Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Preliminary Modelling of the Permeability Reduction in the Injection Zone at Berlin Geothermal Field, El Salvador

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Keywords: Geothermal reservoir, injectivity, silica scaling, thermo-hydraulic-chemical coupled code, water-rock interactions, permeability, reinjection well, Berlin geothermal field, El Salvador.

ABSTRACT

The exploitation of the Berlin geothermal field (El Salvador) started in February 1992 with two 5 MW electrical units. In December 1999, exploitation at a larger scale started with the operation of two turbo-generating condensation units of 27.5 MW_e each. Since the beginning of exploitation until today, all the deep thermal fluids produced during the generation of electricity have been injected back to the reservoir. However, the well injectivities declined because of self-sealing processes of fracture thereby reducing permeability in the injection zones.

Our study focuses on the factors that may have caused the observed loss of injectivity of reinjection wells, using numerical simulation of fluid flow with coupled chemical reaction modelling. Such a model helps quantitatively understand the complex interplay of thermal, hydraulic and chemical processes (THC) and to predict the impact of reinjection on reservoir properties. The first preliminary simulation was carried out with FRACHEM code. This paper presents simulation results that reproduce in some way the observed decrease of permeability in the injection zone with time.

1. INTRODUCTION AND BACKGROUND

Berlin Geothermal Field is located on the N-NW slope of Tecapa volcano in Eastern El Salvador, approximately 110 km ESE of the capital, San Salvador. The main geological feature of the area is a large caldera, filled for the most part with volcanic materials, as well as a 3 to 4 km wide graben extending NNW-SSE. The volcanic chain in this region is related to the subduction between the Coco's Plate below the Caribbean Plate (Molnar and Sykes, 1969). Another important tectonic feature of the area is the boundary of the Caribbean with the North-American Plate in nearby Guatemala that defines the Motagua-Polochic fault system. Parallel to the Central American Pacific Coast, from Guatemala to Nicaragua, a graben system has been formed. This graben crosses El Salvador from West to East (Molnar and Sykes, 1969). The volcanic chain follows the southern margin of this graben. Figure 1 shows the location of Berlin Geothermal Field in El Salvador, Central America and the faults in the area.

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 above sea level on the northern slope of the Berlin-Tecapa volcanic complex, which rises to an elevation of 1300 m. The heat source, due to an active magmatic chamber, has generated the Berlín geothermal field, with a hydrothermal system related to andesitic volcanism (D'Amore and Tenorio, 1999).

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, with a reservoir temperature of 230ºC. During 1978-1981, drilling at Berlin continued 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.

Feasibility studies were 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, two 5 MW_e wellhead units were installed. It was planned to use wells TR-2 and TR-9 as producers and inject 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 plugged with cement. Because of the limited injection 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. The first wellhead unit was taken off line because of carryover of corrosion material from well TR-2 to the turbine on 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 injection purposes namely TR-8, TR-10 and 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 injection capacity. The total hot residual waters were injected into wells TR-1, TR-8 and TR-14.

Expansion of the geothermal field was a priority to address the growing electricity demand of the country. After the first stage of development at Berlin geothermal field, using well head units, a second stage development 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 used as injection wells. Two condensing type units of 27.5 MW_e each, with fluid collection system and injection line, have been built. When the turbo generator condensing units started to operate in 1999, the following wells provided additional steam: TR-4, TR-4B, TR-4C, TR-5, TR-5A, TR-5B, and TR-5C. The total hot residual waters were then injected to wells: TR-1A, TR-1B, TR-1C, TR-3, TR-4A, TR-8A, TR-10, TR-11ST, TR12, and TR-12A. Colder residual waters were injected to wells TR-7 and TR-11A.

An extensive expansion project, aimed at installing an additional 40 MW, has been scheduled. Four additional wells have been drilled in the southern border of the reservoir. At present, there are three condensing units installed in Berlín: two 27.5 MW_e single-flash units and one 44 MW_e single-flash unit constructed by ENEL, the company's strategic partner. An additional 6.5 MW bottoming cycle binary unit is under evaluation.

