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Modelling the impact of forced fluid-rock interactions on reservoir properties at Soultz-sous-Forêts EGS geothermal site.

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ABSTRACT

The development of Enhanced Geothermal Systems (EGS) depends on the creation of permeable fractures. Once the fractures network is created, the success of the long-term exploitation depends on maintaining and enhancing permeability. Sustaining fracture permeability will depend on many variables including rock mineralogy, fluid chemistry, temperature, local stress field, fracture strain rate, and the proximity of natural fractures to the wellbore. Operations exploiting little known, deep heat sources and low permeability reservoirs face new problems involving high temperature and pressure brine-rock interactions. In order to forecast the behaviour of an enhanced geothermal reservoir under exploitation, interaction between flow, heat transfer, transport and chemical reactions must be evaluated. For this purpose, coupled reactive transport modelling can provide useful information, by simulating chemical reactions likely to occur in the system coupled to reactive transport, at large time and space scales.

FRACHEM, a thermo-hydraulic-chemical coupled code, was developed especially to forecast the evolution of the EGS project at Soultz-sous-Forêts, Alsace (France). FRACHEM can simulate thermal, hydraulic and fluid-rock interactions within the fractures connecting the injection and the production wells, and determine the dissolution/precipitation reactions of nine minerals in the Soultz granite (carbonates, pyrite, silicated minerals). Reactive transport modelling with FRACHEM code has been used to simulate re-injection of the formation brine after cooling within the 5000-m deep Soultz reservoir. In the first application, the coupled processes of a single fractured zone between two wells were investigated. In the second application, a more complex geometry has been shaped to represent a realistic reservoir model. This model includes two fractured zones of different widths following two different paths with the dimension of the Soultz reservoir. Depending on their distance and the relative exposure, these fractured zones interact on each other. These interactions have been investigated to predict the geochemical evolution and to quantify the impact on the reservoir. Results of numerical simulations for a long-term circulation confirm the role played by carbonates on the evolution of reservoir porosity and permeability. Due to their fast reaction rates, carbonate minerals are responsible for most of the reservoir evolution. Indeed, occurrence of calcite precipitation near the production well tends to decrease the reservoir porosity and permeability, induced by the decrease of the fractures aperture. Silicates and pyrite behaviour is also simulated between two wells, but their influence on the fractures aperture is limited.

Economic exploitation of enhanced geothermal systems is dependent to mineral precipitation and associated decrease in permeability of the system. This inhibits fluid flow and associated heat extraction from the system. One solution to this problem consists in injecting a reacting fluid into the wells, in order to dissolve the secondary minerals sealing the fractures, to increase the permeability and hence to stimulate the reservoir. Our goal is to simulate the effect of reacting fluid injection, such as acidizing, on permeability evolution in fractures at pressure and temperature conditions of the Soultz geothermal site. Recent acid treatments were performed on the Soultz wells. It appeared that the hydraulic performance of the geothermal reservoir has been improved by acidification. FRACHEM simulations have been tested to forecast the impact of reacting fluids on carbonates and reservoir properties.

1. INTRODUCTION

Enhanced (or engineered) Geothermal Systems (EGS) are defined as engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources. EGS concepts would recover thermal energy contained in subsurface rocks by creating or accessing a system of open, connected fractures through which water can be circulated down injection wells, heated by contact with the rocks, and returned to the surface in production wells to form a closed loop. This large renewable energy resource can be exploited in a sustainable mode in the sense that different reservoir rock volumes can be developed successively from the same surface installation by extending or deviating existing boreholes, and they have practically zero CO_2 emissions.

Abundant geothermal resources sound like a great deal, but in addition to the extraction costs, there are numerous geological problems associated with its exploitation. The heat is extracted by conduction and convection. As a consequence, circulating hot water in the crust inevitably leads to dissolution, transport and re-deposition of minerals. In the case of heat extraction projects, the pores and the fractures in the water-bearing rocks may become clogged by mineral deposition, eventually stemming flow. This can limit the productive lifetime of an engineered geothermal system, even though heat may still be available at depth. Current research into water–rock interaction in geothermal reservoirs is directed at ways to enhance energy production and to avoid clogging of the rock openings.

The principle of an Enhanced Geothermal System (EGS) is to inject cold water into a hot fractured rock reservoir, to extract the heated water by one or several production wells, and to transfer its energy to a working fluid via a surface heat exchanger close to the wells. The feasibility and characteristics of this process rely ultimately on the fact that the natural fissures, opened and/or widened artificially by injection of water at high pressures through the borehole, remain open. However, during the stimulation phase, the injected water is composed of formation and surface fluids and will react with the rocks minerals. The composition of the resulting fluids will be controlled by temperature, time, and by the minerals composition and added natural fluids.

Later, during reservoir exploitation, the formation fluid will be most probably dominant in the water-rock reactions, but a heating-cooling cycle will trigger continuous reactions. Dissolution and precipitation will take place along the pathways of these resulting fluids, and open fissures can potentially close by mineral precipitation. Also, mineral precipitation can potentially create problems along the geothermal loop, from the production casing to the surface tubing, the heat exchanger and the reinjection casing, when the hot fluids are cooled down by approximately 100°C at the heat exchanger.

Evidently, at an EGS site, it is necessary to understand and quantify fluid circulation and composition with time and to predict the dissolution-precipitation behaviour of the fluids along their pathways. Our main goal is to comprehend and quantify fluid circulation and composition with time and to predict the dissolution-precipitation behaviour of the fluids along their pathways. This will be achieved by geochemical modelling.

