

TRACER ANALYSIS FOR THE BERLIN GEOTHERMAL FIELD

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ABSTRACT

Nine radiotracer experiments have been carried out in Berlin geothermal field since 1992, in order to obtain information on the flow of the injected fluid (150-180°C) and to determine rapid connections between wells 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. At the moment, it is only possible to conclude that no fast flow paths have been detected between the reinjection and the production zones and that a thermal breakthrough is therefore not likely to occur. The reinjectors are therefore downstream (natural state) from the production zone. Only one experiment showed some tracer recovery. The tracer was injected in well TR-12A located close to the production zone. After 3 months of monitoring, 9.44 % was recovered in well TR-4C located around 400 m from the injection well TR-12A. Other 3 wells show recovery curves with lower percentages less than 3 %. The injection flow rate was around 30 kg/s and production flow rate 46 kg/s for well TR-4C according to the tracer return, only 3 kg/s of the total fluid injection reached the production well. Simulations of cooling effect showed that in the optimistic case, there should not be a significant decrease in the temperature of production fluids for at least two years of continuous reinjection.

INTRODUCTION

Geothermal exploration of the Berlin geothermal field started in the 1960's with a joint project between the UNDP and CEL. The first deep exploratory well was drilled in 1968 to a depth of 1458 m with temperatures about 230°C. The drilling in Berlin continued in 1978 to 1981. In the early 90's CEL installed a two 5 MW well head units and drilled three reinjection wells 1-2 km to the north of the production area. From 1997 to 1999, 18 more wells were drilled, mostly deviated wells among producers (up to 2400 m depth) and reinjectors (up to 2600 m).

At present, the field has in operation 8 production wells and 10 reinjection wells, feeding two condensing power plant (2x28 MWe) and generating 52 Mwe since late 1999. The current well field is about 4 km long and 3 km wide (Figure 1). All the wells are located within the NNW-SSE graben in the northern part of the Berlin-Tecapa caldera.

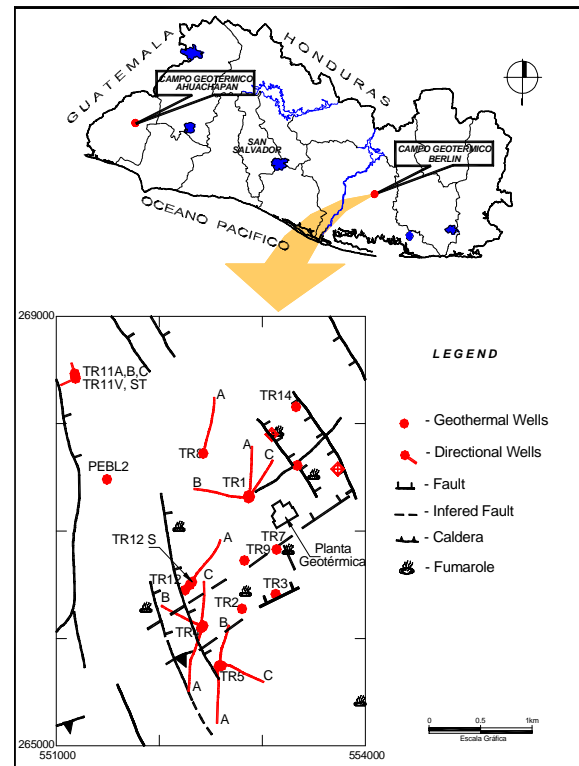


Fig. 1. Berlin Well field location

The only way to dispose the waste water is through reinjection. Since 1992 several tracer experiments have been carried out, with the support of the IAEA. This paper gives a general description about these experiments and focuses in the last one, where some results have been obtained.

THE BERLIN GEOTHERMAL FIELD

The Berlin geothermal field is located 112 km to the east of San Salvador (Fig. 1) on the northern slopes of the Berlin-Tecapa volcanic complex about 5 km to the east of the Berlin city and at an elevation between 600 and 900 masl. The geology in the area features a caldera largely filled by volcanic materials and a 3.5 km wide graben extending NNW-SSE. The geothermal activity on surface is clearly related to the faulting of the graben and the volcanic centre.

The geothermal system is associated with the activity of the Berlin volcano, which rises to an elevation of 1300 masl.

The conceptual model features a heat source underneath the Berlin-Tecapa volcano to the south of well field. From the recharge area the fluid flows laterally towards north to northwest and enters the well field close to well TR-5 where the top of this geothermal aquifer is found at about 2 km depth (elevation -1000 masl). The highest temperature measured in the wells is 305°C. This defines the minimum temperature of the upflow in the roots of the Tecapa volcano, but geothermometers based on fumarole gases indicate recharge temperatures as high as 350 °C.