Figure 1 shows the locations of the wells drilled in the field. 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 injection 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.

The rocks found in this geothermal field are mostly andesitic lava flows intercalated with more silicic tuff layers. At reservoir depth, the main alteration minerals are quartz, calcite, chlorite and phrenite, wairakite, epidote, illite, albite and iron oxides (Renderos, 2002). The average porosity of the reservoir has been estimated between 5-10%. The possible dimensions of the reservoir are around 6x7 km^2 with a thickness of 0.3 km, for a total volume of 12.6 km^3 that includes both the production and injection zones (Monterrosa, 2002).

One important characteristic of the operations at Berlin geothermal field is that the totality of the waste water generated during the process of electrical generation energy (about 350 kg/s) is injected back to the reservoir. Reinjection was the only feasible option for this field. However, silica scaling problems in the injection wells decreased the injection capacity of these wells (Barrios et al, 2007). The silica supersaturated reject brine has deposited silica within the reservoir, incrusting and plugging the pores. The temperature of the injected waters is about 175°C and the reservoir temperature at the reinjection wells ranges from 200 to 290ºC. The understanding of the conditions, evolution, and future behaviour of the silica scaling process is important for the exploitation of this geothermal field.

The objective of this paper is to present the first simulation results of silica scaling induced by temperature contrasts and mixing between reservoir fluid and reinjected waters at Berlin geothermal field, and to compare these results with field observations. These simulations can help understand how the precipitation process is happening and how it is affecting the circulation of the geothermal fluids. The code used for these simulations is FRACHEM (Durst, 2002; Bächler, 2003; Bächler and Kohl, 2005; Rabemana et al., 2003; André et al., 2006; Portier et al., 2007).

2. PROBLEM SETUP

During the seven years of operation of the turbo-generating backpressure units, the injection wells showed a rather stable good injection capacity with a slight decreasing behaviour with time due to the salinity of the residual waters (average TDS=13000 ppm). However, when the exploitation of the field increased and the additional turbo-generating condensing units were installed, the capacity of most of the injection wells declined with time.

