

Chemical Stimulation for EGS: the Use of Chelating Agents at High pH for the Simultaneous Dissolution of Calcium Carbonate, Silicas, and Silicates

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ABSTRACT

Dissolution of silica, silicate and calcite minerals in the presence of a chelating agent (NTA) at a high pH has been successfully demonstrated in laboratory experiments using a high-temperature flow reactor. The mineral dissolution and associated porosity enhancement in the experiments has been reproduced by reactive transport simulation using TOUGHREACT. The chemical stimulation method has been applied by numerical modeling to a field geothermal injection well system, to investigate its effectiveness. Parameters applicable to the quartz monzodiorite unit at the Enhanced Geothermal Systems (EGS) site at Desert Peak (Nevada) were used. Results indicate that the injection of a high pH chelating solution results in dissolution of both calcite and plagioclase minerals, while avoids precipitation of calcite at high temperature conditions. Consequently reservoir porosity and permeability can be enhanced especially near the injection well. Injection at lower temperature results in a porosity increase that is smaller close to the injection point, but extends to larger radial distance. Slower kinetic rate results in less aggressive mineral dissolution close to injection point and larger extent along the flow path, which is favorable for chemical stimulation.

1. INTRODUCTION

The U.S. Department of Energy (DOE) has broadly defined enhanced (or engineered) geothermal systems (EGS) as engineered reservoirs that have been created to extract economical amounts of heat from geothermal resources of low permeability and/or porosity (MIT, 2006). The MIT report indicated that EGS could become a major supplier of primary energy for U.S. base-load generation, with capacity as high as 100,000 MW (electric) by 2050.

The most crucial step in developing EGS for commercial production is "reservoir stimulation," a process that involves injecting fluids under high pressure through boreholes deep underground, with the objective to increase in situ fluid pressures to the point where effective normal stress on pre-existing rock fractures becomes small or negative. This will create favorable conditions for fractures to "fail in shear," meaning that one or both fracture surfaces will experience translational motion, creating a mismatch between rough surfaces that will enhance reservoir porosity and permeability.

In the early days of EGS research (1980-90s), the focus in reservoir stimulation had been almost exclusively on the geomechanical aspects of manipulating effective stress to enhance fracture permeability. Research into EGS field systems in different countries has gradually led to the

recognition that chemical interactions between injected fluids and rocks can be as important as mechanical ones. Stimulation fluids used in EGS development typically are aqueous-based, and water is a powerful ionic solvent, especially so at higher temperatures. Accordingly, aqueous-based reservoir stimulation is likely to promote dissolution of some rock minerals, while precipitating others, with large impacts on the permeability of the fracture network, and the rate at which fluids can be circulated to bring usable heat to the land surface. The chemical interactions between rocks and fluids must be understood and reliably predicted, in order that stimulation treatments can be properly planned and executed.

The conventional method for chemically removing silica minerals is through mineral acid (such as HCl) treatments, which are expensive and hazardous. Laboratory experiments indicated, however, that aqueous solutions at high pH can dissolve wellbore silica and near-wellbore formation silica and quartz reasonably well and at much lower cost than HCl treatments (Rose et al., 2007). What has prevented geothermal operators from using caustic solutions in the past is the fear of calcite deposition, which is strongly favored at high pH. The laboratory studies (Mella et al., 2006) have indicated that calcite is dissolved rather than precipitated at high pH in the presence of a chelating agent. This suggests that thermally stable chelating agent at high pH can provide the basis for an economical and effective mineral dissolution approach.

In this paper, we first discuss the principle of calcite dissolution using chelating agents. Then, we present results of calcite and silica dissolution and porosity enhancement in laboratory experiments, and the calibration of a dissolution model by reactive transport simulation using the TOUGHREACT code. Finally, we present applications of this chemical stimulation method to a geothermal injection well system using mineralogical composition from the Desert Peak (Nevada) geothermal field, to investigate the effectiveness of injecting a high pH solution with chelating agent. An industry-government cost-shared project at Desert Peak is underway to evaluate the technical feasibility of developing an Enhanced Geothermal System. The project is supported by US DOE, co-sponsored by Ormat Nevada, Inc., and is technically coordinated by GeothermEx, Inc.