Overlying the geothermal system are two shallower aquifers. A groundwater aquifer close to the surface is recharged by local rain in the area and a deeper aquifer of a intermediate temperature. This ground water aquifer is believed to feed the warm fresh water springs and wells to the north of the geothermal field. Within the well field the intermediate aquifer is found in the depth interval 500-1500 m with temperatures in the range of 170-230°C. It is not known if there is a hydrological connection between the intermediate aquifer and the hot geothermal aquifer.

TRACER FIELD EXPERIMENTS

Several experiments have been carried out at the Berlin field to date. The main tracer selected for the experiments was radioactive Iodine-131 isotope but sodium chloride and methanol without any significant results also have been used. The first eight tests were described by Steingrimsón (1996 and 1998). The main objective of all the tests is to gain information on the fluid flow within the reservoir and especially how rapidly injected fluids return to the production zone. Hydrological communication with the surface springs has also been investigated.

The design of the radiotracer test was undertaken depending on the different schemes of field operation with the following purposes:

a) Identify the hydraulic connections in the southern part of the field.

b) Evaluate the hydraulic and thermal effects of reinjection in the production zone.

c) Determine the return flow, time, velocity and preference direction of reinjected water.

d) Establish correlation with the chemical changes.

e) Establish correlation between the movement of the induced fluid by reinjection and the geological structure of the system.

f) Obtain quantitative and qualitative information about the nature of reservoir to improve the conceptual model of the system.

The main results indicate no evidence of tracer returns in a monitoring period between 36 to 70 days. At this moment, it is only possible to conclude that no fast flow paths have been detected between the reinjection and the production zones and that a thermal breakthrough is therefore not likely (Steingrimsón, B., 1998). This is of course a very important conclusion for the operation of the field and for the reinjection scheme applied. The reasons for the lack of tracer returns at the production zone can be due to several ways: retention of the tracer by absorption, matrix diffusion or simply that the tracer disperses into a large volume and migrates therefore very slowly through a relatively long distance from the injection to the production zone.

The experiment with some results carried out recently, was when the tracer was injected close to the production zone.

REINJECTION SCHEME

During all these experiments, different schemes of production-reinjection have been operated. At present the water flow rate discharged from the production wells is about 262 kg/s, where 255 kg/s is reinjected (97 %). The rest of the waste water is driven to a couple of ponds. The absorption capacity of reinjection wells and the production wells that feed them is presented in Table 1.

Production wells	Reinjection wells (kg/s)
TR-2 + TR-9	TR-1C (24) TR-8V (35) TR-8A (5) TR-14 (24)
TR-4B + TR-4C + TR-5 + TR-5A + TR-5B + TR-5C	TR-1A (20) TR-3 (30) TR-4A (31) TR-11st (26) TR-12 (25) TR-12A (35)

Table 1. Reinjection flow rate in Berlin wells

The reinjection wells TR-1B (6 kg/s), TR-11A (14 kg/s) and TR-7 (24 kg/s) are eventually used. However it is possible to reinject the total waste water according to the absorption capacity of the reinjection wells, but due to the operational problems at the moment it is not possible.

RESULTS OF THE NINTH RADIOTRACER TEST

The latest tracer test in the Berlin field was conducted during the period from the 16th of May through the 17th of August 2000. The tracer (1.96 Ci I-131) was injected into the deviated well TR-12A (2326 m TVD). The well is in continuous reinjection since Nov 1999 to date (14 months to date).

During this test, 30 kg/s were injected continuously, while wells TR-2, TR-4B, TR-4C, TR-5, TR-5A, TR-5B, TR-5C and TR-9 were discharging.

After 3 months of monitoring, the results indicated that 4 production wells showed signals of tracer. The computed tracer recovered gives very lower results, with exception of well TR-4C that showed the high tracer return of the test. The detection of tracer was in the following sequence: TR-4C, TR-5B, TR-9 and TR-5A. The Table 2 shows data from the production wells with tracer signal (% of recovery, breakthrough time, time at maximum concentration, the computed flow back and production data).

