



CHEMICAL INTERPRETATION AND SCALING POTENTIAL OF FLUID DISCHARGE FROM WELLS IN THE BERLÍN GEOTHERMAL FIELD, EL SALVADOR

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ABSTRACT

Commercial production in the Berlín geothermal field began in 1992 with the installation of one back pressure turbine. In 1994 a second back pressure turbine was installed. At present the total generation is about 9 MWe. Geothermometers suggest temperatures between 270 and 300°C in the producing wells. Chemistry of the producing fluid from wells TR-2 and TR-9 indicates no changes with time for well TR-2 and only slightly change in well TR-9. Evaluation of saturation with respect to anhydrite, calcite and quartz suggests that the aquifer is anhydrite undersaturated but close to equilibrium with respect to calcite and quartz. The state of saturation for anhydrite, calcite and amorphous silica after adiabatic boiling has been evaluated. In order to avoid silica scaling in wells, a minimum separation pressure of 8 bars-a is required for aquifer silica concentration up to 600 mg/l and 10 bars-a for higher silica concentration. Evaluation of the state of saturation for anhydrite, calcite and amorphous silica after conductive cooling/heating suggest that the optimum injection temperature is between 160 and 180°C.

1. INTRODUCTION

The Berlín geothermal field is located in the eastern part of El Salvador, about 100 km from San Salvador, the capital of El Salvador (Figure 1). The first deep well, TR-1, was drilled in 1968. From 1978 to 1981 five additional wells were drilled: TR-2, TR-3, TR-4, TR-5 and TR-9. Due to political problems the project was kept in stand by. In 1990 the project was reactivated and its thermal potential was estimated to be 100 MW (Electroconsult, 1993).

In 1992 a back pressure unit was installed using well TR-2 as a producer and wells TR-1 and the producer TR-9 as injectors. The latter well (TR-9) was used as an injector because at that time there were no injection wells available for disposal of the residual water. TR-9 was used as an injector for about one year, until injector well TR-14 was drilled and put on line in 1994. Two additional injection wells were drilled during 1994-1995, TR-8 and TR-10.

In 1995 a second back pressure unit was installed, using well TR-9 as a producer. The total amount of electricity generated is about 9 MWe and residual water is completely injected, mainly into wells TR-8 and TR-14. A new 55 MW condensation plant is presently under construction. New injection and production wells will be drilled, beginning in March 1997 and commissioning of the plant is scheduled in 1998.

1.1 Geological settings and superficial manifestations

The Berlín geothermal system lies in a weakness zone created by the intersection of a tectonic graben with a conjugated fault systems striking NW-SE and NE-SW. The graben is related to the subduction of the oceanic Cocos plate under the Caribbean plate. Partial fusion of the continental plate has produced andesitic magma. This has risen and accumulated in weakness zones of the crust. A magmatic chamber exists under the south flank of the Berlín field (Figure 1) at a depth of 6-8 km (Electroconsult, 1994).

Volcano-tectonic activity took place in the area during the Pliocene epoch with the formation of the Central American graben and the conjugated fault system. The Berlín volcano lies in the southern part of the graben. Its age is estimated to be more than 1.4 million years. The latest activity of the Berlín volcano (0.1 My ago) involved eruptions of large quantities of ignimbrites and led to the collapse of the volcano and formation of the Berlín caldera. The geometry of this caldera indicates that the collapse occurred simultaneously with the activity of the NW-SE fault systems. This caldera is open to the north as a result of the creation of the Berlín graben, which has a NW-SE direction.

After the caldera formation, volcanic activity continued in the caldera. It has been postulated that an inner and smaller caldera, called Blanca Rosa, was formed inside the outer caldera 75,000 or more years ago. The volume of fall and flow of dacite pyroclastics support the existence of the small Blanca Rosa caldera. A subsequent activity gave origin to the actual Quaternary volcanic complex at Berlín. A phreatomagmatic eruption, at the so-called Hoyón crater, occurred 700 years ago.

One of the main superficial manifestations in the geothermal area consists of a series of hot springs with temperatures between 37 and 80°C and pH between 7.0 and 8.5. From a chemical point of view the water in the area has been classified into three groups (Tenorio, 1996), bicarbonate waters, sulfate waters and chloride waters. The first two are formed in shallow parts of the system, but the chloride water is the water tapped by the geothermal wells.

The other type of manifestation in the area is steaming ground and fumaroles. They are spread over an area of about 5 km² (Figure 1). The main gases discharged from the fumaroles are carbon dioxide (94-95%), hydrogen (0.1-2%), nitrogen (1-5%) and hydrogen sulfide (1-5%). Minor concentrations (less than 0.3%) of methane, helium and argon are also expelled from fumaroles. It has been hypothesized that the gases are partly magmatic and partly meteoric in origin (Tenorio, 1996).

2. DATA HANDLING

All the samples for which chemical data are used in this report were collected either from discharging boreholes during production tests (TR-1, 3, 5 and 10) or from wells in production (TR-2 and 9). The collection pressures for water and steam samples were, in most cases, different. In order to make files to run the WATCH computer program (see below), the gas concentrations in the steam were recalculated to the collection pressure of water samples, most often atmospheric conditions. This correction was made using the relationship:

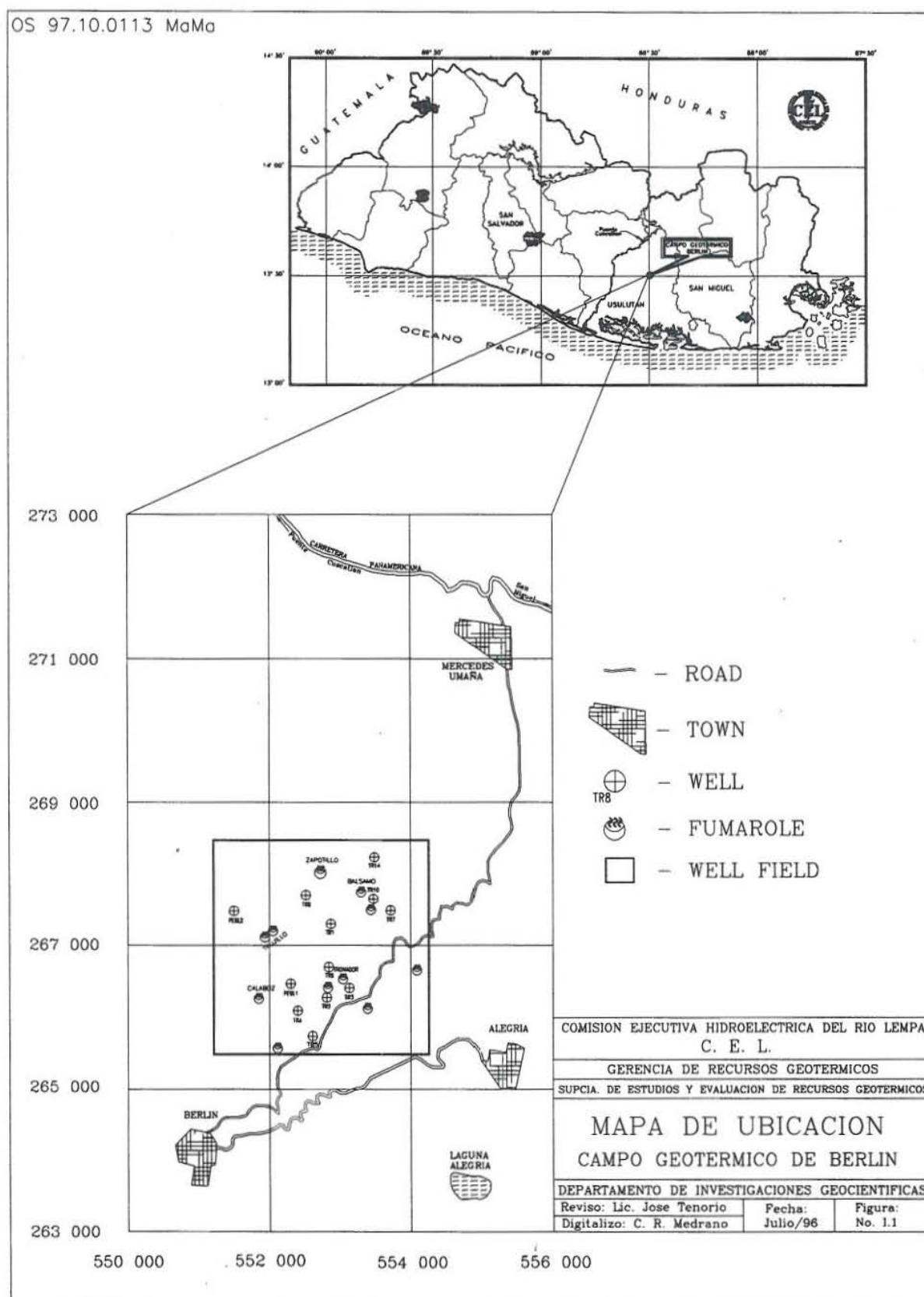


FIGURE 1: Location of the Berlín geothermal field

$$C_2 = C_1 \times (Y_1/Y_2) \quad (1)$$

Here it was assumed that no chemical reactions cause changes from sampling pressure in relative gas concentration to the sampling pressure of water, and that only the increase in steam fraction, due to the pressure drop, causes the decrease in the gas concentration.

The speciation program WATCH (Arnórsson et al., 1982; Bjarnason, 1994), which was developed in Iceland, makes it possible to compute the aqueous speciation, gas pressure and solubility products of many minerals at any temperature from 0 to 350°C. It can also be used to compute the concentrations of species, activity coefficients and solubility products when the aquifer fluid cools conductively or boils adiabatically from aquifer temperature to a lower temperature. This program was used to evaluate the state of saturation of calcite, anhydrite and amorphous silica when the fluid cools by conduction and adiabatic boiling from the aquifer temperature. The state of saturation of quartz, calcite and anhydrite in the aquifer was also evaluated.

In order to select the appropriate reference temperature to be used in the WATCH program, quartz, cation and gas geothermometers were used to estimate the aquifer temperature. The weighted mean geothermometer temperature was used as a reference temperature. In the case of well TR-9, which was used as an injector of fluid from TR-2 for about one year, two temperatures were calculated: one for the initial state, that is before injection, and the other after injection was stopped and production from it was initiated.

3. GEOTHERMOMETRY

In order to evaluate the aquifer temperature for the wells that have been discharged, several geothermometers have been applied to the fluid from the drillholes. They include the NaK geothermometers of Fournier (1979) and Arnórsson et al. (1983a), the NaKCa geothermometer of Fournier and Truesdell (1973) and the quartz geothermometer of Fournier and Potter (1982). The results are presented in Table 1.

TABLE 1: Chemical geothermometers for Berlin geothermal field (temperatures in °C)

Well	¹ T _{NaK}	² T _{NaK}	T _{NaKCa}	T _{Quartz}	T _{H2}	T _{CO2}	T _{H2S}	T _{meas}	T _{mean}
TR-1	202	178	200	206	197	193	231	205	203
TR-2	295	286	293	271	227	236	276	295	284
TR-3	267	261	263	275	234	233	270	293	267
TR-5	308	297	333	287	244	232	271	302	291
³ TR-9	300	291	289	278	230	222	259	290	284
⁴ TR-9	294	280	281	232	230	252	268	275	270
TR-10	261	255	246	227	241	269	247	276	247

1: Fournier (1979) 2: Arnórsson et al. (1983b) 3: Initial state 4: Production
T_{meas}: Measured temperature at the main feed zone