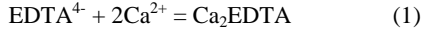
2. CALCITE DISSOLUTION USING CHELATING AGENTS

Removal of calcite scaling from wellbores is commonly accomplished by injecting strong mineral acids, such as HCl. Injected strong acid tends to enter the formation via the first fluid entry zone, dissolving first-contacted minerals aggressively while leaving much of the rest of the wellbore untreated.

An alternative to mineral acid treatments is the use of chelating agents such as ethylenediaminetetraacetic acid (EDTA) or nitrilotriacetic acid (NTA). Mella et al. (2006) performed laboratory experiments using EDTA and NTA to investigate the effectiveness of chelating agents for calcite dissolution in the formation. A laboratory reactor was designed and fabricated for investigating calcite dissolution using these agents under controlled conditions that simulate a geothermal reservoir. The setup and results will be discussed in the next section. Preliminary experimental data indicated that both EDTA and NTA are effective dissolution agents, and that dissolution capacity increases with temperature.

Such agents have the ability to chelate (or bind) metals such as calcium. Through the process of chelation, calcium ions would be solvated by the chelating agent, driving calcite dissolution. The kinetics of calcite dissolution using chelating agents is not as fast as that using strong mineral acids. The lower dissolution rate allows the chelating agent to take a more balanced path through the formation and more evenly dissolve calcite in all available fractures, rather than following the first fluid entry zone and leaving the rest relatively untouched.

The structures of the two chelating agents in anionic form are shown in Figure 1. In the calcite chelating process, one EDTA molecule will associate with two Ca^{2+} ions,



allowing theoretically for the dissolution of two moles of calcite per each mole of EDTA. In contrast, two NTA molecules are required to dissolve three calcite molecules:

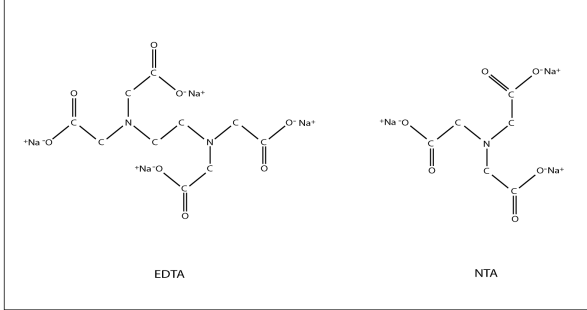
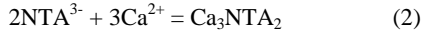


Figure 1: Chemical structures of the sodium salts of EDTA and NTA.

3. NUMERICAL MODELING METHOD

3.1 General Features

The modeling of the laboratory experiment and field example was done with the non-isothermal reactive geochemical transport program TOUGHREACT, whose physical and chemical process capabilities and solution techniques have been discussed by Xu and Pruess (2001) and Xu et al. (2006). The program uses integral finite differences for space discretization (IFD; Narasimhan and Witherspoon, 1976). The IFD method provides for flexible discretization using irregular grids, which is well suited for simulation of flow, transport, and fluid-rock interaction in heterogeneous and fractured rock systems with varying petrology and complex model boundaries due to the presence of engineered structures. For regular grids, the IFD method is equivalent to the conventional finite difference method. An implicit time-weighting scheme is

used for modeling flow, transport, and kinetic geochemical reactions.

The program can be applied to one-, two-, or three-dimensional porous and fractured media with physical and chemical heterogeneity, and can accommodate any number of chemical species present in liquid, gas and solid phases. A broad range of subsurface thermal-physical-chemical processes are considered under various thermohydrological and geochemical conditions of pressure, temperature, water saturation, ionic strength, and pH and Eh. Temporal changes in porosity and permeability due to mineral dissolution and precipitation are considered in the model. Mineral dissolution and precipitation are considered under kinetic conditions. Changes in porosity are calculated from changes in mineral volume fractions. Several porosity-permeability relationships are considered in the simulator as discussed in Xu et al. (2004), including the cubic Kozeny-Carman grain model and the Verma-Pruess model (1988).