Well	Reco v. %	t arrival (days)	t max conc. (days)	Flow back (kg/s)	Total extrac. (kg/s)	Water extrac. (kg/s)
TR-4C	9.44	1	6	2.830	46	30
TR-5B	2.86	3	15	0.868	37	25
TR-9	1.71	11	23	0.513	37	30
TR-5A	0.24	15	23	0.071	77	57

Table 2. Summary of field data

The breakthrough time of tracer for well TR-4C was approximately hours to one day (not determined exactly due to the signal arrived before the first sample was collected). During the test, the mass flow from the well TR-4C was about 46 kg/s, 16 kg/s of steam and 30 kg/s of water. Well TR-4C is located around 400 m from the injection well TR-12A. The percentage of tracer is considered proportional to the volume of the injected water. Considering that the volume of the injected water was constant (30 kg/s), the volume of water that returned to well TR-4C was close to 3 kg/s. Figure 2 shows the tracer recovery curve for well TR-4C.

SIMPLE MODELLING/CALCULATION FOR TRACER TESTS

Information on the connections between injection and production wells can, in turn, be used to predict the time of thermal breakthrough and possible cooling of production wells due to long-term reinjection in the future. Tracer return curves are normally analyzed to yield 1) the amount of tracer recovered in a production well during a test, 2) the volumes of flow

paths connecting reinjection and production wells, and 3) dispersion coefficients of the flow paths.

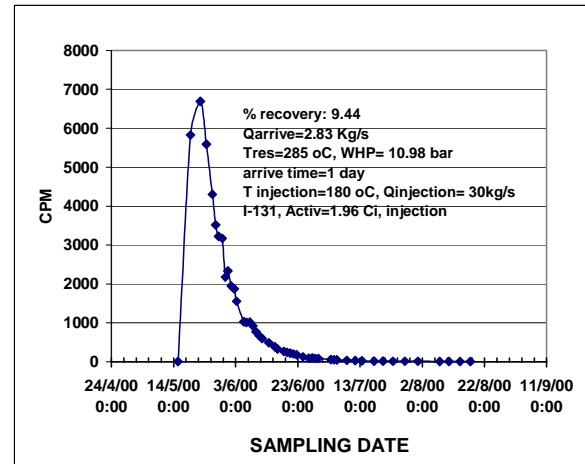


Figure 2. Tracer recovery curve for well TR-4C

These results may, consequently, be used to predict the time of thermal breakthrough and rate of temperature decline, for the well-pair in question, during long-term reinjection. The methodology of this approach is described in more detail by Axelsson et al. (1995). Firstly, the amount of tracer recovered in the well was estimated by calculating the integral:

$$\int Q_s(t)C(t)dt \quad (1)$$

where $Q_s(t)$ is the water flow-rate (the radiotracer is present in the water only), $C(t)$ the tracer concentration, and t the time. Secondly, the average velocity of the water travelling between the wells, u , was estimated from the breakthrough time and the distance between the wells. Consequently, this result was used to estimate the volume of the flow channel connecting the wells. This was done by the equation:

$$A\phi = q / (\rho u) \quad (2)$$

where A is the cross-sectional area of the channel, ϕ its porosity, q the mass flow-rate along the channel, and ρ the water density.

A simple model of a fracture zone connecting a reinjection-production well dipole (modified from Axelsson et al., 1995) is presented in Figure 3.

TRACER SIMULATION RESULTS

The TRINV computer software (part of the ICEBOX software package developed at Orkustofnun in Iceland) can be used to simulate the tracer data and provide an estimation of some reservoir parameters like cross section area of the fracture ($A\phi=m^2$), longitudinal dispersivity ($\alpha L=m$), dispersion

coefficient of the flow channel ($D = \alpha_t \mu = \text{m}^2/\text{s}$), mean velocity of flow ($\mu = \text{m}/\text{d}$), mass recovery (%) etc.

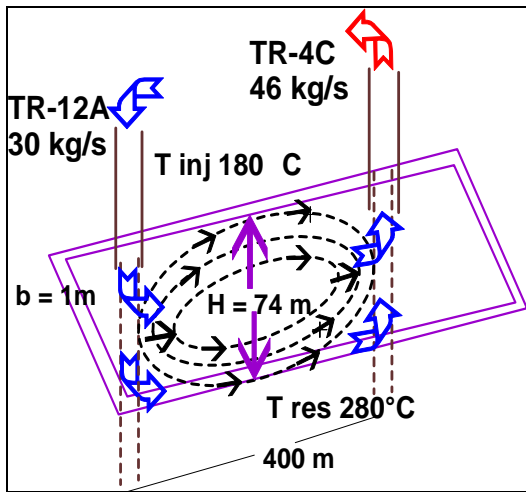


Figure 3. Reinjection-production well dipole

The input used in the code is the production flow rate of the monitoring well ($Q = \text{kg}/\text{s}$), injection flow rate in injector well ($q = \text{kg}/\text{s}$), distance between wells ($x = \text{m}$), total injected mass of tracer ($C = \text{kg}$), maximum concentration of tracer, the time of maximum concentration ($t_m = \text{days}$), half width of the recovery curve ($w = \text{days}$), number of tracer pulses, density of reservoir water etc.

