected to the reinjection line in 1995, shortly after drilling was completed, but was closed in 1998 due to loss of absorption. Figure 3 presents data on the extraction and reinjection flow rates during this period.

3.1 The Berlín Power Plant (1999)

After the first stage of development at Berlin geothermal field, using well head units, a second stage has begun. Since early 1997 fourteen additional wells have been drilled. Four of these are production wells directionally drilled from the TR-4 and TR-5 platforms. Most of the other wells are planned as injection wells. Two condensing type units of 27.5 MW_e each, with a collection system and injection line, have been built.

In February 1999 the first of two units for a condensing power plant was put on line, while the start-up of the second unit is planned for later. During the shakedown period the plant has been generating about 20 MW_e while the various systems are being tested. The acceptance tests are planned to take place in September or October 1999. Units 1 and 2 were operating at the following conditions:

Unit 1: 11.1-11.3 MWe, steam flow to turbine including gland seals = 96.73-104.52 t/h, SSC = 2.42-2.57 kg/s/MW_e;

Unit 2: 8.3 MWe, steam flow to turbine including gland seals = 86.34 t/h, steam consumption = 2.89 kg/s/MW_e.

These are considerably poorer than the expected full operation value of 1.9 kg/s/MW_e, mainly because the units were running at only about 30-40% of their ratings, respectively. By the end of 1999 it is expected that Berlin will be generating 55 MW_e (IDB Panel, 1999).

4. FIELD EVOLUTION UNDER EXPLOITATION

4.1 Production-Reinjection History

In six years of production a total of 21 Mt of fluid have been extracted, 70% of which from well TR-2. The water extracted was about 16 Mt (76%), which have been injected mainly into wells TR-8 and TR-14 (Fig. 3). At present the total flow rate injected is close to 200 kg/s. Well TR-9, after 2 years of continuous reinjection of about 2 Mt of separated water at 8 barg, shows values similar to the original ones; the steam flow rate is around 10 kg/s at a wellhead pressure of 11 barg. The production parameter shows a good stabilization, with a total flow rate of about 75 kg/s at wellhead pressure close to 11 barg for well TR-2. Well TR-9 was operated partially with restriction of the wellhead pressure (close to 23 barg) due to a lack of absorption of the reinjection wells.

Table 1 provides information about some wells drilled in the field and Fig. 1 shows their locations. All the production wells are located in an area of about 2 km^2 within the NNW-SSE graben, in the northern part of the Berlin-Tecapa caldera. Most of the reinjection wells are located about 1 - 2 km north of the production wells. The current well field is about 4 km long and 3 km wide.

4.2 Lumped Modelling of Pressure Decline

The most significant change occurring in the Berlin system as a result of production during the last 7 years is the pressure decline. The reservoir pressures at Berlin field have been monitored in part in well TR-4 (0 m a.s.l.) from the start of production from the field. The pressure changes observed in well TR-4 were simulated by using LUMPFIT. Lumped parameter modelling has been used successfully to simulate, and consequently predict, the pressure changes in numerous geothermal systems world-wide (Axelsson, 1989). Unfortunately, the data available for Berlin field in different periods appeared not to be fully comparable, since different tools were used during different periods, some less reliable than others. This can easily cause discrepancies of 1-2 bar. The approach used, therefore, was to simulate the first two years of data, which were considered of good quality, and then use the most recent measurements, taken after operations started in the first 25 MW unit, as a constraint on the long-term behaviour. In other words, the program fitted the first two years automatically, while the parameters of the model were then varied to fit the last point of the data-set. The results of the simulation are presented in Fig. 4, showing the results obtained using the total mass extraction from the field as input. The net extraction (total extraction minus reinjection) was also used as input yielding fully comparable results. The reason for this is that the net extraction in Berlin is always close to being a fixed percentage of the total extraction. Figure 4 also shows predictions for the next five years, assuming the two 25 MW_e units will be on-line at the end of 1999. According to these predictions the pressure will have declined by about 15 bars, from its initial value, at the end of the prediction period.

At the moment the predictions presented here can be considered somewhat pessimistic.

The parameters characterising the response of the model, as well as the properties of the model, are the κ_i, which reflect the volumetric storage of different parts of the geothermal reservoir (depending on volume, porosity and storage mechanism), while the σ_i reflect the water conductivity of the reservoir (permeability, viscosity and geometry). Based on these, the following estimates are obtained, assuming an average porosity of 10% and thickness of 1 km:

κ_1 represents the areal extent of the production part of the reservoir: 5.3 km^2

κ_2 is the areal extent of the outer part of the geothermal system: 147 km^2

σ_1 is the permeability of the production area: 35 Darcy-m

σ_2 is the permeability of the outer part: 2.4 Darcy-m.