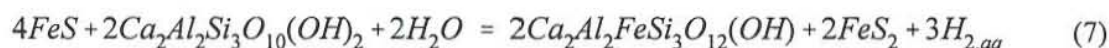
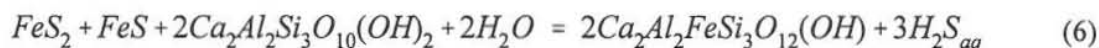
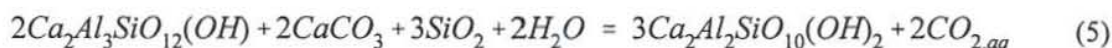
The cation geothermometers indicate temperatures higher than the quartz geothermometer, except for wells TR-1 and 3. This could either be due to deposition of silica during ascent of the fluid to the surface or mixing with colder fluid. Mixing does not affect the cation geothermometers as much as the quartz geothermometer. After injection into well TR-9 was stopped, the quartz geothermometer indicated very low temperature, but the cation geothermometers still reflected the temperature for the initial state, that is before injection started. In addition, the CO_2 , H_2S and H_2 gas geothermometers from Arnórsson et al. (1997) were applied to the steam samples. The equations relating temperature and gas compositions are

$$\log(\text{CO}_2) = k_{o,\text{CO}_2} + 5.520 - \frac{412.50}{T} + 0.0144 \times T - 5.029 \times \log T \quad (T > 230^\circ\text{C}) \quad (2)$$

$$\log(\text{H}_2\text{S}) = k_{o,\text{H}_2\text{S}} + 16.451 - \frac{3635.08}{T} + 0.00839 \times T - 6.074 \times \log T \quad (3)$$

$$\log(\text{H}_2) = k_{o,\text{H}_2} + 17.266 - \frac{4587.39}{T} + 0.00547 \times T - 5.356 \times \log T \quad (4)$$

They are based on the following reactions:



The equilibrium constant for each reaction is given by

$$K_{\text{CO}_2} = \frac{a_{\text{pre}}^3 \times a_{\text{CO}_{2,\text{aq}}}^2}{a_{\text{czo}}^2 \times a_{\text{cal}}^2 \times a_{\text{qtz}}^3 \times a_{\text{H}_2\text{O}}^2} \quad (8)$$

$$K_{\text{H}_2\text{S}} = \frac{a_{\text{epi}}^2 \times a_{\text{H}_2\text{S},\text{aq}}^3}{a_{\text{pyr}} \times a_{\text{pyrr}} \times a_{\text{pre}}^2 \times a_{\text{H}_2\text{O}}^2} \quad (9)$$

$$K_{\text{H}_2} = \frac{a_{\text{epi}}^2 \times a_{\text{pyr}}^2 \times a_{\text{H}_2,\text{aq}}^3}{a_{\text{pyrr}}^4 \times a_{\text{pre}}^2 \times a_{\text{H}_2\text{O}}^2} \quad (10)$$

k_0 for CO_2 , H_2S and H_2 are defined as:

$$k_{o,\text{CO}_2} = \log \frac{a_{\text{czo}} \times a_{\text{cal}} \times a_{\text{qtz}}^{1.5} \times a_{\text{H}_2\text{O}}}{a_{\text{pre}}^{1.5}} \quad (11)$$

$$k_{o,\text{H}_2\text{S}} = \log \frac{a_{\text{pyr}}^{0.33} \times a_{\text{pyrr}}^{0.33} \times a_{\text{pre}}^{0.67} \times a_{\text{H}_2\text{O}}^{0.67}}{a_{\text{epi}}^{0.67}} \quad (12)$$

$$k_{o,\text{H}_2} = \log \frac{a_{\text{pyrr}}^{1.33} \times a_{\text{pre}}^{0.67} \times a_{\text{H}_2\text{O}}^{0.67}}{a_{\text{epi}}^{0.67} \times a_{\text{pyr}}^{0.67}} \quad (13)$$

In order to evaluate the aquifer temperature from the composition of steam samples collected at the wellhead, Equations 3 and 4 were refitted to give a polynomial in temperature in terms of the gas composition for an anticipated epidote composition in andesitic rocks. First, k_0 was estimated assuming the activities (a_i) of water and all minerals except a_{epi} , to be one. The activity of epidote depends on the concentration of Fe in the mineral. It is known that the activity of epidote in basalt is on average 0.7 (Arnórsson et al., 1997) and because the concentration of Fe in andesite is less than in basalt, it was assumed that the activity of epidote in andesite was 0.3. This gives a value for k_0 of 0.350 for H_2S and H_2 , which must be regarded as only an approximation. This approximation can be improved by analysing the concentration of Fe in epidote in rock samples from Berlín.

Once the value for k_0 was chosen it was used in Equations 3 and 4 to obtain values for $\log(\text{H}_2\text{S})$ and $\log(\text{H}_2)$ as a function of temperature. These values were refitted to obtain a new set of equations describing the concentration of H_2 and H_2S as a function of temperature. These equations are:

$$t_{\text{H}_2} = 3.67 \times Q^2 + 53.95 \times Q + 242.02 \quad (14)$$

$$t_{\text{H}_2\text{S}} = 3.86 \times Q^2 + 55.84 \times Q + 222.23 \quad (15)$$

For CO_2 and $a_{\text{epi}}=0.3$, Arnórsson et al. (1997) have derived the equation below:

$$t_{\text{CO}_2} = 4.724 \times Q^3 - 11.068 \times Q^2 + 72.012 \times Q + 121.8 \quad (16)$$

As can be seen from Table 1 the gas geothermometers give temperatures comparable to the solute geothermometers,

Calculated temperatures from the H_2S geothermometer are higher than those of the other gas geothermometers, except in well TR-10, but similar to that of the solute geothermometers. This discrepancy could be accounted for by slight degassing of an initially equilibrated reservoir water. H_2S is the most soluble of the gases in question and H_2 the least soluble. Boiling causes, thus, variable depletion for different gases.

Because temperatures in geothermal reservoirs are in general not homogeneous, but variable both vertically and horizontally, it is expected that the temperature estimated using geothermometers will be the aquifer temperature beyond the zone of depressurization around each producing well. So, taking into account the results of the different geothermometers, the mean value of the solute geothermometers (Na/K, Na/K/Ca and quartz) and the H_2S geothermometer (Table 1) is considered to give the most reliable aquifer temperature for each well. The H_2S geothermometer was selected because H_2S is the most soluble gas. Accordingly, this geothermometer is the least sensitive of the gas geothermometers to boiling and degassing of the aquifer fluid.