3.2 Reaction Kinetics

Kinetics of mineral dissolution is very important for chemical stimulation of an EGS reservoir. A general kinetic rate law for mineral dissolution and precipitation is used in TOUGHREACT (Lasaga et al., 1994),

$$r_n = \pm k_n A_n \left| 1 - \left(\frac{Q_n}{K_n} \right)^{\theta} \right|^{\eta} \quad (3)$$

where n denotes kinetic mineral index, positive values of r_n indicate dissolution, and negative values precipitation, k_n is the rate constant (moles per unit mineral surface area and unit time) which is temperature-dependent, A_n is the specific reactive surface area of the mineral, K_n is the equilibrium constant for the mineral-water reaction written for the destruction of one mole of mineral n , and Q_n is the reaction quotient. The parameters θ and η must be determined from experiments; usually, but not always, they are taken equal to one (like in the present work).

For many minerals, the kinetic rate constant k can be summed from three mechanisms (Lasaga et al., 1994; Palandri and Kharaka, 2004),

$$k = k_{25}^{\text{nu}} \exp \left[\frac{-E_a^{\text{nu}}}{R} \left(\frac{1}{T} - \frac{1}{29815} \right) \right] + k_{25}^{\text{H}} \exp \left[\frac{-E_a^{\text{H}}}{R} \left(\frac{1}{T} - \frac{1}{29815} \right) \right] a_{\text{H}}^{\eta_{\text{H}}} \quad (4)$$

$$+ k_{25}^{\text{OH}} \exp \left[\frac{-E_a^{\text{OH}}}{R} \left(\frac{1}{T} - \frac{1}{29815} \right) \right] a_{\text{OH}}^{\eta_{\text{OH}}}$$

where superscripts or subscripts nu, H, and OH indicate neutral, acid and base mechanisms, respectively, E_a is the activation energy, k_{25} is the rate constant at 25°C, R is the gas constant, T is absolute temperature, a is the activity of the species; and n is an exponent (constant).

4. MODEL CALIBRATION FROM EXPERIMENTAL DATA

4.1. Experiment Setup

Laboratory experiments of calcite and silica dissolution using a high pH solution with NTA were performed using the flow reactor shown in Figure 1. The reactor flow cell was 6 inches long with a 1-inch internal diameter. The top 3 inches (7.62 cm) were filled with calcite chunks (30 g limestone) and the bottom 3 inches with silicate glass beads (or silica or quartz for different experiments). Water was injected from the top of the reactor with a flow rate of

3.333×10^{-5} kg/s (2 ml/min). Experiments were conducted for a range of temperatures from 150 to 300°C. The injection water was prepared by adding Na-NTA reagent and NaOH to distilled water (representing steam condensate), the resulting injection water had a NTA^{3-} concentration of 0.1 mol/kgw (w denotes H_2O), and a high value of pH. In the modeling a pH of 11.5 was used because the maximum value of pH decreases with temperature, the highest pH possible at 150°C being 11.63, while at 300°C it is 11.3. Measured total amounts of silica and calcite dissolved (in percent) after each experiment are presented in Figures 3 and 4. Each data point represents one experiment at a constant temperature. Most experiments were performed for a time period of 6 hours. For experiments with less duration time, the amount of dissolution was multiplied by a factor. For example, for a 3-hour experiment, the dissolution amount was multiplied by a factor of 2.

A 1-D model using TOUGHREACT was developed in order to simulate the dissolution experiments described above. Experimental data are then compared to model outputs and model parameters were adjusted as necessary to match the data.

4.2 Silica Dissolution

For silica, the following expression was used in the calibration of the kinetic model for its dissolution,

$$r = Ak_{25} \exp \left[\frac{-E_a}{R} \left(\frac{1}{T} - \frac{1}{298.15} \right) \right] \left(1 - \frac{c}{K} \right) \quad (5)$$

where r is silica dissolution rate (moles per unit mineral surface area and per unit time, $\text{mol/m}^2/\text{s}$), and c is the dissolved silica (SiO_2) concentration (mol/kgw). Other parameters are the same as defined in Eqs. (3) and (4). Eq. (5) has only one mechanism, which is a special case of the general multi-mechanism rate law defined in Eqs. (3) and (4).

The rate expression Eq. (5) has three parameters, A , k_{25} , and E_a , which are obtained by calibrating measured data of

silica dissolution. In fact, only the product of A and k_{25} appears in Eq. (5), we used a reactive surface area of $A = 98 \text{ cm}^2/\text{g}$, which is calculated by assuming a cubic array of truncated spheres (Sonnenenthal, 2005). Therefore, only k_{25} and E_a need to be calibrated for the silica dissolution rate model. A large number of simulations corresponding to temperatures of 120, 140, 160, 200, 230, and 250°C were performed. The simulated total amounts of silica dissolved were matched to measurements by adjusting values of k_{25} and E_a (trial and error method).