The proposed study consists of modelling fluid–rock interaction and scale formation during geothermal heat extraction with application to Soultz project. FRACHEM code has been developed to realistically simulate the long-term (years to decades) evolution of permeability and heat-exchange efficiency in an EGS reservoir. The latter are dependent on the interaction of chemical processes (mineral dissolution and precipitation in rock fractures and technical installations) with the flow of the reactive fluids through a geometrically complex, and changing fracture network.

A great deal of specific and detailed information is required to assess the chemical impact of an injection operation. The present study is not intended to represent any specific site. However, well configuration and data for mineralogical composition were taken from the European Enhanced Geothermal System at Soultz-sous-Forêts (Soultz project; Jacquot, 2000; Durst, 2002; Bächler, 2003). The simulations will use data for the Soultz reservoir derived in petrological and geochemical studies, and supplied by the site developers.

2. SOULTZ-SOUS-FORETS EGS PROJECT

The Soultz-sous-Forêts EGS is located in Alsace, about 50 km north of Strasbourg (France). The Soultz area was selected as the European EGS pilot site because of its strong temperature gradient in the sedimentary cover (up to 100°C/km) and its high heat flow, locally reaching 0.15 W/m^2 (Kohl and Rybach, 2001). The geology of the Soultz region is characterized by a graben structure affected by several N-S striking faults. The crystalline basement, covered by 1’400 m of Triassic and Tertiary sediments, is composed of three facies in granitic rocks: (1) an unaltered granite in which fracture density is close to zero; (2) a hydrothermally altered granite facies and (3) altered veins within the hydrothermally altered granite (Jacquot, 2000). The hydrothermally altered granite is the most porous facies (Genter et al., 1997) and altered veins are highly fractured. Natural circulation of formation fluid and fluid-rock interaction processes take place mainly within the hydrothermally altered granite, and to a lesser extent within altered veins. Flow in the unaltered granite is essentially nil. To extract the heat from the Soultz reservoir, three deviated wells have been installed to a depth of 5’000 m, with lower ends separated by 600 m. The reservoir encountered at this depth presents an initial temperature of 200°C. One well (GPK3) will be dedicated to the injection of cold water in the granitic reservoir at a rate of about 50 $L.s^{-1}$, whereas the two other wells (GPK2 and GPK4), located on both sides of the injector, will be used to produce about 25 $L.s^{-1}$ each of the formation fluid. At Soultz, the injection–production system has been designed as a closed loop. The fluid used is a formation fluid existing in the altered granite, namely a brine with a total dissolved solids value of around 100’000 ppm. Injection of cooled brine disturbs the equilibrium between the formation fluid and reactive minerals. The resulting change in temperature and pressure in the reservoir, and the forced circulation in fractured granite, will drive geochemical reactions able to affect the physical properties of the reservoir through mineral precipitation and dissolution.

2.1 Fractured granitic reservoir

The geothermal reservoir at Soultz is made up of three types of granite (Jacquot, 2000; Hooijkaas et al., André et al., 2006) (Table 1). The first is non-altered (fresh) granite that is characterized by a predominance of feldspar, plagioclase and quartz, and by an extremely low fracture density. Consequently, its porosity is close to zero and does not contain significant amounts of water. The properties of this granite are that of the impermeable rock matrix. Fluid exchange, by advection or diffusion processes, will be disregarded for this granite; it will only act as a good heat convector.

Table 1: Mean composition (in %) of the different types of granite in the Soultz reservoir (Jacquot, 2000).

	Fresh granite	**Hydrothermally altered granite**	**Alteration veins**
Quartz	24.2	40.9	43.9
K-feldspar	23.6	13.9	
Plagioclase	42.5		
Illite		24.6	40.2
Smectite		9.7	9.6
Mica	9.4		
Calcite	0.3	3.3	4.3
Dolomite		0.8	0.7
Pyrite		0.7	1.0
Galena		1.3	0.3
Chlorite		4.8	

The second rock facies is a fractured, hydrothermally altered granite, with quartz as the major mineral component; because of alteration the amount of feldspar decreases and some secondary minerals such as galena, pyrite, smectite or illite are present. This facies is the most porous (porosity ranging from 5 to 10%) and contains most of the formation fluid. The third rock facies is the most altered; it corresponds to alteration veins that present minerals such as illite, smectite and quartz. Precipitated secondary minerals (clays, carbonates) fully cement the fractures, resulting in a decrease of porosity and permeability. As a consequence, fluid circulation within the rock mass takes place through the second facies only (Genter et al., 1998).

2.2 Geofluid chemistry

The formation fluid circulating through the fracture network is a sodium-chloride brine with a total mineralization close to 100 g L^{-1}. Its pH is approximately 4.9 and its temperature (200°C) is in equilibrium with that of the rock at 5’000-m depth. The composition of the formation brine extracted during a 1999 production test is given in Table 2. The chemistry of the deep fluid is not very different from that of the fluid produced from the shallower reservoir (Durst, 2002). Its silica and carbon concentrations are higher because of the elevated temperatures and CO_2 partial pressures.

Table 2: Representative chemical analysis of the fluid sampled at the wellhead of GPK2 after being deepened to 5000 m in 1999 (Durst, 2002)

Species	**Concentration (mmol/kg)**
Na^+	1148.00
K^+	73.40
Ca^{2+}	169.50
Mg^{2+}	3.21
Cl^-	1648.00
S	1.77
C	42.76
Fe^{2+}	2.61
SiO_2	6.06
Al^{3+}	$3.7.10^{-3}$

3. NUMERICAL MODEL

The main task of the research on THC coupled modeling for this site has been to forecast the evolution of reservoir porosity and permeability. Different researchers (Durst, 2002, Bächler, 2003, Rabemanana et al. 2003, André et al., 2005) have incrementally built a reactive transport simulator, FRACHEM, able to simulate the main characteristics of the Soultz reservoir.