First of all, an initial guess of the model parameters is applied with observed concentration data providing a model of variable complexity. The code uses a non linear least squares solutions algorithm for the model parameters. Inverting for the tracer recovery curve in a production-injection well dipole produces a “best” fracture flow model. Finally some graphs of observed and calculated data for individual tracer pulses are drawn.

The basic assumptions for simple fracture model are:

- flow channel between wells is along a narrow fracture zone
- one dimensional flow model
- neglected molecular diffusion
- assuming constant injection flow rate
- extremely high speed indicates fracture flow
- fracture anesite → heat energy mostly stored in rocks
- increase heat mining → reduce pressure drawdown

The governing equations used by the TRINV program are:

Differential equation describing tracer concentration in the flow channel :

$$D \frac{\partial^2 C}{\partial x^2} = \mu \frac{\partial C}{\partial x} + \frac{\partial C}{\partial t}; \quad \mu = \frac{q}{(\rho A \phi)} \quad (3)$$

The cross section area for the flow channel is $A = h * b$ (height and thickness of the channel).

The tracer concentration is correlated to the fracture zone concentration by using conservation of tracer mass flow $c * Q = q * C$. Where c is the tracer concentration in the producer fluid, C the tracer concentration in the fracture, Q the production flow rate and q the injection flow rate.

The solution for the governing equation is :

$$c(t) = \mu \frac{M}{Q} \frac{1}{2\sqrt{\pi D t}} \exp \frac{-(x - \mu t)^2}{4 D t} \quad (4)$$

The simulated curves for the test are presented in the Figure 4. As mentioned before, the recovery of 9.44 % for the well TR-4C represents the highest recovery for all the experiments at Berlin field.

The simulation on Figure 4 gives a determination coefficient of 91% using one main flow channel and 3 pulses simulating the small concentration peaks present. This could reflect one fracture channelling most of the flow and a matrix flow channel for the others and the widest pulse. Due to the presence of scattering data, it was not possible to get higher determination coefficient.

Table 3 shows the simulation results for the 4 pulses. Due to the very low values for the small pulses, it is considered the first pulse as a representative of the reservoir parameters estimated. The recovery for this main pulse is 7.7 % meantime the others represent 1.5 % producing a cumulative tracer recovery of 9.3 % for the simulated data. The longitudinal dispersivity is around 260 m and the cross section area of the fracture is 74 m^2 . The mean flow velocity in the first channel is around 36 m/d, compared with velocity tracer breakthrough time which is 398 m/d. The difference is due to the velocity in the flow fracture from TRINV corresponding to the mean breakthrough time value, whereas the data field takes the first arrival in the curve.

These results may indicate that the higher dispersivity values are due to the presence of several fractures between the wells as shown in the Figure 3.

The results obtained were finally used to carry out temperature predictions for well TR-4C, as mentioned above. This was done using the program TRCOOL (also part of the ICEBOX package). The

methodology of this approach is also described in more detail by Axelsson et al. (1994).

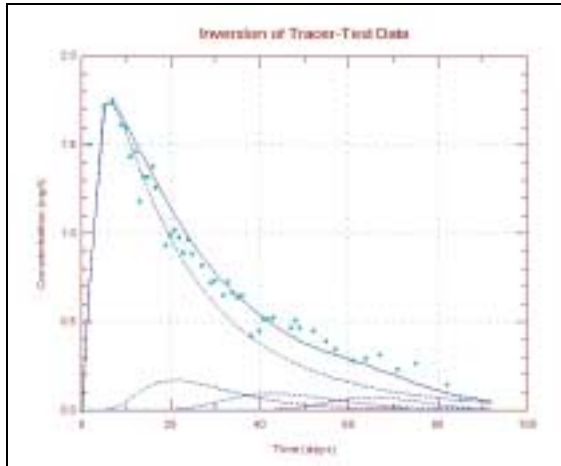


Figure 4. Tracer recovery curve simulation for well TR-4C

Several calculations have been carried out for different cases, with a flow rate in the fracture (q) between 3 and 6 kg/s; porosity (ϕ) values of 100, 50, 25 and 10% and also different values of the width of fracture b (1-2 m) and height of the fracture H (74 – 148 m). For the reservoir temperature, a measured values of 280 °C corresponding to the main feed zone into the well was used. The injection temperature used was 180 °C.