Three curves for different parameter values are presented together with measured data in Figure 3. Curve 1 has $k_{25} = 1.05 \times 10^{-8} \text{ mol/m}^2/\text{s}$ and $E_a = 39 \text{ kJ/mol}$, and fits well with measured silica dissolution data for temperature range from 160 to 250°C. Curve 2 has $k_{25} = 1.85 \times 10^{-8} \text{ mol/m}^2/\text{s}$ and $E_a = 33.8 \text{ kJ/mol}$, and agrees with measured glass bead data for 160 to 220°C temperatures. Curve 3 has $k_{25} = 1.14 \times 10^{-8} \text{ mol/m}^2/\text{s}$ and $E_a = 32.8 \text{ kJ/mol}$, and matches well with quartz dissolution data for 160-230°C temperatures. Variations with temperature of the amount of silica dissolved are reflected by the activation energy term E_a .

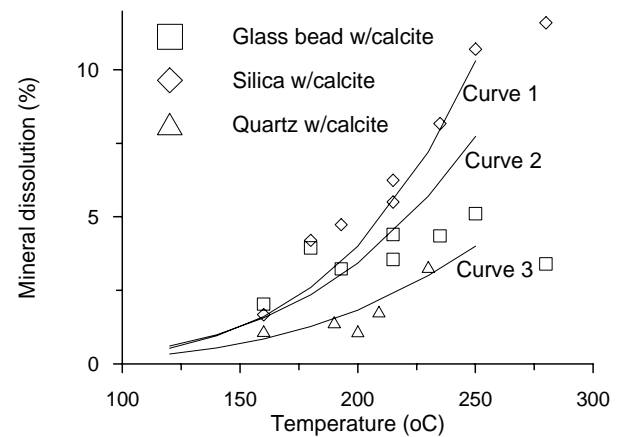


Figure 3: Measured total silica dissolution together with model results.

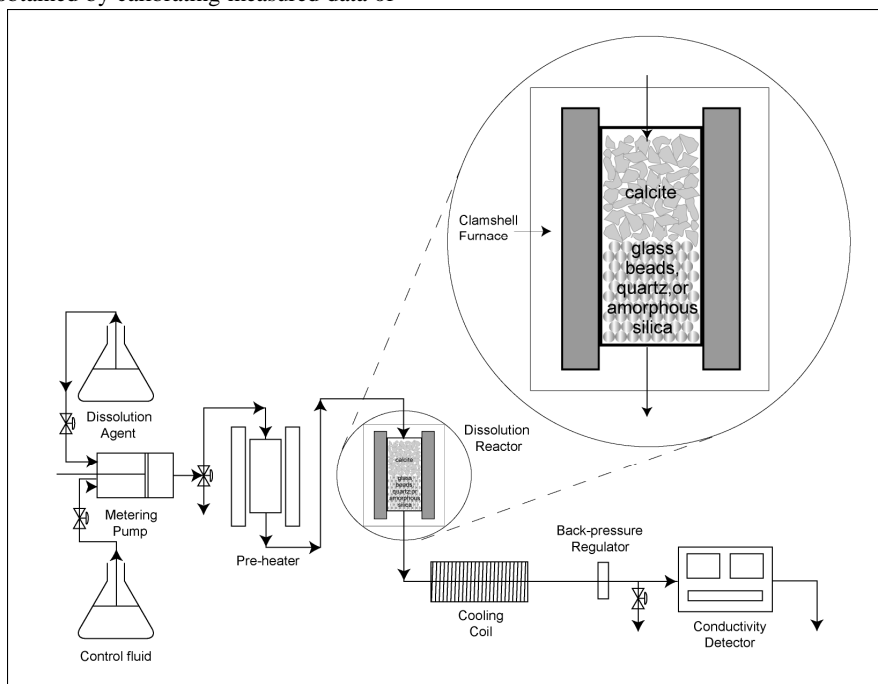


Figure 2: Schematic drawing of the high-temperature flow reactor.