FRACHEM is a THC simulator issued from the combination of two existing codes: FRACTure and CHEMTOUGH2. FRACTure is a 3-D 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 & Hopkirk, 1995). CHEMTOUGH2 (White, 1995) is a THC code developed after the TOUGH2 simulator (Pruess, 1991), a 3-D numerical model for simulating the coupled transport of water, vapor, noncondensable gas, and heat in porous and fractured media. CHEMTOUGH2 presents the possibility to transport chemical species and to model the chemical water-rock interactions as well as the chemical reactions driven by pressure and temperature changes. The transport and reaction are coupled using a one-step approach. FRACHEM has been built by introducing geochemical subroutines from CHEMTOUGH2 (White, 1995) 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 program 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, the porosity and permeability are updated and fed into the FRACTure part of the code. The program then returns to the start of the loop until the end of the simulation time (sequential noniterative approach, SNIA).

FRACHEM has been developed specially for the granitic reservoir of Soultz-sous-Forêts and consequently, specific implementations have been added to the chemical part of this code. Considering the high salinity of the geofluid, the Debye-Hückel model, initially implemented in the CHEMTOUGH2 routines to determine the activity coefficients, has been replaced by a Pitzer activity model. It should be mentioned here that the activity coefficients calculations are carried out in an indirect manner by means of another code, TEQUIL model of the Na-K-H-Ca-Cl-SO_4-HCO_3-CO_3-CO_2-H_2 system for 0 to 250°C (Moller et al., 1998). The TEQUIL application package includes chemical models based on the Pitzer formalism, and calculates liquid-solid-gas equilibria in complex brine systems by globally minimizing the free energy of a system at constant temperature and pressure. Using this model, total concentrations obtained from chemical analyses (Table 2) were input into TEQUIL, which then computed speciation and corresponding activity coefficients. Computations were done using a typical Soultz fluid at a temperature of 200°C. This fluid was initially equilibrated with calcite and anhydrite at 200°C, which resulted in a decrease of Ca^{2+} and SO_4^{2-} concentrations (compared to input concentrations) due to precipitation of calcite and anhydrite. The pH value of 4.9 at 200°C was calculated from the equilibration with calcite and input total aqueous carbonate concentration. Using the fluid composition at 200°C, TEQUIL was then used to numerically cool the solution, recompute pH, and determine activity coefficients at temperatures down to 20°C. It should be noted that the cooling simulation was performed without allowing reactions with gases or minerals. Mg, Fe, and Al are not included in the TEQUIL database. For this reason, the geochemical program EQ3nr (Wolery, 1992) was applied to determine the activity coefficients of Mg^{2+}, Fe^{2+} and Al^{3+} by using the Pitzer model and the EQ3nr thermodynamic database data0.hmw (Harvie et al. 1984). Activity coefficients determined in this way were then input into FRACHEM as polynomial functions of temperature, for the specific ionic strength of the fluid. This approach works well for the case of Soultz simulations because the ionic strength of the circulated fluid remains more or less constant.

Presently, a limited number of minerals are considered, which correspond to the minerals constituting the Soultz granite. The precipitation/dissolution reactions of carbonates (calcite, dolomite), quartz, amorphous silica, pyrite, and some aluminosilicates (K-feldspar, albite, illite) can be modeled under kinetic constraints. Rate laws follow more or less the transition state theory (TST)-derived equation (e.g., Lasaga et al., 1994). The implemented kinetic-rate laws are specific to each mineral and taken from published experiments conducted at high temperature in NaCl brines.

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. The effect of pressure on equilibrium constants is explicitly taken into account. The equilibrium constants input into FRACHEM were initially computed along the water-saturation pressure curve, however, these constants are recomputed with changes in pressure during run time.

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 Soultz granite, the flow is assumed to circulate in a medium composed of fractures and grains. Therefore, a combination of fracture model (Norton and Knapp, 1977; Steefel and Lasaga, 1994) and grain model (Bolton et al., 1996) is used to determine the permeability evolution. In this model, we assume that the fracture aperture and the thickness of the mineral layer follow Gaussian distributions (Durst, 2002).

4. SIMULATION RESULTS

This paper describes the application of the model to two simple cases: single 1-D fracture and two 1-D fractures models. First, mesh discretization, geometrical model, models parameters and initial- and boundary conditions are described. Then, results of simulations are described to test if the fracture geometry has an impact on the chemical model results. Thermal and chemical processes were coupled and the porosity and permeability changes affect the hydraulic field. The simulations time was 600 days.

The model consists of a 750*300 m granitic matrix zone (Fig. 1). An injection and a production well separated by 650 m have been set. Because of symmetry, only half (the upper part) of fractured zones and of the adjacent porous matrix is modelled, by subdividing them into 502 elements (Fig. 1). The size of the elements ranges from a minimum of 0.5 m × 0.05 m near the injection and the production wells to a maximum of 50 m × 35 m. The fractured zones are located between 50 and 700 m; injection is made at 50 m and production occurs at point 750m (Fig. 1).