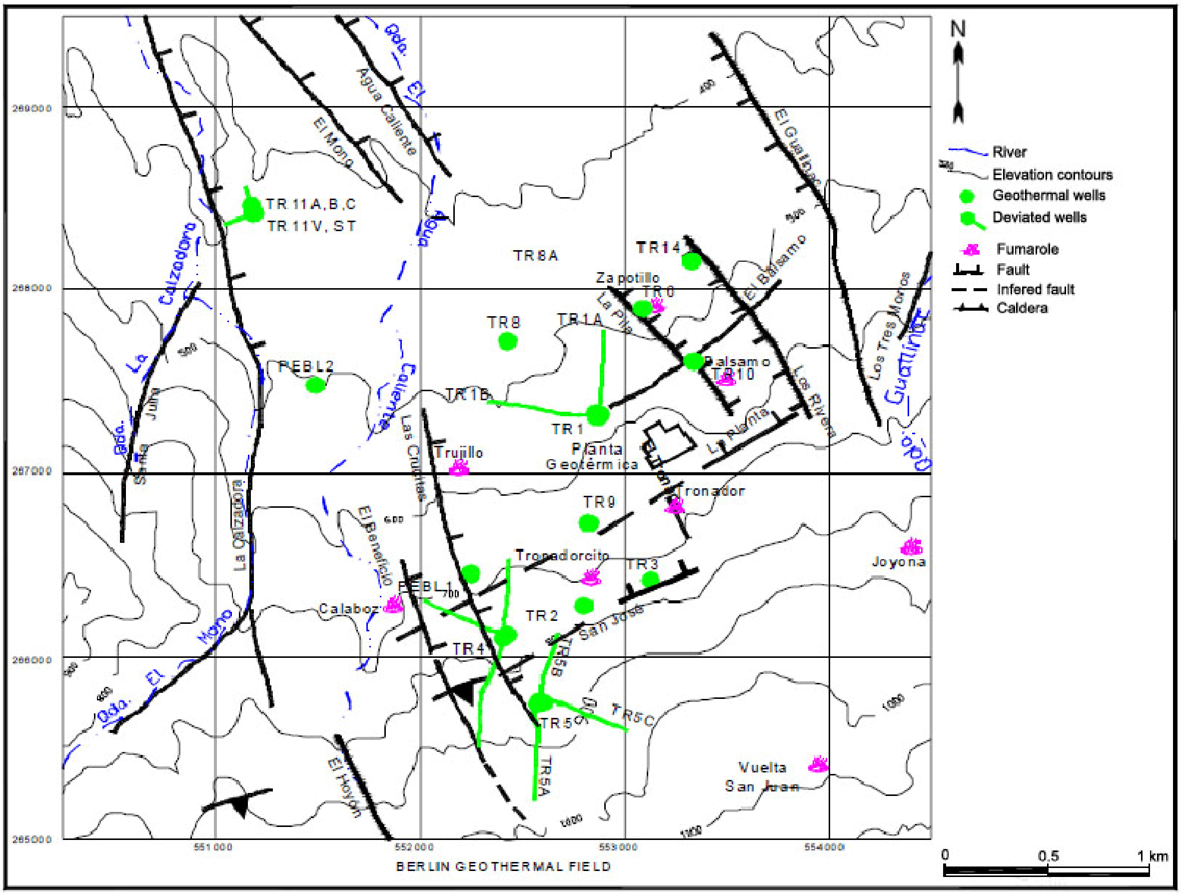

Figure 1: Location map of Berlìn geothermal field, showing tectonic features and wells (after Monterrosa, 2002).

Figure 2 shows the injection history of wells TR-14, TR-1A, and TR-11ST. It is clearly shown that just after injection started at well TR-1A, the injection capacity of well TR-14 decreased from an average of 40 kg/s to an average of 10 kg/s during a time span of 1.25 years. Injection well TR-14 was very stable in its injection capacity during 4 years of operation prior to reinjection in well TR-1A. Well TR-14 was cleaned mechanically in July 2000 and in October 2001 to improve its injection capacity. In addition, chemical stimulation to remove the precipitated minerals was carried out within the open-hole section (Barrios et al, 2002). A decrease in the pipe diameter due to mineral deposition was not found during the mechanical cleaning, from the top to the bottom of the well. This observation implies that mineral deposition was not happening along the casing but more likely within the reservoir (Castro et al, 2006). The chemical stimulation performed by injecting a pre-flush of hydrochloric acid (10%) followed by a main flush of a mixture of hydrochloric acid (10%) – hydrofluoric acid (5%) improved the capacity of the well to almost the original conditions (Barrios et al, 2002). After the chemical treatment, reinjection was initiated again. However, afterwards the well has shown a similar decreasing injection capacity as it can be observed in Figure 2.

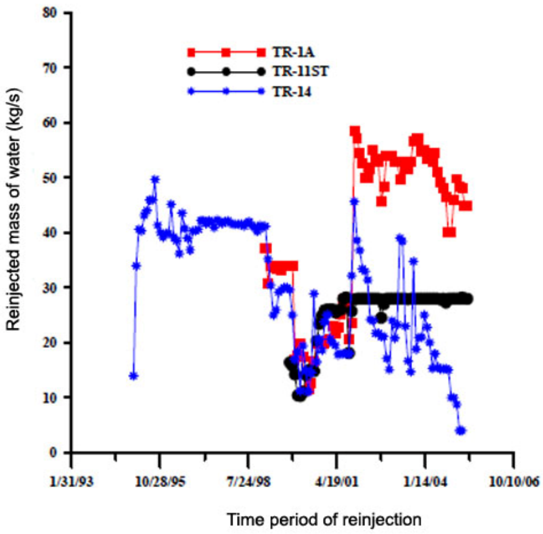

Figure 2: History of the injectivity capacity of some of the wells at Berlin geothermal field (after Castro et al, 2006).