The results of the calculation carried out for some cases are presented in Figure 5 considering the option of fracture temperature. The Figure shows how sensitive the results are to the assumptions given. In particular, a reliable estimate of q is required. This may be obtained on the basis of a successful tracer test. The Figure also shows that a rapid temperature decline is not expected for this well pair in the optimistic case resulting a cooling of 14 °C after 4 years of reinjection. Meantime, in the worst case is expected a cooling of around 10 °C in one year when the porosity change at higher values and the flow rate and the parameters b and H remain constants. In the case of same porosity but higher value of H , the drop in temperature is much lower. This is due to the surface contact of the rocks which is higher related to the low flow rate in the fracture.

The Figure 6 shows the simulations using the option of production temperature producing lower cooling. The low tracer recovery and the scattered tracer recovery lead to low values for the fracture cross section area $A\phi$ and are assumed to reflect low confidence for the interpretation of the fracture model and also for the cooling and thermal efficiency predictions. We must also take into account that the

low cumulative recovery tests and their scattered results could indicate high mixing volume for the tracer (matrix flow) reflected by the higher dispersivity values.

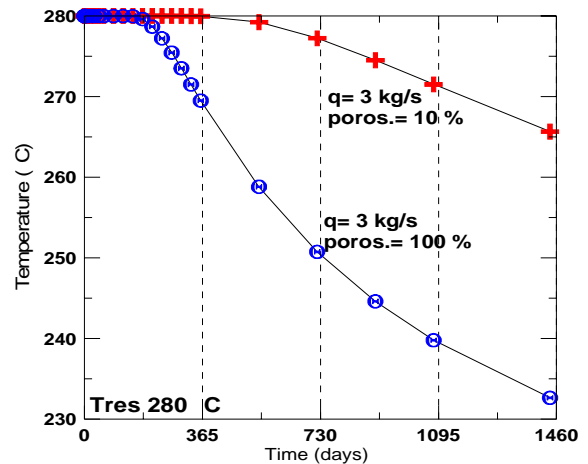


Figure 5. Temperature simulations for well TR-4C.

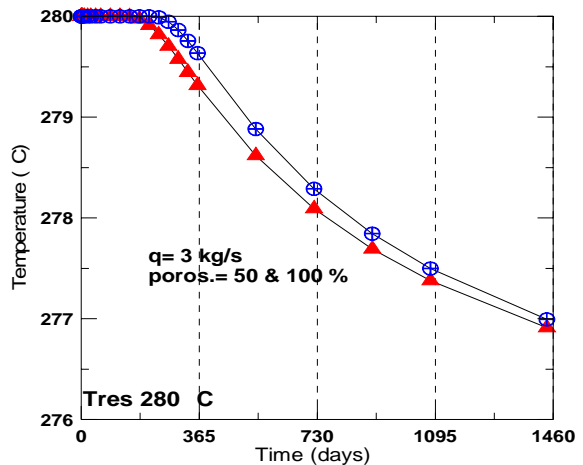


Figure 6. Temperature simulations for well TR-4C.

PRODUCTION AND CHEMICAL EVOLUTION

The production and chemical characteristics of the well TR-4C have been monitored. There is no clear change in these characteristics, that can be related to reinjection effect. The Figure 7 shows, the discharging water flow rate in well TR-4C since it went on line. The change in water flow rate is probably due to a natural change in the well discharge or different operation conditions in the well field.

Chemical monitoring of fluids from well TR-4C showed a gradual increase in salinity (chloride content), irregular silica temperature, decrease in gas content and positive shift for the isotopes.