These values should only be considered as order of magnitude estimates, but they appear to be reasonable as such, in particular the area of the production part of the field. The permeability values also appear reasonable, i.e. high permeability inside the system with lower permeability on the outside. The area of the outer part, however, appears very large. This may be an overestimate reflecting storage resulting from lowering of a free surface in the upper parts of the system or even boiling in the reservoir.

4.3 Chemistry of the Fluids

The chemical evolution in the production fluids shows an increase in reservoir chloride in the first year from 4000 to 5000 mg/L for well TR-2, using well TR-9 as a reinjector, and some stabilization was also seen when reinjection into well TR-9 was stopped in 1994. After that the reservoir chloride remains almost constant until 1995, when an increase takes place again up to 6000 mg/L. This could be interpreted as an effect of reinjection into well TR-9 for the first increase and a boiling process for the second. The first hypothesis could explain some decrease in non-condensable gases at the same time. The second hypothesis is demostrated using the comparison between measured enthalpy and the silica and NaKCa enthalpy values (Fig. 5). In well TR-9 the reservoir chloride increased from 5000 mg/L to 6000 mg/L when the well started production. The quartz geothermometer (F&P) shows clearly the cooling produced by reinjection and after recovery (Fig. 6). In general the geotemperatures for both wells in production are very stable (except for SiO_2) and similar to the measured ones, producing an average of 292°C for well TR-2 and 285°C for well TR-9.

The non-condensables show an increase for well TR-2 up to 0.5 wt % in 1995, after which the contents remain constant at a lower value (0.28 wt %). TR-9 shows almost the same (increasing in 1995 up to 0.5 wt % and decreasing to 0.3 wt %). Table 2 shows different chemical parameters for the present production wells including new wells (TR-4B and TR-4C). The new wells, with the available data to date, probably do not yet show representative values, because the discharge and testing period is not long enough. According to mineral saturation analysis (Bjarnasson, 1994) only well TR-9 shows a slight saturation of calcite. A minimum separation pressure of 8–10 bara is required due to the higher content of silica in the separated water (Martinez, 1997).

4.4 Simple Modelling of Production-Induced Chemical Changes

The chemical content of steam and water discharged by geothermal wells provides important information on the nature of a geothermal system. Variations in the chemical content during long-term utilisation provide additional information on processes taking place in a geothermal reservoir. These include boiling or condensation, colder water infiltration or increased high-enthalpy recharge, as well as processes associated with reinjection. Careful monitoring of the chemical content, before and during utilisation, is therefore an important part of geothermal systems management. The chemical content of the production wells in the Berlin field has been monitored carefully during the discharge history of the field, and in particular that of wells TR-2 and TR-9.

An analysis of the chemical and isotopic data, directed at extracting information on the natural state of the system, has been presented elsewhere (D'Amore and Tenorio, 1999).

The chemical data were modelled using the computer code LUMPCEM. No significant changes have been observed in the Berlin field, which may be attributed to inflow of colder, less saline water. In fact, hardly any significant changes in chemical content can be seen in the chemical monitoring data. The only changes evident are some variations in the chloride content for wells TR-2 and TR-9, calculating an average chloride content for the two wells, weighted by the production from each of the wells. This weighted average chloride content for the six-seven years of production history of the Berlin field is presented in Fig. 7. Despite the fact that a weighted average is presented, the variations are very similar in wells TR-2 and TR-9. A slight increase in chloride content may be seen in the figure, but partly masked by short-term variations. The cause of these variations could be one or more of the following: (1) production-induced boiling in the reservoir, (2) production-induced inflow of higher salinity water and/or (3) reinjection of higher salinity separator water.