In Figure 2, the injection capacity of well TR-11ST seems to have been stable during the whole period of operation. TR-11ST is located in the colder region of the geothermal field, away from the hot zone. This well presents the highest silica supersaturation of all the wells at the wellhead temperature of 60°C. The behaviour of this well suggests that silica precipitation is not happening at wellhead conditions and along the casing but in the internal deep zones of the reservoir. It also suggests that very likely silica precipitation is not the only cause of the decline in capacity of the other injection wells, but other hydraulic conditions are probably also affecting the capacity to absorb water in the reservoir (Castro et al., 2006).

For purpose of simulation we select the chemical composition and mineral assemblages for the wells TR-2, TR-9 and TR-1A. The injection well TR-1A, is operated at separation pressure of 9.9 barg, and starts with a stable injection capacity of around 30 kg/s with WHP = 26.3 barg (Montalvo et al., 2005). The well has a main permeable zone below 2,000 m depth and amorphous silica scales were collected at around 2,300 meters. After more than two years of injection, the well capacity declined drastically to around 20 kg/s after which the well improved after an acid stimulation job in October 2001 as shown in Fig.2 (Barrios et al., 2007).

3. MODEL SETUP

The thickness of the permeable zone for injection well TR-1A is around 200 meters. The geothermal reservoir itself is mainly composed of highly fractured andesite rocks (Monterrosa, 2002).

Simulation described below was performed with a simplified, horizontal, confined 2D model (Figure 3). If we consider that the andesitic reservoir can be represented by a series of alternating fractured and impermeable matrix zones, only one of these fractured zones needs to be modelled. Injection and production wells are linked by a 1,300 m long fractured zone in the andesitic rock mass with a mean porosity of 8.0%, a thickness of 10 cm and a horizontal width of 10 m. We consider that the fluid exchange between fractured zone and the surrounding low-permeability matrix is insignificant and thus can be neglected. Only heat transfer between the matrix and the fractured zone is allowed. Because of symmetry, only half (the upper part) of a fractured zone and of the adjacent porous matrix is modelled. The size of the elements ranges from a minimum of 0.5 m × 0.05 m near the injection well to a maximum of 50 m × 35 m (Figure 3).

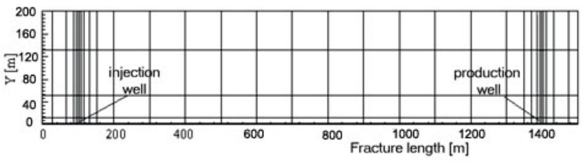

Figure 3: Spatial discretization of the model with a finer mesh discretization near the injection well. The black bar near the bottom corresponds to the fractured zone.

The initial temperature throughout the modelled area was set to 290°C, the average natural-state reservoir temperature. During the simulations, the fluid was injected into the modelled fractured zone at a constant temperature of 175°C. In FRACHEM, hydrostatic pressure distribution was assumed in the production well, while a constant overpressure of 1.5 MPa was set at the injection well. Mineral dissolution and precipitation bring about changes in the porosity and permeability of the modelled fractured zone affecting the flow rates through the mesh elements. Therefore the hydraulic rock properties were updated and recalculated after each time step. Dirichlet boundary conditions (i.e. constant temperature and pressure conditions) were applied to the upper, left and right boundaries of the modelled zone. The values of the thermo-hydraulic parameters considered in the simulations are listed in Table 1.

3.1 Initial Mineralogical Composition

The mineral assemblage found in Berlin geothermal field contains quartz, calcite, penninite and phrenite, wairakite, epidote, illite, albite and iron oxides (Renderos, 2002). The mineral percentage, used as an input of simulation, in terms of volume fraction (Table 2) are estimated from mineral composition for phyllitic-propyllitic facies to propyllitic at

1500-2000 meters depth in production wells TR-2 and TR-9 and injection well TR-1A (Montalvo et al., 2005).

Table 1: Values of the thermo-hydraulic parameters used in the simulations.

Reservoir properties			
Parameters	Fractured zone	Matrix	Fluid
Hydraulic conductivity (m^2/Pa.s)	$1.89.10^{-7}$	10^{-15}	-
Thermal conductivity (W/m.K)	2.9	3	0.6
Density (kg/m^3)	-	2600	1000
Heat capacity (J/kg.K)	-	1000	4200
Porosity (%)	8	0	-
Initial and boundary conditions			
Injection Overpressure (bar)	15		
Temperature (°C)	290		
Injection conditions			
Temperature (°C)	175		
Rate (L/s)	30		
Duration (years)	6		

Table 2: Mean values (in %) of the secondary minerals distribution.