4.3. Calcite dissolution

Calcite is assumed to react with aqueous species at local equilibrium. Calcite dissolution is driven by the chelating processes as described above. For the example of an injection solution with NTA, the chelating reaction is given by Eq. (2) and is assumed to proceed according to a kinetic rate. A simple linear kinetic rate expression for formation of Ca_3NTA_2 was used,

$$r_{\text{Ca}} = k_{\text{Ca}} C_{\text{NTA}} \quad (6)$$

where r_{Ca} is the rate (mol/kgw/s), k_{Ca} is the rate constant (1/s), C_{NTA} is NTA concentration (mol/kgw). As for the silica dissolution kinetic rates, we used an activation energy term k_{Ca} to describe the temperature-dependence,

$$k_{\text{Ca}} = k_{25}^{\text{Ca}} \exp \left[\frac{-E_a^{\text{Ca}}}{R} \left(\frac{1}{T} - \frac{1}{298.15} \right) \right] \quad (7)$$

Two parameters, k_{25}^{Ca} and E_a^{Ca} , are needed to calibrate the chelating process model (or calcite dissolution model). The simulated total amounts of calcite dissolved were matched to measurements by adjusting values of the two parameters. The fitted curve in Figure 4 has $k_{25}^{\text{Ca}} = 1.78 \times 10^{-4}$ 1/s and $E_a^{\text{Ca}} = 10$ kJ/mol.

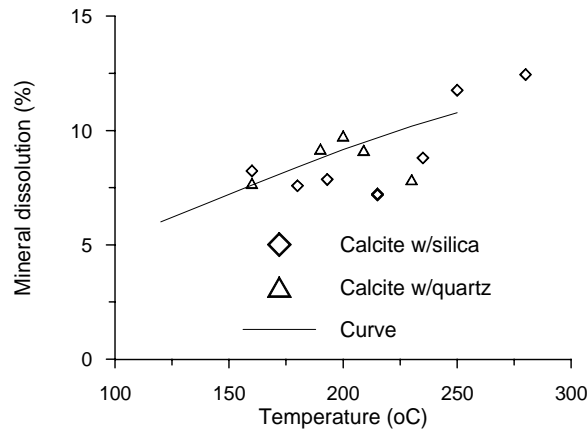


Figure 4: Measured total calcite dissolution together with model results.

Simulated aqueous concentrations along the column for the calibrated calcite dissolution model are presented in Figure 5. NTA^{3-} complexing with Ca^{2+} results in a decrease in its concentration and an increase in Ca_3NTA_2 concentration along the column. Ca^{2+} concentration remains low, maintaining calcite dissolution. Consequently dissolved carbon concentration increases continuously.

5. A FIELD APPLICATION

To investigate the effectiveness of injecting a high pH solution with chelating agent for the dissolution of calcite and silica minerals, we applied the model of chemical stimulation together with the calibrated parameters to a geothermal injection well system using a mineralogical composition from the Desert Peak (Nevada) geothermal field.