The LUMPCEM program was used to simulate the chloride content data (Björnsson et al., 1994). The program involves a model of a geothermal reservoir of fixed volume with a constant hot recharge. Initially the reservoir chemical content and temperature equal that of the fixed recharge. Variable production starts from the model at time t = 0, causing a drop in reservoir pressure. As a consequence, variable inflow from a peripheral reservoir, or hydrological system, with a different chemical content and/or temperature is initiated. Most often this is a colder overlying reservoir. Consequently, the model and program simulate the resulting variations in chemical content and/or temperature. The following equations are used to calculate the response of the model:

$$C_i = C_{i-1}\exp(-\alpha Q_i \Delta t_i) + [(Q_i - R)C' + RC_0]\,(1 - \exp(-\alpha Q_i \Delta t_i))/Q_i \quad \text{for } i = 1,2,\ldots \qquad (1)$$

$$T_i = T_{i-1}\exp(-\beta Q_i \Delta t_i) + [(Q_i - R)T' + RT_0]\,(1 - \exp(-\beta Q_i \Delta t_i))/Q_i \quad \text{for } i = 1,2,\ldots \qquad (2)$$

where C indicates chemical content, such as chloride concentration, T temperature and t time. The following definitions apply:

$$\begin{aligned} & Q(t) \approx Q_i \quad \text{for} \quad t_i > t \geq t_{i-1} \\ & C_i = C(t_i) \quad \text{and} \quad T_i = T(t_i) \\ & \Delta t_i = t_i - t_{i-1}, \\ & \text{for } i = 1,2,\ldots \\ & \alpha = 1 / (V \rho_w \phi) \\ & \beta = c_w / (V \langle\rho c\rangle) \end{aligned} \qquad (3)$$

where V is the volume of the reservoir, ϕ its porosity, ρ_w the water density, c_w the water heat capacity, and $\langle\rho c\rangle$ the wet rock volumetric heat capacity. Furthermore, C_i and T_i represent the chemical content and temperature of the reservoir, C' and T' those of the peripheral inflow, and C_0 and T_0 those of the fixed (hot) inflow (denoted by R), as well as indicating initial conditions. The program LUMPCEM is used to simulate both chemical and temperature variations, by substituting C with T and α with β.

Figure 7 shows the simulated weighted average chloride for wells TR-2 and TR-9 in the Berlin field. The figure also shows predictions for the next few years assuming that both 25 MW_e units at Berlin will be on-line. The figure clearly shows, however, a considerable scatter in the data, which obviously cannot be attributed to variations in production. Perhaps some of this scatter can be attributed to the variable boiling in the reservoir and/or reinjection. The parameters of the model used were:

$$\begin{aligned} & C' = 7000 \text{ ppm} \\ & C_0 = 4700 \text{ ppm} \\ & R = 200 \text{ kT/mo} \ (76 \text{ kg/s}) \\ & \alpha = 10^{-10} \text{ kg}^{-1} \ (0.0001 \text{ kT}^{-1}) \end{aligned}$$

If this interpretation is assumed correct then the chloride content of the peripheral inflow is considerably higher than that of the initial reservoir conditions. At the moment this is considered doubtful. The fixed hot recharge of the model is 76 kg/s compared with the fixed inflow of 50 kg/s into the

TOUGH model for Berlin (at present in development by CEL). Finally, the parameter α can be used to estimate the reservoir volume (see equation 3). Assuming a porosity of 10% it yields a volume of 0.14 km^3. This is much smaller than the reservoir volume indicated by the lumped model (5.3 km^3). This may be because the volume in which the chemical processes are taking place is much smaller than the volume influenced by pressure changes. Alternatively, this may indicate that the assumption that the chemical changes are due to production-induced inflow of higher salinity water is not valid.

4.5 Isotopes

According to the conceptual model, the outflow from the Berlin geothermal system, in the natural state, is manifested in a number of warm springs along the Lempa River north of the field. Isotopic data have not yet confirmed that a connection exists between the Berlin system and these hot springs, but the results of isotopic monitoring indicate an average altitude of 1300 m a.s.l., which is in agreement with the hydrological studies, corresponding to an infiltration zone located around the Berlin-Tecapa volcanic complex.

Figure 8 shows the isotopic composition for the wells, defining three regions related to the producers, injectors and new wells. Isotopic monitoring, which started systematically in 1995, shows that there is no evidence that the injected fluid reaches the production area. As regards the new wells, it is also clear that the isotopic composition of the fluid shifts to the production values after several discharge tests.