Figures 8, 9, 10 and 11 show the evolution for these chemical parameters since the well started in production. These changes however have been started

before the reinjection in well TR-12A. The well TR-4C is defined as a high enthalpy well (1300 kJ/kg)

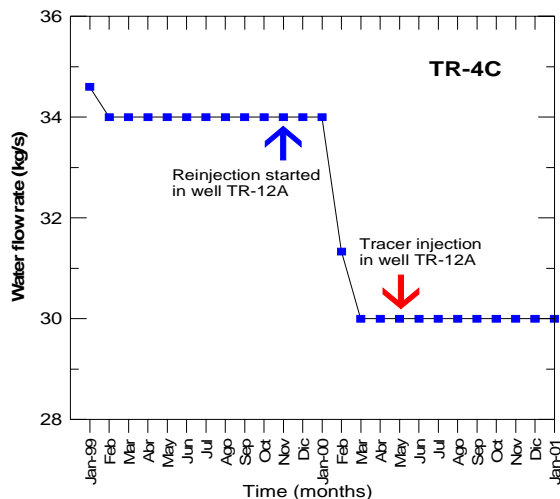


Figure 7. Water flow rate evolution for well TR-4C

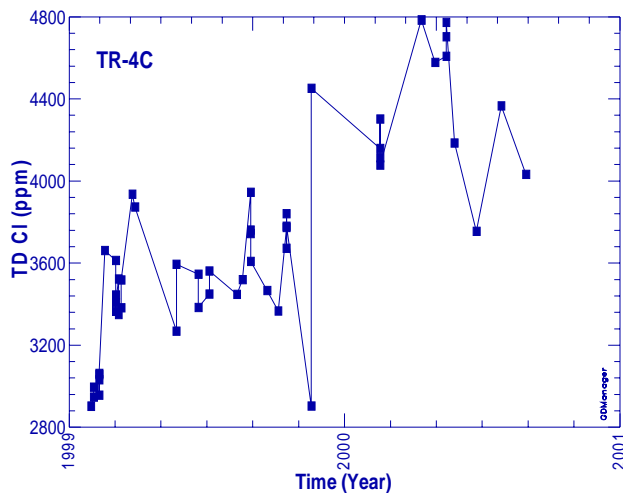


Figure 8. Chloride total discharge for well TR-4C

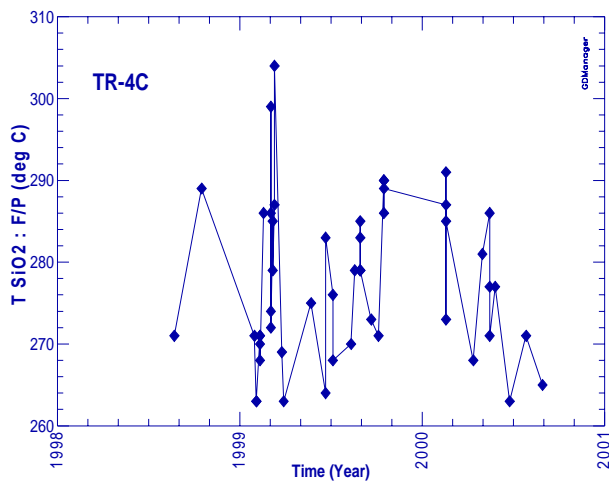


Figure 9. Silica temperature evolution for well TR-4C

and the comparison of measured and chemical enthalpies suggest that the fluid has an excess enthalpy due to boiling process.

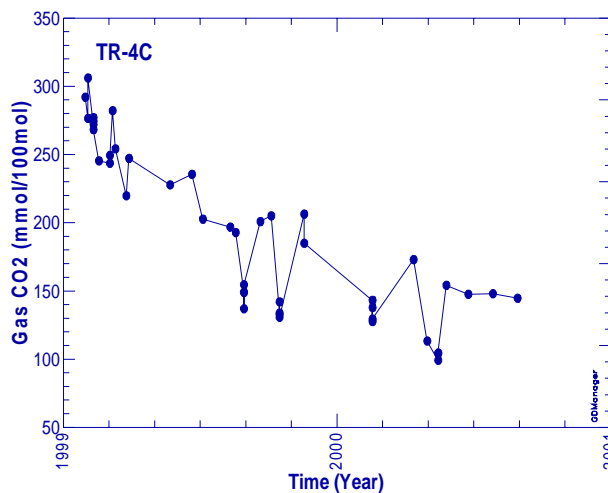


Figure 10. CO₂ content evolution for well TR-4C

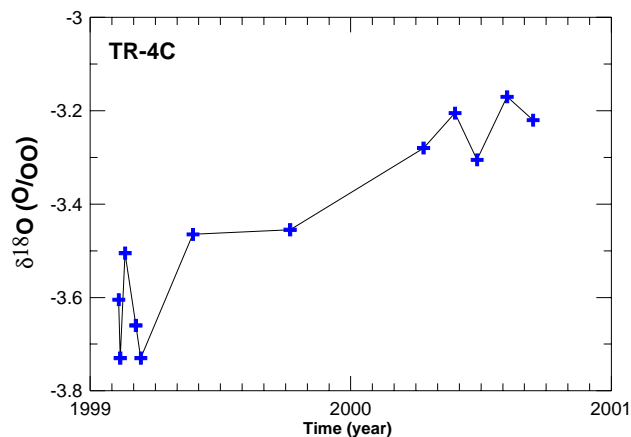


Figure 11. Oxygen isotope evolution for well TR-4C

The chemical changes observed since the well was put in discharge can be related mostly to the change in natural conditions and also affected for the boiling process occurring in the well.