As can be seen from Table 1, the average aquifer temperatures calculated from the geothermometers are in good agreement with the measured temperatures, except for wells TR-3 and 10, where the difference is about $30^\circ C$. The maximum difference between measured and mean temperatures from geothermometers in others wells is about $10^\circ C$. It is considered that the feed zones for wells TR-3 and TR-10 are about 270 and $250^\circ C$, respectively, but not as high as inferred from temperature loggings.

4. CHANGES IN WELL DISCHARGE COMPOSITION WITH TIME

In order to evaluate the response of the reservoir due to the production load, the concentrations of chloride (Cl), silica (SiO_2), hydrogen (H_2), hydrogen sulfide (H_2S) and carbon dioxide (CO_2) have been plotted against time in Figures 2 and 3 for wells TR-2 and TR-9. The concentrations of the species corresponded to those at atmospheric conditions.

The Cl concentration in the water from well TR-2 shows large scatter (Figure 2) and in general does not indicate change during the whole production period. In the beginning (first 1.5 years) of production the concentration tended to increase, but thereafter there was a tendency to decrease with time. In general, the chloride concentration of the water from well TR-2 is not stable, showing a cyclic pattern during the whole production period. The SiO_2 concentration shows less scatter than chloride and indicates stable aquifer temperature conditions during the whole production period (Figure 2).

The Cl concentration in water from well TR-9 increased from 7055 ± 242 mg/l in 1995 to 7748 ± 176 mg/l in 1996. The SiO_2 concentrations increased from 559 ± 74 to 795 ± 35 during the same period. This increase in chloride and silica could be either due to deep recharge of more saline fluid or increased vaporization of the fluid passing through the aquifer.

The gaseous species CO_2 , H_2S and H_2 in the geothermal fluid from wells TR-2 and TR-9 show great scatter during the whole production period (Figure 3). There is no clear tendency for individual concentrations to change with time, suggesting that there are no big changes in the gas composition of the geothermal fluid due to production.

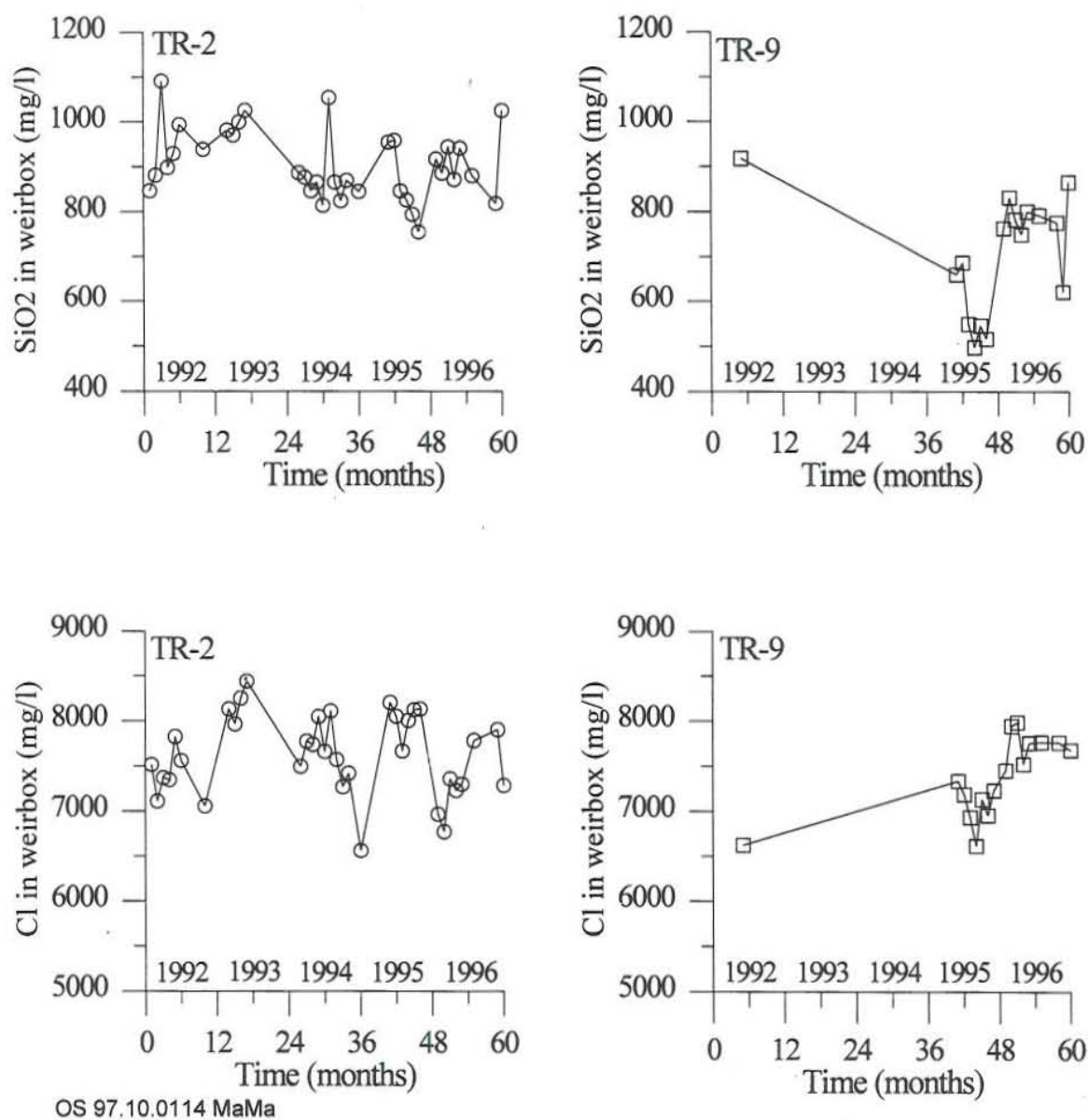


FIGURE 2: Change with time in chloride (CL) and silica (SiO₂) concentrations of wells TR-2 and TR-9 during the period 1992-1996

5. MINERAL SATURATION IN RESERVOIR

It has been proposed that chemical equilibrium is closely approached between solution and hydrothermal minerals in geothermal systems for most, if not all, major aqueous components except Cl and B (Giggenbach, 1980, 1981; Arnórsson et al., 1983a; Michard, 1991). When the reservoir fluid boils or cools by conductive heat transfer, either in upflow zones or in discharging wells, the chemical equilibrium existing in the aquifer is upset.