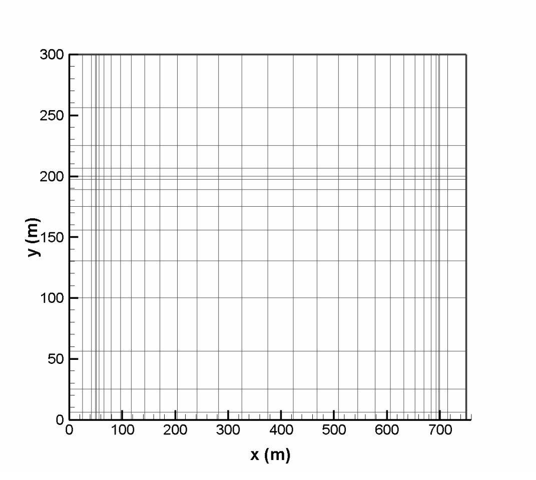

Figure 1. Whole model spatial discretization (distances are in m). The y-axis represents model width and the x-axis is along the fractured zone between injection and production wells, located at x=50m and x=700m, respectively.

The initial temperature in the model was set to 200°C, which corresponds to the temperature at 5000 m depth in the reservoir. The pressure at the production point was held constant at 50 MPa (bottom well pressure at GPK2). A constant over-pressure of 8 MPa was assumed at the injection well. In each of the fractured zones, fluid was injected at qinj= $4*10^{-2}$ $L.s^{-1}$ in the first volume element of the fractured zones. The injection rate for each fracture was based on the fluid production rate qtot= 50 $L.s^{-1}$ and assuming 1250 fractured zones (qtot/qinj= 1250 fractured zones) consisting of 200 fractures. The fluid flowing out of the last volume element is reinjected in the first one through a buffer of 2000 m^3 representing the fluid volume contained in wells and surface installation.

The fluid density is 1000 $kg.m^{-3}$, the rock density 2650 $kg.m^{-3}$, the heat capacity of the rock is 1000 $J.kg^{-1}.K^{-1}$ and the heat capacity of the fluid is 4200 $J.kg^{-1}.K^{-1}$. No radiogenic heat production was integrated in the model. Only heat transfer between the matrix and the fractured zones is allowed.

The fluid flow in the matrix is negligible due to low hydraulic conductivity and zero matrix porosity. Thus, all chemical reactions happen in the fractures, whereas in the matrix no reactions take place. Though, we assume that major circulation occurs in hydrothermally altered granite. Cooled brine interacts with quartz, carbonates, K-feldspars, sulfides and clays. Secondary precipitation of amorphous silica was considered.

Initial water chemistry was obtained by equilibrating the sample water of formation fluid (Table 2) with the corresponding mineral compositions (Table 3) at 200°C. The initial fluid pH computed with the code, assuming saturation with respect to calcite, was 4.95. In each of the fractured zones fluid was injected at a temperature of 65°C.

Finally, three types of injection waters were considered, and were held constant over time. The first is the produced reservoir water (base case). The second was obtained by mixing one unit of reservoir water with one unit of fresh water (mixing case). The third was obtained by the addition of concentrated HCl in formation brine (acidification case).

4.1 Fracture geometry effect

4.1.1 Models description

The first complete application of FRACHEM code was a single fracture model. The model consists of a single 650 m long, 0.1 m wide and 10 m deep fractured zone surrounded by rock matrix.

The second application consisted in a more complex model with two fractured zones of different widths. The two wells are linked by two types of fracture: a 0.1 m wide fracture going directly from injection to production and a set of 0.05 m wide fracture traversing 1050 m between the two wells. The model set up represents only the upper half of the overall model. The lower part of the model, not set up, is mirror-inverted along the x-axis. Therefore only half of the fracture (0.05 m) along the x-axis is taken into the model. The model is discretized finer along the fractures as shown in Figure 1 which illustrates the mesh discretization. The fluid is injected at the beginning of both fracture, and produced at the end of both fractures.

4.1.2 Reservoir temperature

Before fluid circulation in the fractured zone, all the system (rock and brine) is chemically and thermally at equilibrium. The brine is in chemical equilibrium with the granite and these two components are at a constant temperature of 200°C. But, during the injection of cold fluid at 65°C in the reservoir, the system is disturbed and the rock progressively cools down (Figs. 2 and 3).

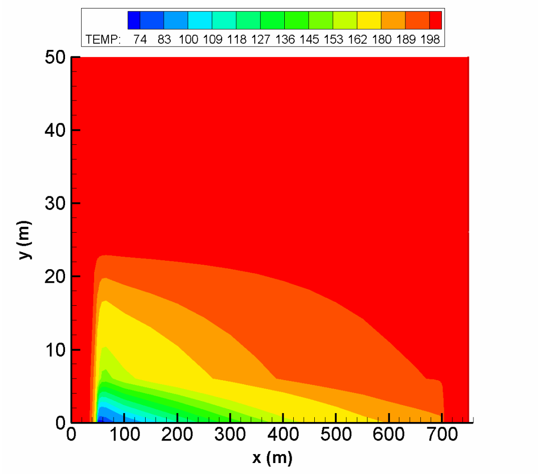

Figure 2: Temperature of rock around the single fractured zone after one year of forced fluid circulation.