Minerals (%)	Production zone	Injection zone
Quartz	16	40
Albite	-	4
Am.Silica	-	4
Illite	15	5
Prehnite	4	3
Epidote	10	20
Calcite	10	5
Pyrite	1	8
Wairakite	30	1
Penninite	10	10

3.2 Water Chemistry

LaGeo, which is the company operating the Berlin geothermal field, makes routine and systematic analysis of waters and gases of the production and injection fluids of this geothermal field (Magana, 1999; Montalvo and Axelsson, 2000; Renderos, 2002). The formation fluid circulating through the fracture is a sodium-chloride fluid. In the simulations, the fluid compositions of the production wells TR-9 and TR-2 were used as representative of the reservoir fluid composition, and the composition of the water injected at well TR-1A was used as representative of the injection fluids. Restoration of the reservoir water from the composition of separated waters and gases of wells TR-2 and TR-9 as well as cooling of the reservoir water along the well were modelled using WATCHWORKS code (Bjarnason, 1994). Examples of these chemical analyses are presented in Table 3.

Table 3: Representative chemical analysis of geothermal fluids from production and injection wells.

Characteristics		Formation fluid	Reinjected water
Temperature (°C)		290	175
pH		6.72	6.09
Concentration (mol/kg)	Na^+	0.149	0.160
	K^+	0.0157	0.0194
	Ca^{2+}	0.00467	0.00285
	Mg^{2+}	$4.09.10^{-7}$	$4.16.10^{-7}$
	SiO_2	0.0124	0.013
	Cl^-	0.188	0.185
	SO_4^{2-}	$1.96.10^{-4}$	$2.04.10^{-4}$
	HCO_3^-	$1.11.10^{-4}$	$3.71.10^{-5}$
	Fe^{2+}	$6.4.10^{-6}$	$5.5.10^{-6}$

3.3 Modelling Tool

The computer programme FRACHEM was used in our simulation work. FRACHEM is a THC simulator issued from the combination of two existing codes: FRACTure and CHEMTOUGH2. FRACTure is a 3D finite-element code for modelling hydrological, transport and elastic processes. It was developed originally for the study of flow-driven interactions in fractured rock (Kohl and Hopkirk, 1995). CHEMTOUGH2 (White, 1995) is a THC code based on the TOUGH2 simulator (Pruess, 1991), a 3D numerical model for simulating the coupled transport of water, vapour, non-condensable gas, and heat in porous and fractured media. CHEMTOUGH2 represents the possibility to transport chemical species and to model the chemical water-rock interactions, as well as chemical reactions driven by pressure and temperature changes. Transport and reactions are coupled in a one-step approach.

FRACHEM has been built by introducing geochemical subroutines from CHEMTOUGH2 into the framework of the code FRACTure (Bächler, 2003; Bächler and Kohl, 2005). After an initialization phase, FRACTure calculates, over each time step, the thermal and hydrological conditions within each element volume and determines the advective flow between each of them. Resulting thermal and hydrological variables are stored in arrays common to FRACTure and the geochemical modules. At this point, the programme calculates the chemical reactions using a mass balance/mass action approach, the advective transport of chemical species, and the variations of porosity and permeability. Once this calculation is performed, porosity and permeability are updated and fed into the FRACTure part of the code. The programme then returns to the start of the loop until the end of the simulation time (sequential non-iterative approach, SNIA).