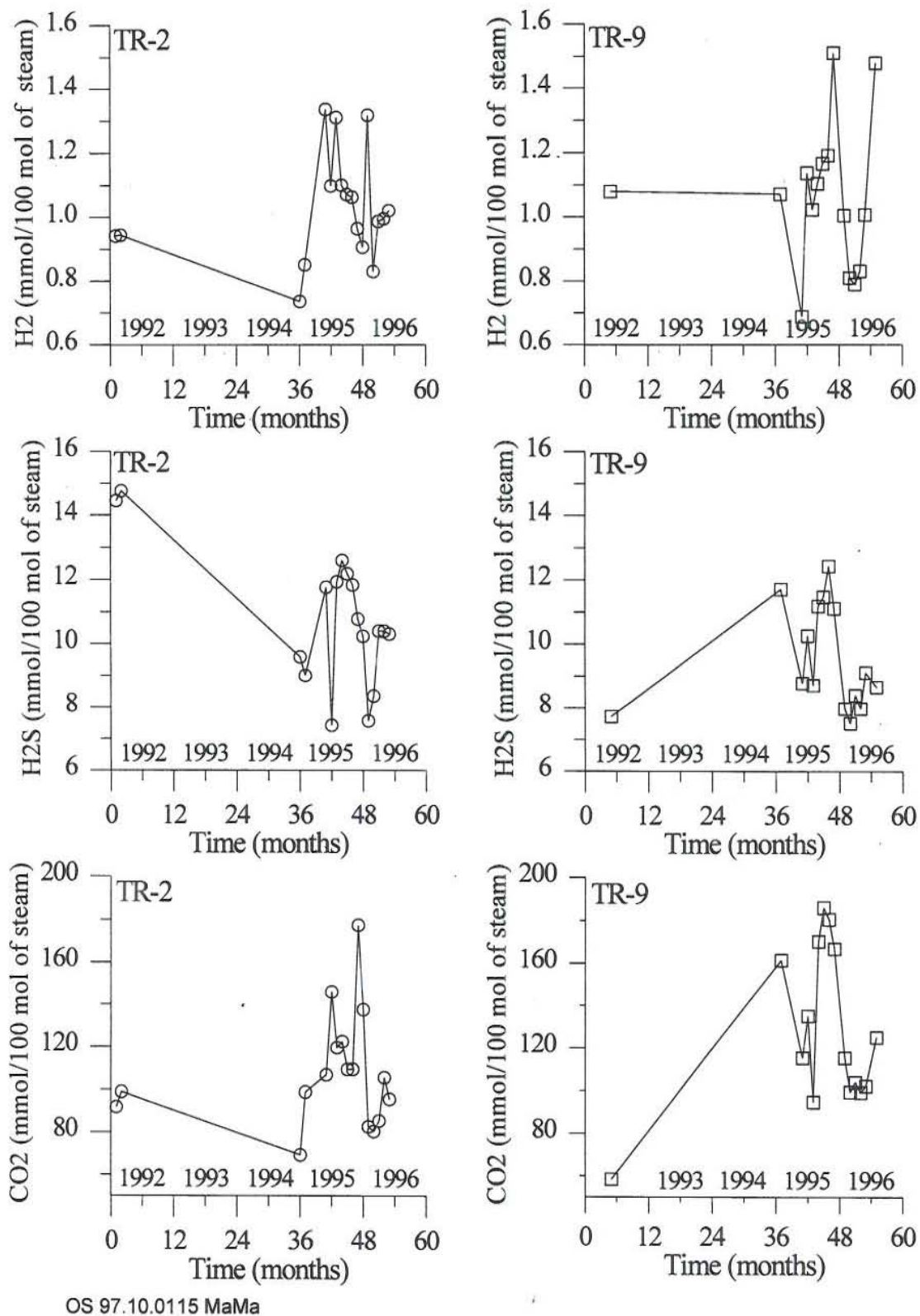


FIGURE 3: Change with time in CO₂, H₂S and H₂ concentrations for wells TR-2 and TR-9 during the period 1992-1996, concentrations recalculated to atmospheric conditions

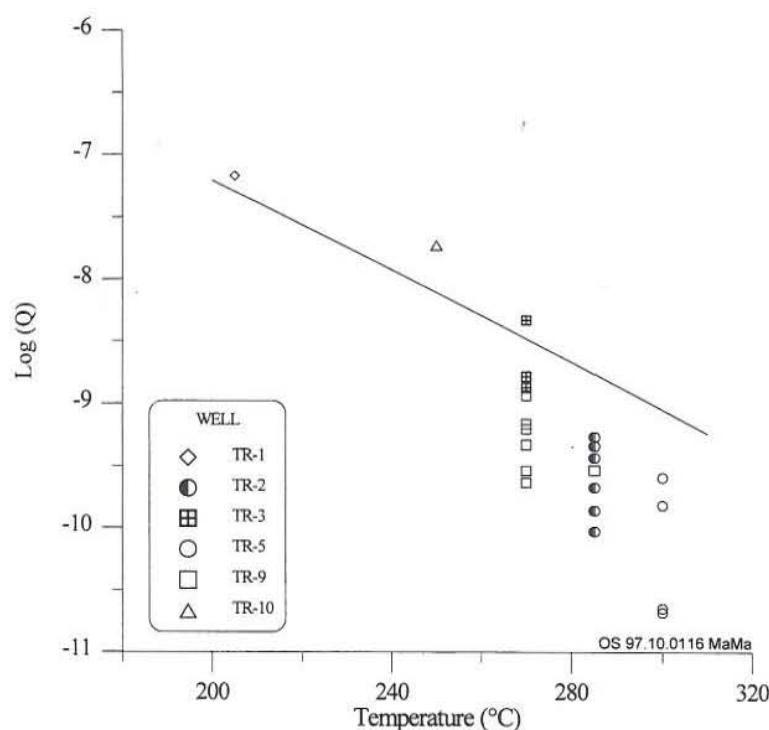


FIGURE 4: State of anhydrite saturation for geothermal fluid from Berlin wells, the curve represents saturation