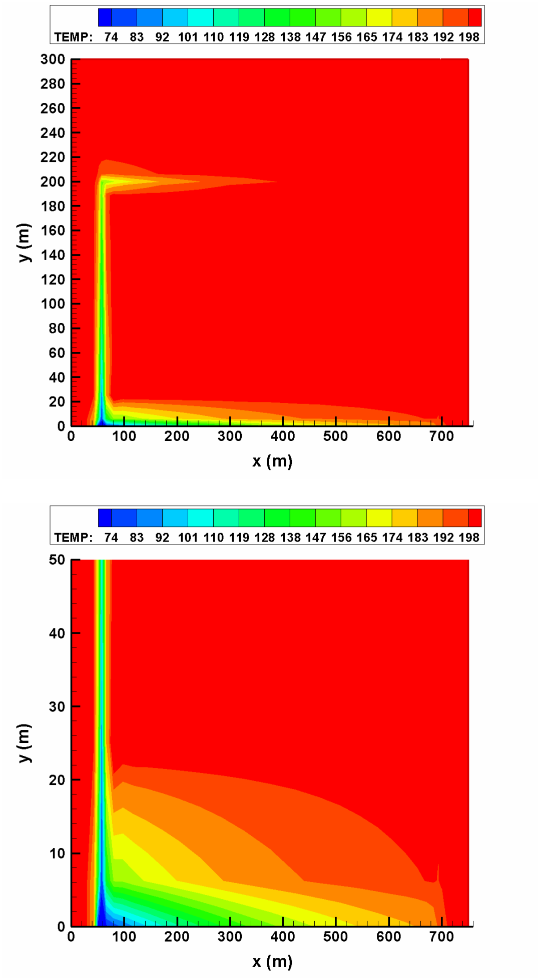

Figure 3: Temperature of rock around the two fractured zones after one year of fluid circulation. a) Whole model. b) 50*750 m zone around the injection point.

For the first application, all along the fractured zone, we observe a global decrease of temperature, especially near the injection well, due to the temperature of the re-injected fluid (Fig. 2). After one year of fluid circulation, the temperature in the vicinity of the production well is close to 180°C. The development of this thermal front due to the thermal diffusion from rock to fluid affects a zone of 10 to 20 meters around the fractured zone (Figure 2). This temperature decrease of the produced fluid is particularly important but it is strongly dependent of the geometric model.

In the second application, we consider two parallel pathways. The temperature distribution in the fracture and the matrix after one year is shown in Figure 3. The temperature was decreased from 200°C to 65°C near the injection well. Along the fractured zones it increases to 190°C towards the production point. Due to thermal diffusion, the temperature of the matrix is decreased around the fractured zones.

As a consequence, the cooling effect on the produced fluid modeled, when we consider a straight line flow between injection and production wells, without taking in consideration parallel pathways, is most probably overvalued compared to the real reservoir.

4.1.3 Mineral-brine interactions

The two-fracture simulation results are concordant to those of the single fracture simulation. Calcite dissolves at the vicinity of the injection zone and reprecipitates when the temperature rises. With time, the calcite dissolution rate in the injection elements decreases due to the diminution of available calcite that is almost totally dissolved after one year. Dolomite shows a similar dissolution trend but is removed faster at the injection point. The quartz precipitates in the low temperature zone and dissolves when the fluid warms up. Due to the relatively low reaction rates both precipitation and dissolution occur on a wide portion of the fracture. The pyrite does not present significant variations.

The injection of cold fluid creates a chemical non-equilibrium, which induces dissolution of calcite and dolomite as well as precipitation of quartz and pyrite. The results show that the main chemical process are the fluid-calcite reactions that lead to porosity and permeability increases near the injection point, due to calcite dissolution. Because of the progressive temperature increase along the fracture, precipitation of calcite occurs towards the production point.

Calcite dissolves near the injection point at a maximum rate of $2.7.10^{-4}$ $mol.m^{-3}.s^{-1}$ and precipitates at maximum $7.6.10^{-6}$ $mol.m^{-3}.s^{-1}$ at the production well (Fig. 4). With increasing simulation time, the dissolution zone moves towards the production point. Near the injection well all calcite has dissolved after one year with a reaction rate reducing correspondingly to zero. In contrast, dolomite never precipitates (Fig. 5). At the beginning of the simulation, dissolution only takes place near the injection point at a maximum rate of 6.10^{-6} $mol.m^{-3}.s^{-1}$. After one year, the dissolution zone moves slightly towards the production point and the reaction rate increases to $1.4.\ 10^{-5}$ $mol.m^{-3}.s^{-1}$.

These results show the interdependence of pH, temperature and carbonate behaviour: the cold fluid at low pH dissolves calcite and dolomite near the injection well at a high rate (Fig. 6). Reheating the fluid causes the calcite to precipitate and the pH to rise. Since the calcite precipitation rate is higher than that of dolomite, calcite precipitation prevents the precipitation of dolomite. According to the temperature evolution in the fracture, this process moves towards the production well and the reaction rates decrease. With increasing reaction time, the reaction rates reduce strongly due to the decrease of available carbonates. At the beginning, the dissolution of dolomite is controlled by temperature, whereas with time it depends more on calcite precipitation.

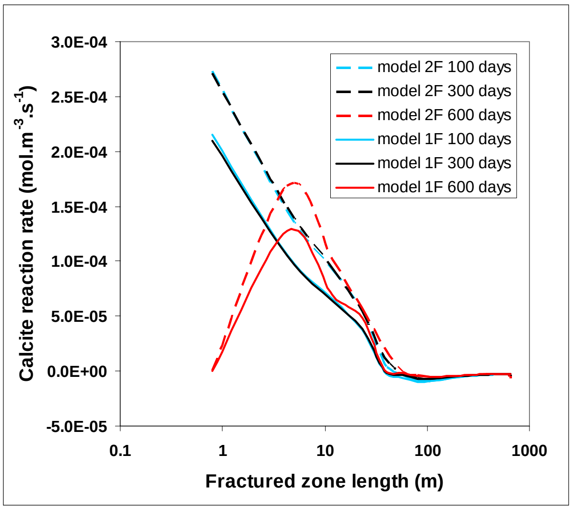

Figure 4: Calcite reaction rate along the fractured zone at different times (positive values indicate dissolution).