FRACHEM has been adapted for the geothermal deep reservoir of Berlin and consequently, specific implementations have been added to the chemical part of this code. Considering the salinity of the fluid, the extended Debye-Hückel model, to determine the activity coefficients, has been used. Total concentrations obtained from chemical analyses are used to compute speciation and corresponding activity coefficients. Presently, a limited number of minerals are considered, which correspond to the main alteration minerals found at depth in the Berlin andesitic formation. The precipitation/dissolution reactions of calcite, dolomite, siderite, anhydrite, galena, quartz, amorphous silica, pyrite, wairakite, epidote, prehnite, K-feldspar, albite, illite and chlorite can be modelled under kinetic constraints. Rate laws follow the transition state theory (e.g., Lasaga et al., 1994). The implemented kinetic rate laws are specific to each mineral and are taken from published experiments conducted at high temperature. Thermodynamic data (equilibrium constants) are taken mostly from SUPCRT92 (Johnson et al., 1992) and Helgeson et al. (1978) and are functions of temperature and pressure.

Finally, a supplementary module allows the determination of porosity and permeability variations linked with chemical processes occurring in the reservoir. Considering the alteration of the Berlin formation, the flow is assumed to circulate in a medium composed of fractures and grains. Therefore, a combination of a fracture model (Norton and Knapp, 1977; Steefel and Lasaga, 1994) and a grain model (Bolton et al., 1996) is used to determine the permeability evolution.

4. SIMULATION RESULTS

The results obtained from the first coupled chemical model for well TR-1A are shown in the following graphics. The temperature simulation in the injection well TR-1A shows a decrease near the injection well in a short period of simulation time, reaching the water injection temperature.

The results of the simulations are presented in several graphs. In Figure 4 the evolution of the precipitation of quartz and amorphous silica in the fractured zone against the time of injection is shown. Amorphous silica is deposited near the well, but quartz also is present at some distance from the well. The most reactive of the silicates are amorphous silica. It precipitates near the injection well at a maximum amount of 140 kg/m^3 (Fig. 4). With increasing injection time, the zone of amorphous silica precipitation increases. Quartz precipitates in the injection zone at a maximum amount of 0.4 kg/m^3 (Fig. 4). Due to the relatively low reaction rates precipitation occurs on a wide portion of the fracture.

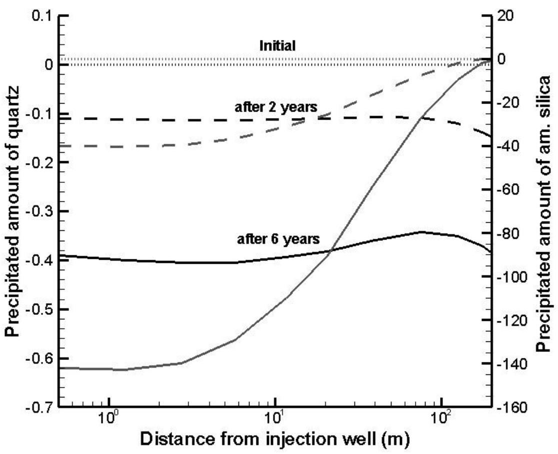

Figure 4: Quartz (grey curves) and amorphous silica (black curves) precipitated amounts (in kg.m^{-3}) in the fractured zone with time during injection. Negative amounts indicate mineral precipitation.

Figure 5 shows behaviour of other secondary minerals in the fractured zone with time during injection. Epidote, wairakite, prehnite, penninite and albite present a similar behaviour and are initially in equilibrium at a distance of 10 meters from the injection well. After 6 years of injection, results show that these minerals precipitate around the well. Illite precipitation tends to decrease with time during injection, but a slight dissolution of calcite appears close to the injection well with time during injection (Fig. 5). Pyrite does not present significant variations.