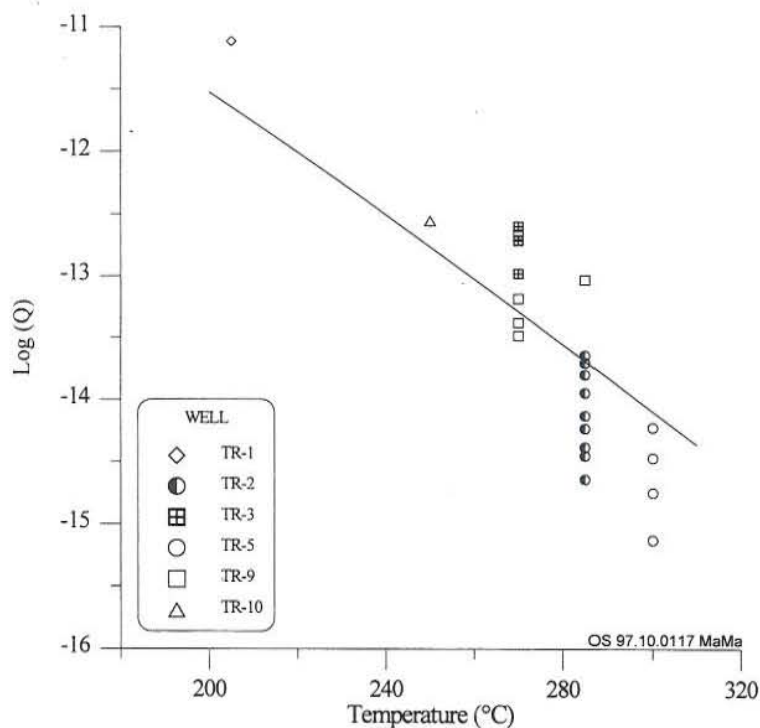


FIGURE 5: State of calcite saturation for geothermal fluid from Berlin wells, the curve represents saturation

The state of saturation of calcite, quartz and anhydrite in the aquifer fluid of individual wells has been assessed with the aid of the WATCH program. The results are presented in Figures 4-6. The fluid from wells TR-1, TR-10 and TR-3 appears to be close to saturation with respect to anhydrite. The hottest wells (TR-2, 5 and 9), on the other hand, appear to be undersaturated. According to Arnórsson (1997) anhydrite saturation is observed for shallow aquifers in some geothermal fields but undersaturation in deeper (hotter) aquifers. This also appears to be the case for Berlin. The evaluation of the state of saturation of aluminosilicates could support this idea. There are, however, no data on aqueous aluminium to test saturation with respect to such minerals.

The aquifer water appears to be close to saturation with calcite or slightly oversaturated for all wells, except well TR-5 which seems to be undersaturated. Calculated calcite undersaturation is generally the product of too low apparent pH which results from high gas content in the fluid. This does not seem to be the case, because the CO_2 concentration of the TR-5 fluid is low compared to other wells, i.e. TR-2 and TR-9, which also have lower pH than TR-5. Another explanation could be that the concentration of CO_2 was not sufficiently high to maintain calcite saturation, that is CO_2 is depleted from the fluid. It must be pointed out that the data present some scatter, which could be due to deposition of calcite in the well due to boiling. This could explain the difference of one and two orders of magnitude between concentrations

of calcium in the samples from well TR-5 (about 4 mg/l), 50-79 mg/l for TR-2 and 9 and 232-259 mg/l for TR-1, 3 and 10.

Quartz appears to be close to equilibrium at the selected aquifer temperature in all the wells, except well TR-10, which is undersaturated according to calculations. The data show some scatter as is the case with calcite. This is more evident for wells TR-2 and TR-9, which are currently in production. This scatter could be explained by deposition of silica during the ascent of the fluid to the surface due to its cooling by boiling.

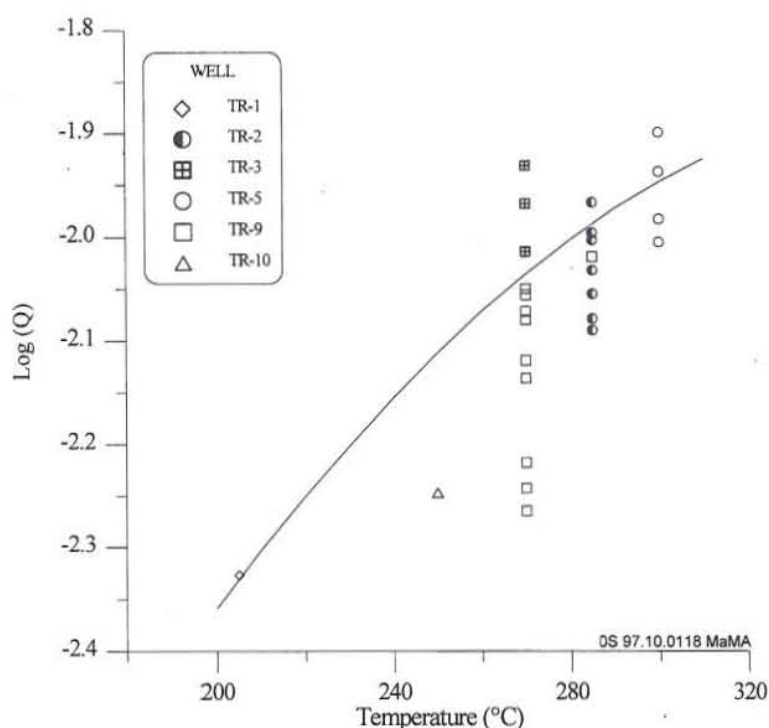


FIGURE 6: State of quartz saturation for geothermal fluid from Berlin wells, the curve represents saturation

6. CHANGES IN MINERAL SATURATION DURING BOILING AND CONDUCTIVE COOLING/HEATING OF SEPARATED WELL WATER

One of the major concerns during the exploitation of the Berlin geothermal field, is the high concentration of silica. In order to minimize the problems regarding silica scaling, a minimum separation pressure has to be selected. The scaling potential not only for silica, but also for calcite and anhydrite has been calculated at different temperatures during one step adiabatic boiling and conductive cooling and heating from the selected aquifer temperature.