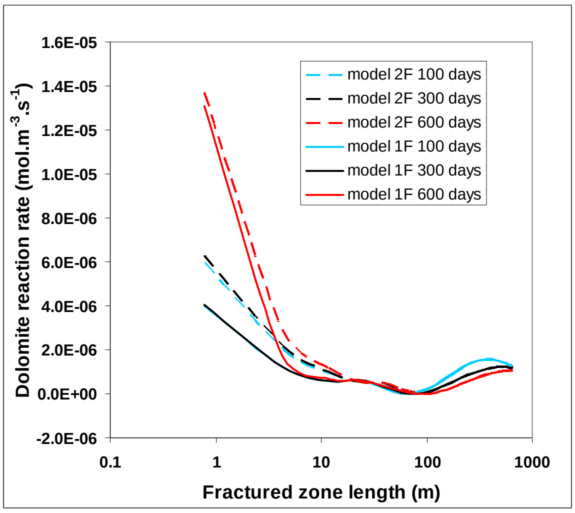

Figure 5: Dolomite reaction rate along the fractured zone at different times (positive values indicate dissolution).

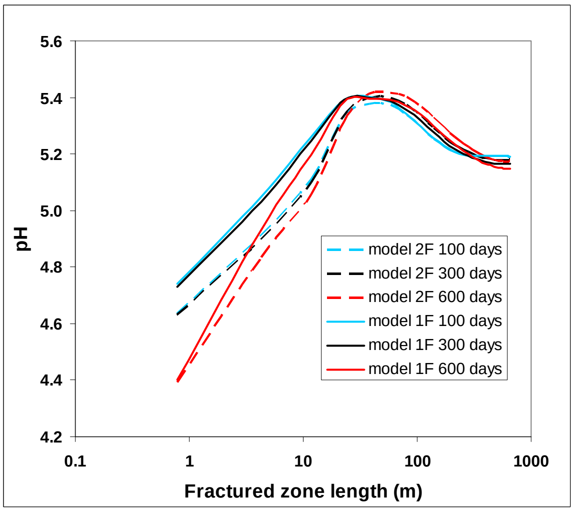

Figure 6: pH evolution along the fractured zone at different times.

The most reactive of the silicates are amorphous silica. It precipitates near the injection well at a maximum rate of $2.8.10^{-5}$ $mol.m^{-3}.s^{-1}$ (Fig. 7). With increasing circulation time, the zone of amorphous silica precipitation spreads towards the production well. Quartz precipitates all along the fracture at a maximum rate of $5.5.10^{-10}$ $mol.m^{-3}.s^{-1}$ (Fig. 8). Depending on the temperature evolution, with time the maximum reaction rate moves towards the production point and decreases. K-feldspar and pyrite present a similar behaviour. Precipitation of K-feldspar occurs close to the injection point. Unlike quartz, some punctual dissolution events of pyrite occur. These differences are due to the fact that even if the pyrite reaction depends on the temperature evolution, there is still an influence from the pH.

The differences in the reaction rates result in varying porosities. This difference is expected to increase further when calculating more than one year.

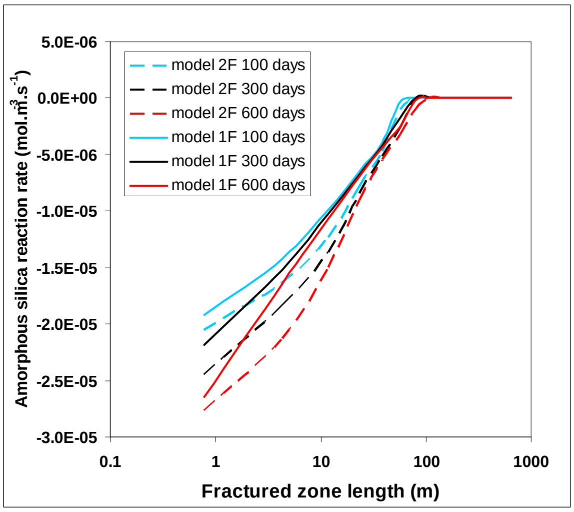

Figure 7: Amorphous silica reaction rate along the fractured zone at different times (negative values indicate precipitation).

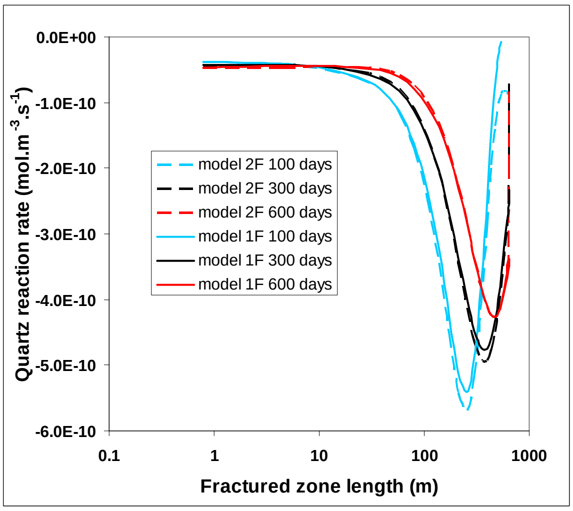

Figure 8: Quartz reaction rate along the fractured zone at different times (negative values indicate precipitation).

4.1.4 Evolution of reservoir properties

In both cases, porosity and permeability increase near the injection point due to dissolution of carbonates and decrease near the production point due to calcite precipitation (Fig. 9).