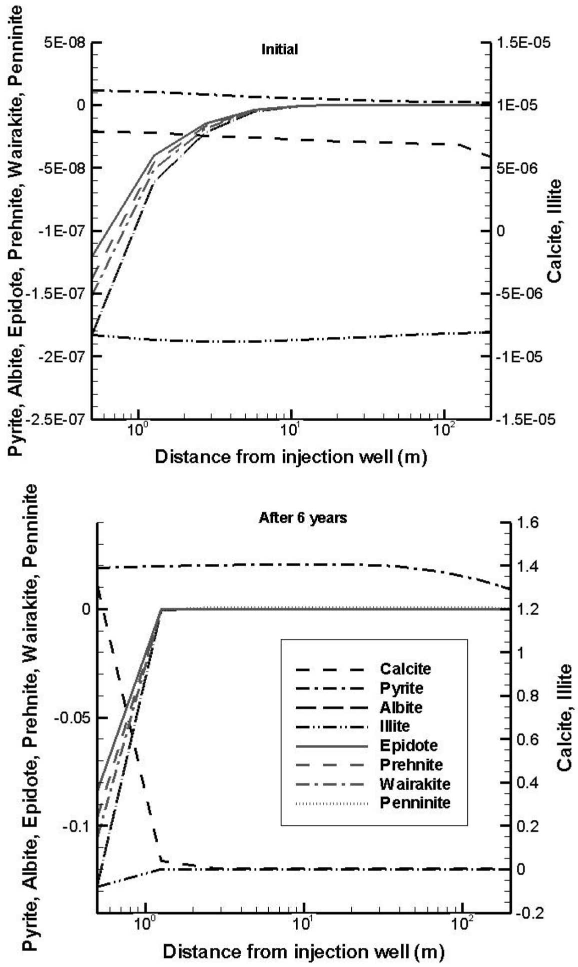

Figure 5: Dissolved or precipitated amounts of selected minerals (in kg.m^{-3}) in the fractured zone with time during reinjection. Negative amounts indicate mineral precipitation and positive dissolution.

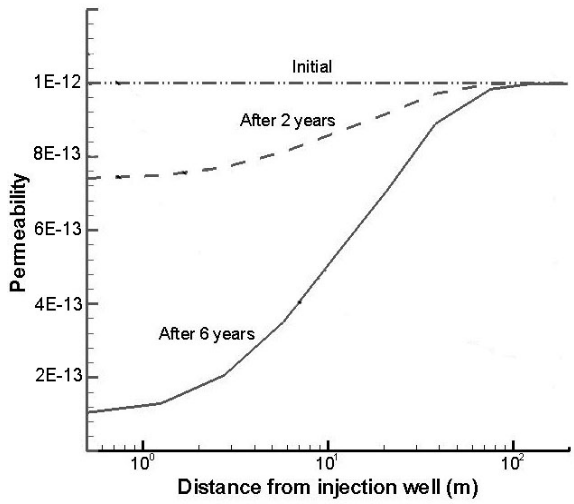

Figure 6: Permeability (in m^2) reduction against distance from injection well, with time during injection.

The injection of fluid creates a chemical non-equilibrium, which induces precipitation of quartz, amorphous silica and illite as well as slight dissolution of calcite in the fractured zone. Results show that the main chemical process are the fluid-silica reactions that lead to porosity and permeability decreases due to the silica scaling in the vicinity of the injection well and occurring at some distance in the reservoir (Figure 6).

Simulation reproduces in some way the decrease in injection capacity of well TR-1A due to the increase in quartz mass fraction and mostly for amorphous silica mass fraction.

5. CONCLUSION

The injection wells at Berlin geothermal field all encountered low permeability formations with small fractures that can be relatively easily plugged with scale or particles. The first preliminary simulation to study silica scaling problems at the Berlin geothermal field in El Salvador has been performed using the thermo-hydraulic and chemical (THC) coupled code FRACHEM. Injection well TR-1A at Berlin field was used for studying silica scaling. Amorphous silica and quartz precipitation was obtained in the simulation. Simulation results show the reduction in porosity and permeability close to the well TR-1A with time during injection.

However, to model silica transport and to understand the scaling process and loss of injectivity in hot water injection wells, several factors have been identified that cause the deposition of amorphous silica and quartz in the near-well formation and their effect will be simulated using FRACHEM. These factors include silica concentration in the hot water injected, temperature of the injected fluid, flowrate of the injected fluid, pH of the injected fluid, as well as temperature and pressure conditions of the reservoir in the vicinity of the injection well. Finally we will perform a large number of numerical simulations to reproduce the loss of injectivity and its recovery by acid or chelatant injection.

ACKNOWLEDGEMENTS

The authors would like to thank the Swiss Federal Office of Energy (Project N°102'888) for funding this project. The authors are also grateful to LAGEO SA of El Salvador.

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