4.6 Tracer Tests

Nine tracer experiments have been carried out at Berlin field in order to gain information on the flow of the injected fluid (150-180°C) and to determine whether and at what rate the injected fluids are returning to the production zone. Hydrological communication between the injection zone and the surface springs has also been investigated. The tracer selected for all the experiments was the radioactive Iodine-131 isotope. The first two experiments were carried out in 1992 when well TR-2 was the only producer and most of the separated water was reinjected into well TR-9 and only a minor amount into well TR-1. The distance between wells TR-2 and 9 is about 460 m. The second tracer test had to be stopped after only ten days due to problems at power Unit I. A tracer return, however, was observed in well TR-2 within seven days, and the tracer concentration was still rising on day ten, when unfortunately the test had to be abandoned.

Once well TR-9 had been put into production another five tracer tests were carried out in the reinjection wells TR-8, 14 and TR-10, 1-1.5 km north of the production zone. Two more tracer tests have been performed in the production area, and one of them is at present being monitored.

During the first and the third experiments only the production wells were monitored for tracer breakthrough, but in the others water from some surface springs in the area were also sampled and analysed for tracer returns. No increase in tracer concentrations was observed in the hot springs.

The main results show no evidence of tracer returns in monitoring periods ranging from 36 to 70 days. At the moment we can only conclude that no fast flow paths have been detected between the reinjection and the production zone and that a thermal breakthrough is therefore unlikely (Steingrimsson,1998). The reinjectors are therefore downstream (natural state) from the production area.

CONCLUSIONS

The production-reinjection characteristics of the wells showed very stable conditions during the first stage of development of Berlin geothermal field. Only well TR-10 seems to be affected by deposition resulting from reinjection. Well TR-9 showed a good recovery after it was used as an reinjector. Taking into account the chemical and physical results, the main process in the Berlin reservoir is boiling. This process results from pressure drawdown from 40 to 34 barg, and is demonstrated by the use of geochemical methodologies and lumped simulations. It is predicted that more boiling will be produced in the near future, probably because of the lack of connection between the production and reinjection zones. There is no evidence that a colder inflow has yet affected the reservoir. Several tracer tests corroborate this theory, as do the isotopes. The recharge area has been estimated from isotopes to lie close to 1300 m a.s.l., but the discharge of the system is still unknown.

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Table 1. Production characteristics for present-day production wells at Berlin geothermal field

Well	Depth(m)	Tmeas (°C)	Water (kg/s)	Steam(kg/s)	Enth(kJ/kg)	Quality %	WHP (bar-g)	MWe
TR-2	1903	295	54	20	1324	.27	11.6	10.5
TR-9	2298	285	40	11	1310	.22	11.8	5.8
TR-4B	2293	285	18	5	1100	.22	10.4	2.6
TR-4C	2179	295	34	15	1100	.30	11.5	7.8

Table 2. Chemical characteristics for present-day production wells at Berlin geothermal field. Chemical and isotope composition computed at total discharge conditions

Well	Cl res (mg/L)	CO_2 wt. %	Qtz F&P(°C)	NaK T(°C)	NaKCa(°C)	GT D&P(°C)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
TR-2	4733	.28	291	288	299	292	-3.85	-44.79
TR-9	4772	.3	282	284	288	287	-3.44	-44.44
TR-4B	3590	.57	267	261	271	294	-3.9	-42..5
TR-4C	3873	.60	264	283	285	290	-4.1	-44.5