After one year the porosity at the injection point reaches 0.13 and goes down to 0.09 and 0.1 respectively in the large and thin fracture. The more porous zone extends up to 20 m in the large fracture and 10 m in the thin fracture. After 600 days, the area affected by the porosity reduction is wider.

The differences in the reaction rates result in varying porosities. This difference is expected to increase further when calculating more than one year.

Considering that there are only two fluid pathways and that the value of the permeability reduction in these two paths are small and close to each other, the geochemical reactions do not significantly modify the thermal-hydraulic parameter in the model.

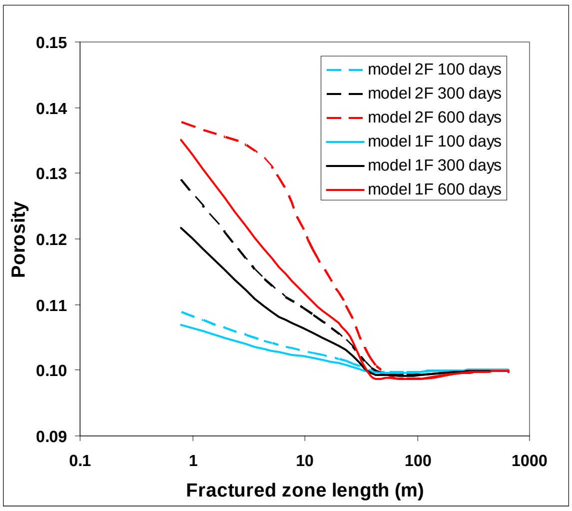

Figure 9: Porosity evolution along the fractured zone after five years of forced fluid circulation.
Initial porosity was 0.1.

4.2 Effect of fluid chemistry on fracture porosity

To explore chemically-induced effects of fluid circulation in the system, we examine ways in which the chemical composition of reinjected waters can be modified to improve reservoir performance.

Two types of injection waters were considered, and were held constant over time. The first was obtained by mixing one unit of reservoir water with one unit of fresh water (mixing case). The second was obtained by the addition of concentrated HCl in formation brine (acidification case). The pH of the acidified injected solution was close to 3.2. In each of the fractured zones fluid was injected at a temperature of 65°C.

4.2.1 Chemistry evolution of the produced fluid

Concerning the evolution of the fluid concentration in the whole model, one major evolution appears (Figures 10 and 11). In the mixing case, pH of the produced fluid increases and the total calcium concentration of the produced fluid decreases from its initial 0.12 mol.kg^{-1} and stabilizes at 0.09 mol.kg^{-1} after 20 days. In the acidification case, pH of the produced fluid decreases from 5 to 4.65 and consequently, the total calcium concentration of the produced fluid slightly increases. This illustrates the dissolution of calcite.

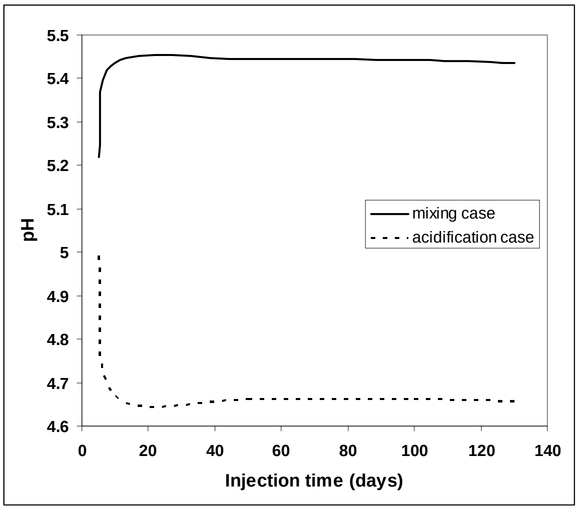

Figure 10: pH evolution in the produced fluid as a function of injection time.

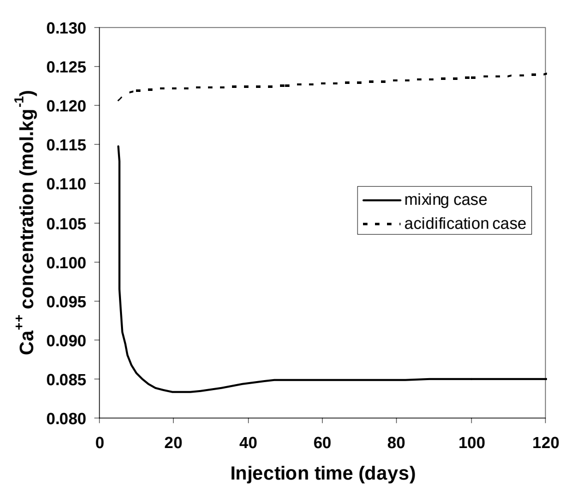

Figure 11: Calcium concentration evolution in the produced fluid as a function of injection time.

4.2.2 Evolution of fracture porosity

The mixing water is less prone to precipitating calcite (Fig. 12), and therefore is favorable for porosity development and maintaining injectivity. Though, alteration of injection water chemistry, for example by dilution with fresh water, can greatly alter precipitation and dissolution effects along the entire flow paths, and can offer a powerful tool for operating EGS reservoirs in a sustainable manner.

Another possible means to reduce the tendency towards calcite precipitation is to add HCl acid to injection water. Variations of the initial pH (3.2) have a significant effect on the reaction rates of carbonates (Fig. 12), but this effect should disappear during the first months of simulation, when the system will tend to recover equilibrium and will not have significant effects for long time simulations. The acidified brine injection water contributes to a porosity increase of about 0.035 in the vicinity of injection well (Fig. 13). Short injection of acidified water is favorable for porosity development and maintaining injectivity.