6.1 Adiabatic boiling

The state of saturation for anhydrite, calcite and amorphous silica, when the water boils adiabatically, is presented in Figures 7, 8 and 9 as a function of temperature of the boiled water. Anhydrite calculates to be undersaturated over the whole temperature range, so scaling of this mineral should not be a problem for the production wells.

Calcite appears to be undersaturated or close to equilibrium for wells TR-2, TR-5 and TR-9. Calcite scaling should not be a problem for these wells at any separation temperature selected, but

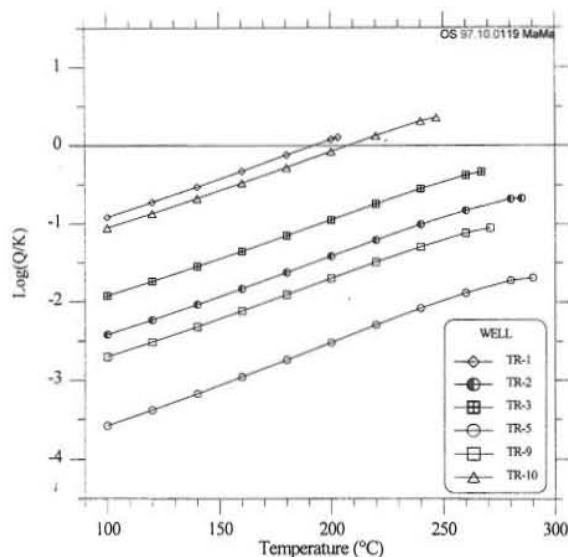


FIGURE 7: Calculated change in the saturation index ($\log Q/K$) of anhydrite during one step adiabatic boiling of the geothermal water from Berlin wells

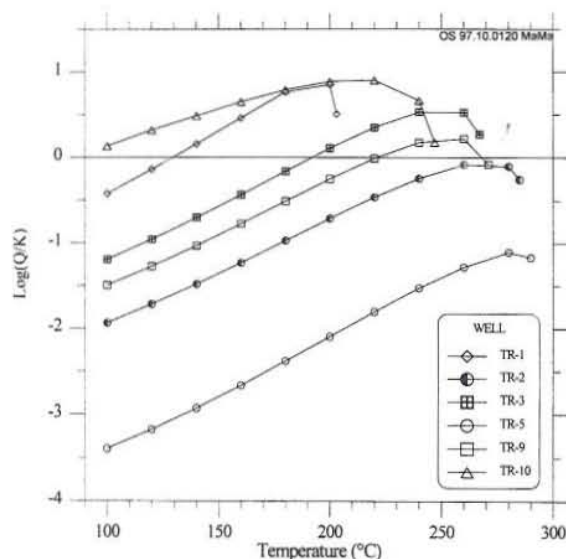


FIGURE 8: Calculated change in the saturation index ($\log Q/K$) of calcite during one step adiabatic boiling of the geothermal water from Berlin wells

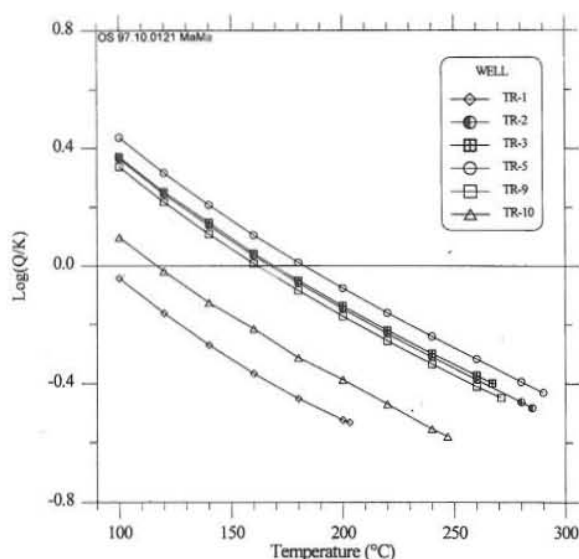


FIGURE 9: Calculated change in the saturation index ($\log Q/K$) of amorphous silica during one step adiabatic boiling of the geothermal water from Berlin wells

for well TR-3 the separation temperature should be less than about 200°C in order to avoid scaling at the wellhead during production.

Amorphous silica scaling is expected to be a problem if the temperature of separation is less than 170°C for wells TR-2 and TR-3, less than 180°C for well TR-5 and less than 160°C for well TR-9. So the optimum separation pressure for the geothermal water is 8 bars-a (170°C) for a fluid with reservoir silica concentration of less than about 600 ppm and 10 bars-a (180°C) for a fluid with higher silica concentration.

6.2 Conductive cooling/heating

Due to environmental constraints, all the waste water from the geothermal wells has to be injected through injection wells. At present the water from the two production wells (TR-2 and TR-9) is injected directly from the separator under a pressure of about 9 bar-a. The injector wells are TR-14 and TR-8 mainly, but also wells TR-1 and TR-10. New injection wells will be drilled for the 55 MW power plant, now under construction.

The state of saturation of the waste water with respect to anhydrite, calcite and amorphous silica has been evaluated at different temperatures for conductive cooling or heating after separation at 8-10 bars-a (Figures 10, 11 and 12). The temperature range for evaluations of the saturation state is 100- 280°C.