GEOLOGICAL MODEL

Figure 12 shows a cross section of production wells and well TR-12A including the lithology and main geological features of the different layers, the wells elevation, the distance between the wells, the circulation loss, feed zones and assumed tracer flow in the permeable zones.

Well TR-12C was designed and drilled directionally toward NE to intercept the permeable structures NNO-SSE and intercept the circular fractures of the north border of the Berlin caldera. It is assumed that most of fluid is discharged towards the reinjection zone at north and the volume of fluid that returns to

producing wells depends not only on the mass of fluid to extract but also this will be controlled by the moderate permeability and fractures that govern all the zone.

Figure 13 shows the areal distribution for the movement of fluid coming preferentially when it is channeled along the defined corridors NNO-SSE of fault Las Crucitas and the hidden fault near the well TR-9 and the corridor NNO-SSE defined by faults Las Crucitas and El Beneficio, where the last one is less permeable. This is evidenced by the different mass discharge of wells TR-4 and TR-4B.

The tracer was not highly detected in well TR-5C probably due to the fact that the movement of the reinjected fluid is not enough towards the south (according the natural hydrological model, the fluid moves from S to N along the local fracture system). In well TR-5 (vertical one) was not registered any signal due to the fact that the permeable zone is located at shallow elevation, the same as for well TR-2. The general trend of the movement of the injected tracer from well TR-12C was possibly radial, but to a certain distance of the well, it turns towards the N-S direction with a main component towards the north.

CONCLUSIONS

The percentage values of tracer recovering show that although there exists connection between the reinjector well TR-12A and the monitoring wells TR-4C, TR-5A, TR-5B y TR-9, the quantity of reinjected water which arrives to wells is considered low. The total recovery injected in well TR-12A registered in the production wells was 14.25 % (4.3 kg/s returns to the production zone). Therefore, it can inferred that the water won't affect negatively the production characteristics of wells in a short time. In the case of the dipole reinjection-production wells TR-12A → TR-4C, the recovery of the well TR-4C was 9.44 % which represents around of 3 kg/s of injected fluid reaching the production well.

The tracer breakthrough occurred, indicating a tracer flow velocity of about 36 meters per day according simulations. This relative fast breakthrough indicates a good hydrological connection between these two wells, which are spaced about 400 m apart. A thermal breakthrough should therefore be expected but on a quite different time scale than the tracer breakthrough, probably within several months or few years.

According to this results and the chemical and production data collected at the time of the monitoring during the experiment, the probably effects due to the presence of the injected fluids in the production zone should be not significant in terms of short or moderate long time, taking into account the

results of thermal effect simulations. Only when the reinjection is applied into the production zone will the thermal breakthrough be a problem in next future.

Hydraulic connections between the main reservoir (lower) and the intermediate aquifer (upper) and the surface water system was not determined. The injection scheme depends however on whether the reinjected fluid travels straight back to the production zone (the lower reservoir). It is also of great importance for the reservoir modelling work to determine whether the two reservoirs are connected or not.

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Pulse	Cmax. (kg/m ³)	Tmax. (days)	W (days)	u (m/s)	D (m ² /s)	M (kg/m ²)	Aφ (m ²)	aL (m) (dispersivity)	Mr (%) (Mass recovery)
1	.175e ⁻⁸	6	20	.42e ⁻³	.109	.17e ⁻⁵	74	260	7.7
2	.17e ⁻⁹	21	25	.20e ⁻³	.92e ⁻²	.80e ⁻⁷	158	47	.77
3	.95e ⁻¹⁰	43	30	.10e ⁻³	.176e ⁻²	.28e ⁻⁷	300	17	.5
4	.75e ⁻¹⁰	65	25	.70e ⁻³	.37e ⁻²	.12e ⁻⁷	440	5	.33

Table 3. Simulation results for well TR-4C (four pulses)