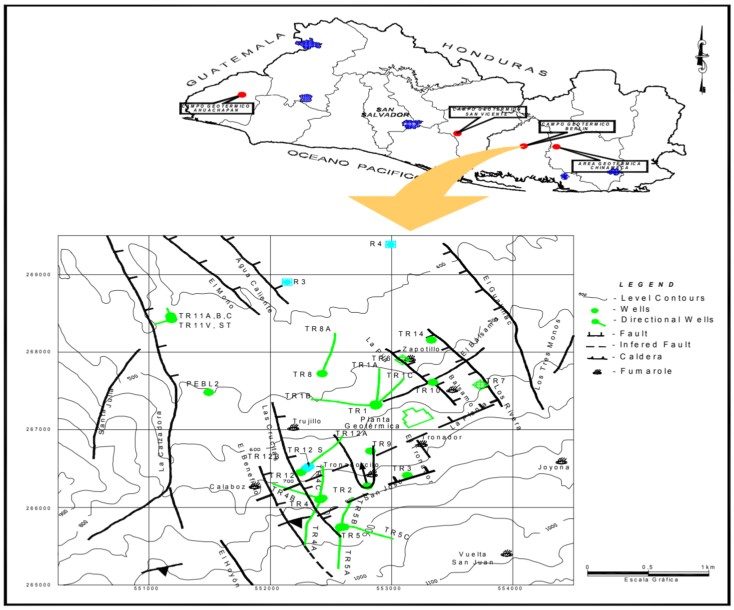

Figure 1. Well location in the Berlin geothermal field

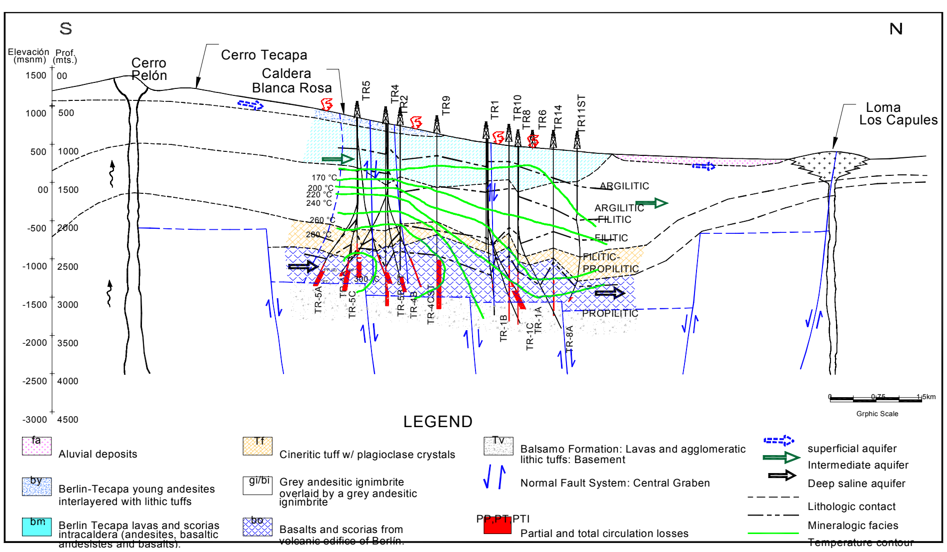

Figure 2. Conceptual model for Berlin geothermal field

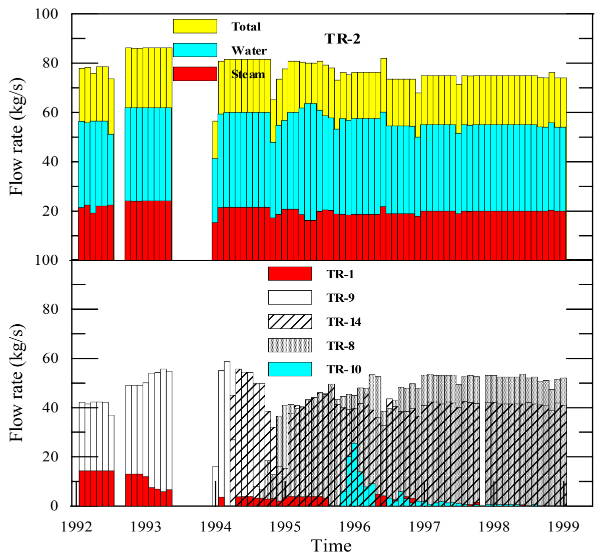

Figure 3. Extraction for well TR-2 and reinjection flow rates

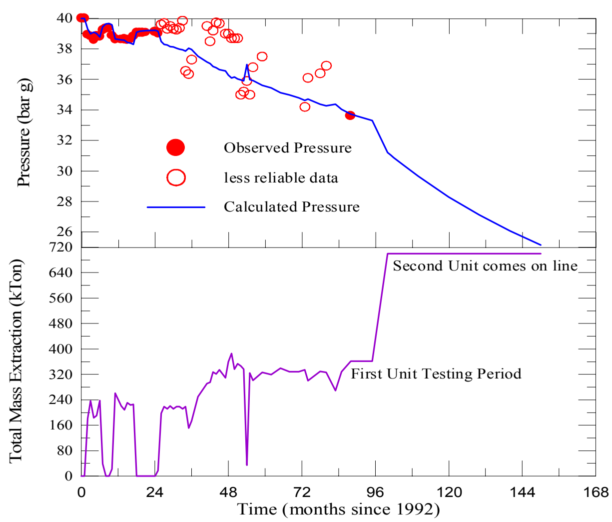

Figure 4. Lumped model for Berlin geothermal field