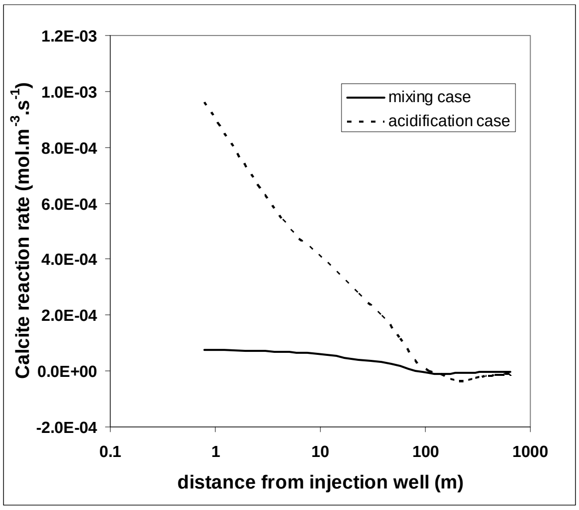

Figure 13: Calcite reaction rate along the fractured zone after 100 days of injection.

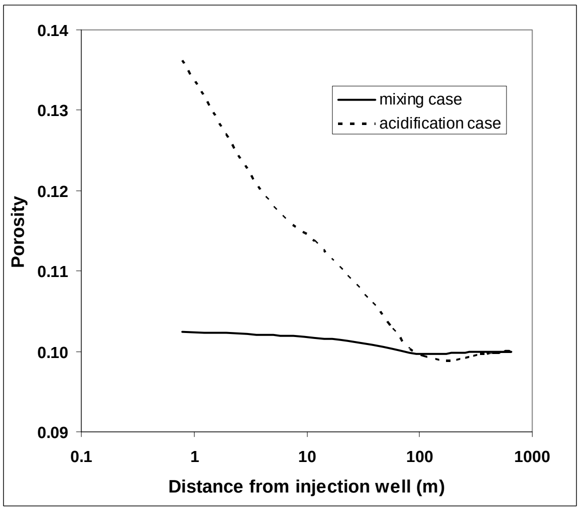

Figure 13: Porosity evolution along the fractured zone after 100 days of injection. Initial porosity was 0.1.

5. CONCLUSIONS

The first application of the new code FRACHEM consisted of the modelling of a simplified system, including a cooled fluid reinjected in a hot reservoir composed of a 650-m long by 0.1-m wide fracture surrounded by an impermeable matrix. The results show that at the beginning of the simulation, calcite and dolomite are rapidly dissolved near the injection point. Then, warming up induces carbonates precipitation on a wider zone. Later, the carbonates being less available in the injection area, reactions rates decrease significantly. Amorphous silica, K-feldspar, quartz and pyrite precipitate in the fracture. Moreover, some exceptional events of pyrite dissolution are also observed. Porosity evolution mainly shows a high increase near the injection point, due to carbonates dissolution. On the other hand, a small decrease of porosity is observed later, due to calcite re-precipitation. The second application was a 2-D model with the dimension of the upper Soultz reservoir. This model includes two fractures of different widths following two different paths. The geochemical evolution is similar to the previous simulation with carbonates dissolving near the injection point and re-precipitating further in the fracture. During the first 600 days this lead to a porosity increase of 0.04 followed by a decrease of 0.005. The variations are similar in both fractures and affected the first 10 m of the thin fracture and the first 20 m of the large one.

Both models are still simple and clearly do not represent the complex and heterogeneous situation at Soultz. However, fully coupled models of the Soultz EGS reservoir were developed and the model sensitivity can be tested. No true sensitivity analysis has been made concerning the spatial discretization and fracture network density, but the comparison between the results of the two simulations indicates that the permeability variation depends principally on the evolution of the temperature field calculated by FRACTure and not much on the spatial discretization or the fluid flow rate. But changes in the porosity/permeability, and thus in the hydraulic conductivity, impact the fluid velocity and the pressure distribution in the fracture: mineral precipitation causes the porosity and therefore also the permeability and the hydraulic conductivity to decrease. Lower hydraulic conductivity results in lower fluid velocities. Since the fluid velocities are smaller, the rate of temperature decrease in the fractured zone is lower

In the mixing and acidification cases presented, the results differ much from the basic model: the largest porosity difference in the fractured zone is 0.015. This is more than 15% of the initial porosity. Various reacting fluids can be injected to enhance fracture permeability in the vicinity of the wells. the FRACHEM code could be used to identify the most efficient chemical stimulation for EGS projects.

Finally, fluid-rock interactions may have a long-term effect on reservoir operation. While more or less detailed studies of the interaction of the reservoir rock with the injected fluid have been made at most of the EGS sites, there is still a good deal to learn about how the injected fluid will interact with the rock over the long term. The most conductive fractures often show evidence of fluid flow in earlier geologic time such as hydrothermal alteration and secondary mineral deposition. This is encouraging in that it suggests that the most connected pathways will already have experienced some reaction between water and the rock fracture surface. Fresh rock surfaces will not have the protection of a layer of deposited minerals or alteration products. The amount of surface or shallow water, which cannot be in equilibrium with the reservoir rock, required to add to the system over the long term is although unknown. The longest field tests have seen some evidence for dissolution of rock leading to development of preferred pathways and short-circuits. Moreover, the produced fluid will be cooled through a heat exchanger, in the surface equipment, possibly resulting in precipitation of scale or corrosion. To conclude, despite efforts to model fluid-rock interactions, there are still major questions to be answered.

6. ACKNOWLEDGEMENTS

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