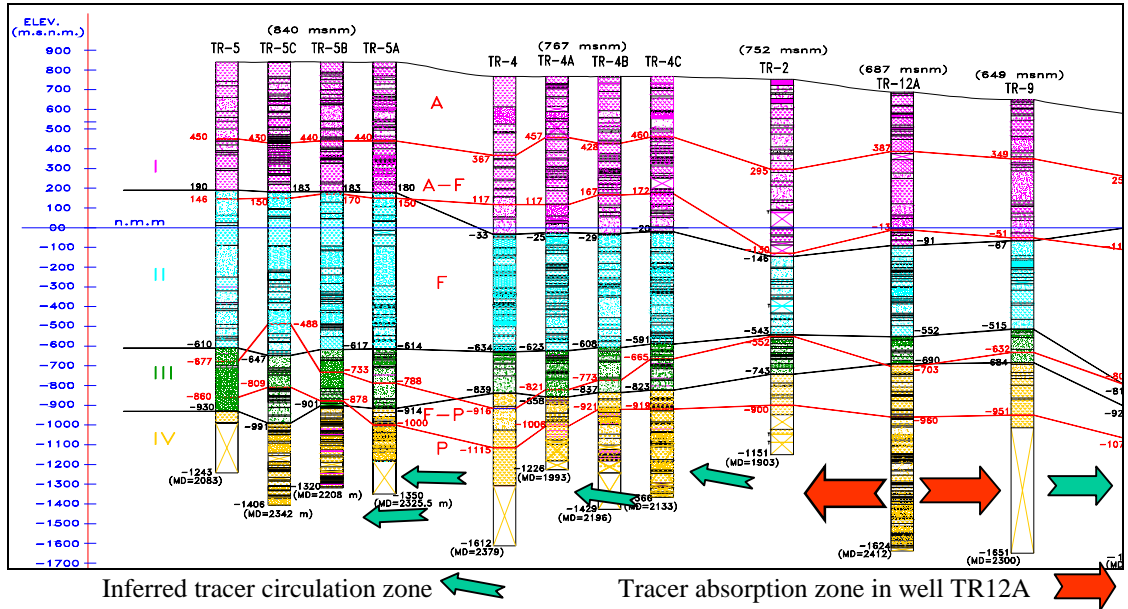


Figure 12. Geological cross section model showing the assumed tracer flow circulation from well TR-12A

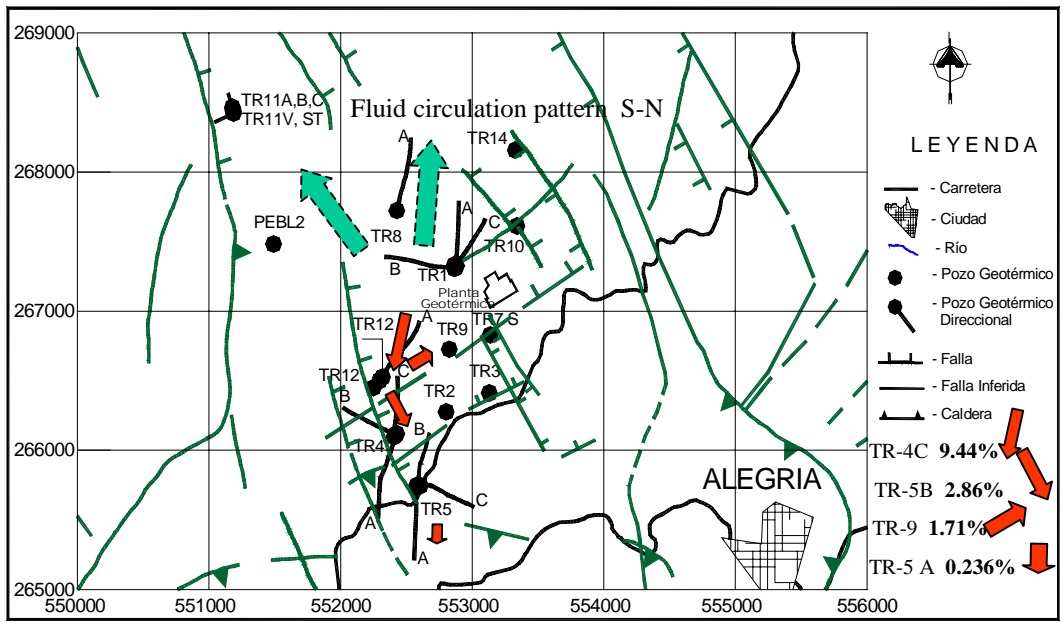


Figure 13. Tracer flow and areal distribution showing tracer movement () and natural flow ()