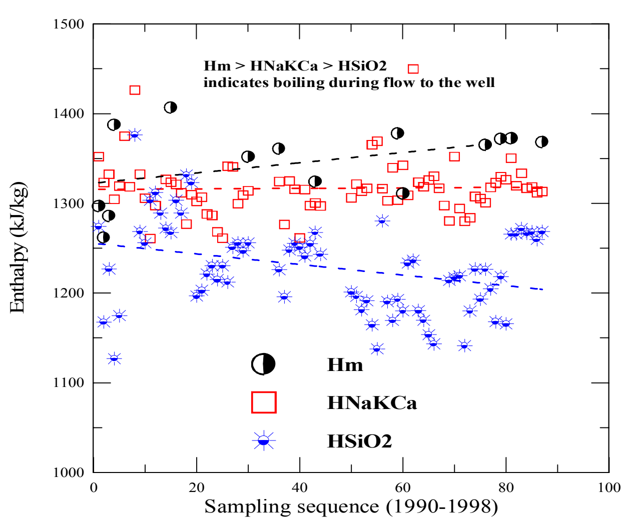

Figure 5. Enthalpy evolution trend for well TR-2

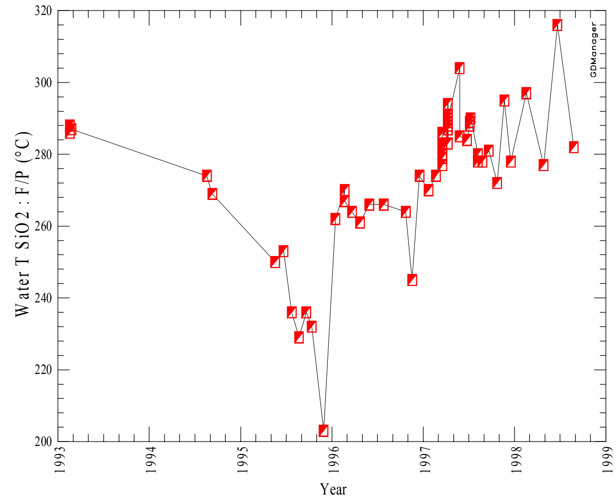

Fig 6. Quartz geotemperature evolution for well TR-9

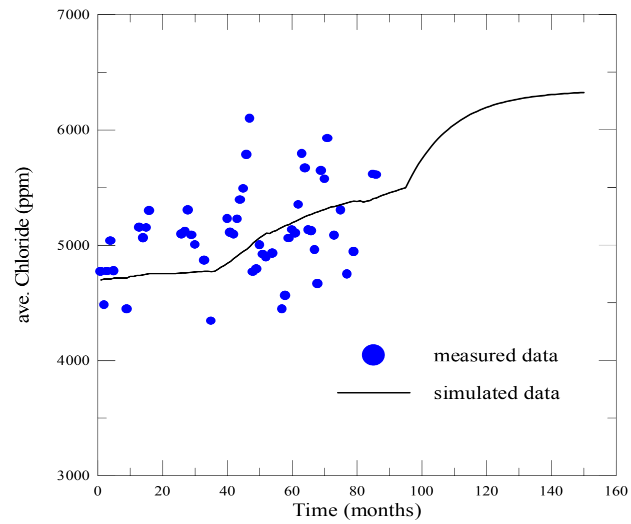

Figure 7. Chloride modelling for Berlin geothermal field

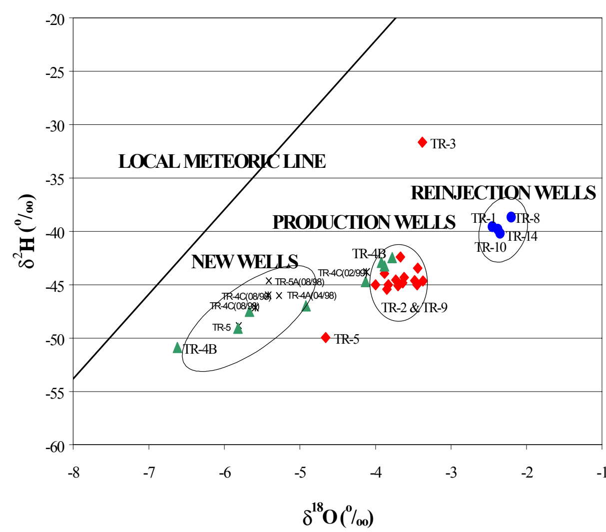

Figure 8. Isotopic composition for Berlin geothermal wells