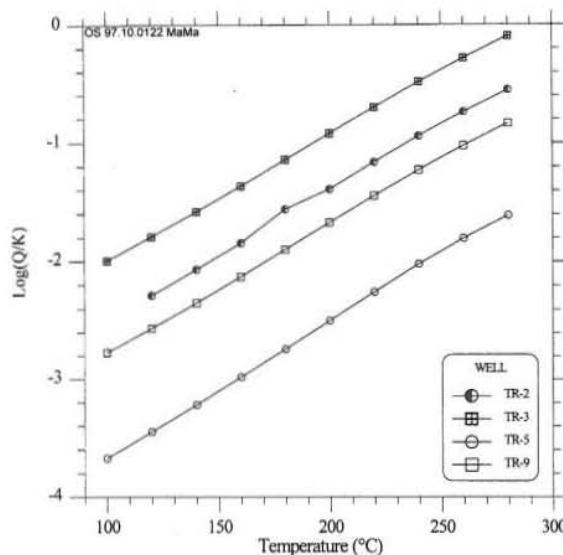


FIGURE 10: Calculated change in anhydrite saturation index ($\log Q/K$) when the separated water from Berlin wells is cooled or heated conductively

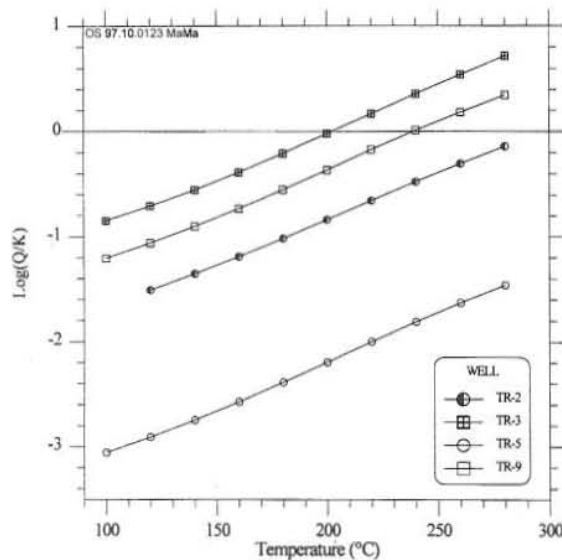


FIGURE 11: Calculated change in calcite saturation index ($\log Q/K$) when the separated water from Berlín wells is cooled or heated conductively

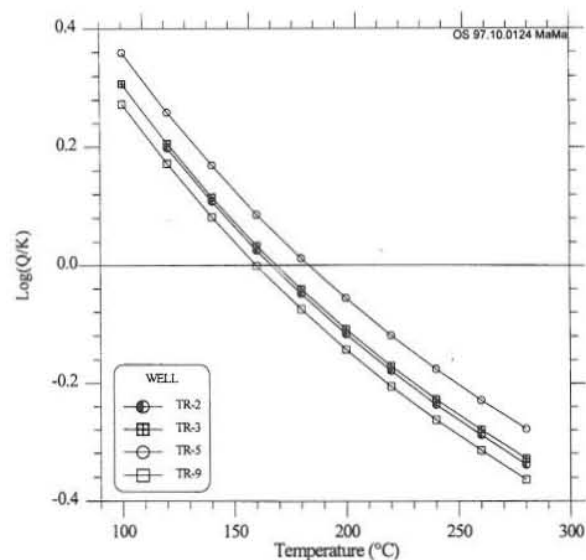


FIGURE 12: Calculated change in amorphous silica saturation index ($\log Q/K$) when the separated water from Berlín wells is cooled or heated conductively

The water from the selected wells (TR-2, 3, 5 and 9) seems to be anhydrite undersaturated over the whole temperature range. Calcite calculates to be undersaturated over the whole temperature range for wells TR-2 and TR-5. Wells TR-3 and TR-9 appear to be undersaturated at temperatures below 190 and 240°C, respectively, but oversaturated at higher temperatures. Amorphous silica is undersaturated at temperature higher than 160-180°C, but over-saturated at lower temperatures.

The results depicted in Figures 10-12 indicate that the optimum injection temperature for the residual water is 160-180°C. At these temperatures the water is undersaturated with respect to the phases that precipitate easily, that is anhydrite, calcite and amorphous silica.

7. CONCLUSIONS

1. Solute and gas geothermometers indicate that the aquifer temperature of producing wells (TR-2, TR-3, TR-5 and TR-9) at Berlín is between 270 and 300°C.
2. During production well TR-2 shows no changes in chemistry. For well TR-9 there are slight changes, probably due to an increase of the deep fluid recharge.
3. The state of saturation with respect to anhydrite, calcite and quartz in the aquifer has been evaluated with the aid of the WATCH program. The results indicate that the water is anhydrite undersaturated for the hottest wells (TR-2, TR-5 and TR-9) but close to equilibrium for the coldest wells (TR-1, TR-3 and TR-10). Calcite is close to equilibrium or slightly supersaturated for most of the wells, except TR-5. Quartz is close to equilibrium for most of the wells except in well TR-10, which seems to be undersaturated. The reason is most likely precipitation of quartz in the producing aquifer where the water boils extensively.
4. The state of saturation of anhydrite, calcite and amorphous silica has been evaluated during boiling and heating/cooling of the geothermal water. The results indicate that the minimum

separation pressure for the geothermal water is 8 bar-a for a fluid with reservoir silica concentrations of less than 600 mg/l, and 10 bar-a for a fluid with higher silica concentrations. In order to minimize the risk of deposition in the injection wells, the optimum injection temperature is calculated to be between 160 and 180°C.

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NOMENCLATURE

a_i	= Activity for the i -th specie;
C	= Concentration of gas (mmol/100 mol of vapor);
(CO_2)	= Concentration of carbon dioxide (mol/kg);
(H_2S)	= Concentration of hydrogen sulfide (mol/kg);
(H_2)	= Concentration of hydrogen (mol/kg);
k_0	= Constant value for the i -th gas (it depends on the epidote composition);
K	= Equilibrium constant;
Q	= Logarithm of gas (carbon dioxide, hydrogen sulfide or hydrogen) concentration (mmol/kg);
T	= Temperature (Kelvin);
Y	= Steam fraction;
t	= Temperature in centigrade;

Subscripts

1	= Sampling point of gases (usually wellhead)
2	= Sampling point of water (usually weirbox)
<i>cal</i>	= Calcite
<i>czo</i>	= Clinozoisite
<i>epi</i>	= Epidote
<i>pyr</i>	= Pyrite
<i>pyrr</i>	= Pyrrotite
<i>pre</i>	= Prehnite
<i>qtz</i>	= Quartz

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