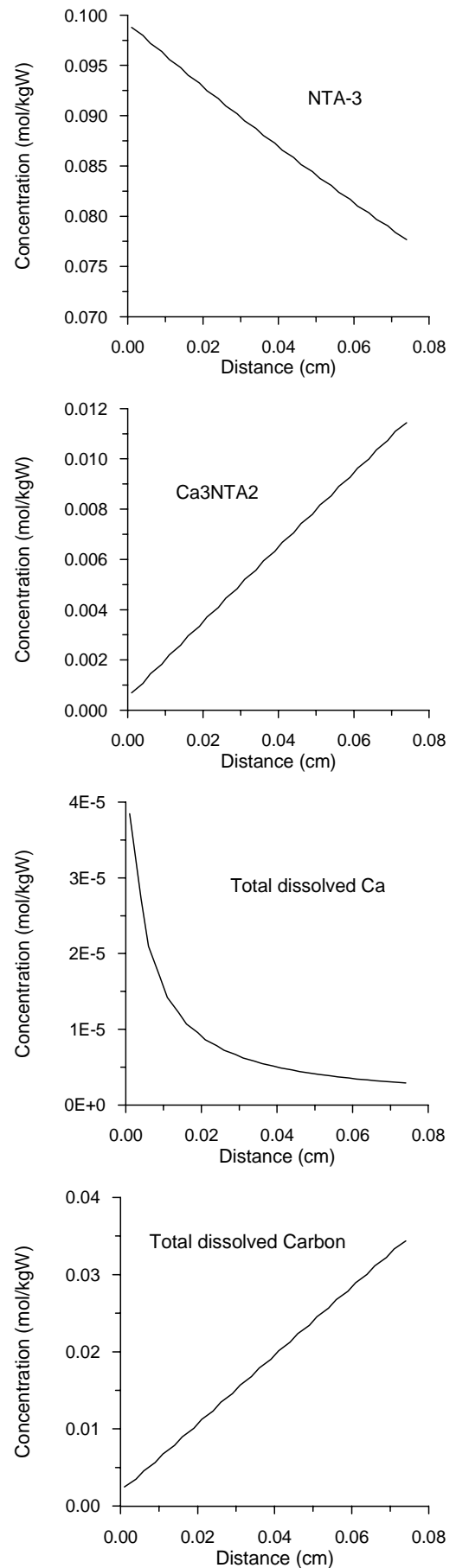


Figure 5: Simulated aqueous concentrations along the column for the calibrated calcite dissolution model.

5.1. Geologic Setting and Mineralogy

In our model, the mineralogical composition was defined based on a pre-tertiary unit 2 (pT2) from well DP 23-1, which is a quartz monzodiorite with 7-10 wt % quartz, 40-45 wt% plagioclase, 10-15 wt % potassium feldspar and 1-4 wt % sphene. A clinopyroxene and hornblende-bearing diorite directly overlies the main granodiorite intrusive body. The diorite is medium crystalline and contains primary hornblende phenocrysts with cores of clinopyroxene. The diorite is strongly propylitically altered to epidote, chlorite, pyrite and calcite, is moderately sericitized, and has also been thermally metamorphosed by the underlying granodiorite intrusive.

Initial mineralogical composition used in the modeling is summarized in Table 1. The compositions specified were based on the original crystalline rock mineralogy considering altered fracture vein mineralogy (Figure 6). Plagioclase was modeled using 50% low-albite and 50% anorthite. Other minerals including epidote, pyrite, and biotite were not considered in the model, because their reactions with injection solution are slow and not important for the chemical stimulation purpose.

5.2 Reaction Kinetics

Table 2 lists parameters for the kinetics of mineral reactions used in the model. For quartz, specific reactive surface area and kinetic parameters k_{25} and E_a were taken from the calibration of the laboratory experiment (Curve 3 of Figure 3). Specific reactive surface areas for low-albite, anorthite, and K-feldspar are set the same as for quartz. Surface area for chlorite and illite was from Sonnenthal et al. (2005), calculated assuming a cubic array of truncated spheres constituting the rock framework. The larger surface areas for these clay minerals are due to smaller grain sizes. Kinetic parameters k_{25} and E_a for low-albite, anorthite, K-feldspar kaolinite, chlorite, and illite were taken from Palandri and Kharaka (2004), who compiled and fitted experimental data reported by many investigators. The detailed list of the original data sources is given in Palandri and Kharaka (2004). Calcite dissolution is controlled by the kinetics of the chelating process and the calibrated parameters mentioned above were used.

5.3 Flow Conditions

A 120 m thick reservoir formation with an injection well was modeled. A simple one-dimensional radial flow model was used, consisting of 50 radial blocks with logarithmically increasing radii out to a distance of 1000 m from the wall of the drilled open hole (Figure 7). Only the fracture network is considered in the model, with the assumption that the fluid exchange with the surrounding low permeability matrix is insignificant for the short period of chemical stimulation. An initial fracture permeability of $5.2 \times 10^{-12} \text{ m}^2$ was assumed. A fracture porosity of 1% (ratio of fracture volume to the total formation volume) was assumed. The 1% volume of wall rock was included in the fracture domain, to allow minerals on the fracture walls to interact chemically with injection water. Therefore, a fraction of 2% of total volume was included in fracture domain, with an initial porosity of 0.5, and a permeability of $2.6 \times 10^{-12} \text{ m}^2$.

Table 1: Initial mineralogical compositions used in the numerical modeling

Mineral	% of Solid
Quartz	9
Calcite	12
Low-Albite	21.5
Anorthite	21.5
K-Feldspar	13
Chlorite	8
Illite	7
Others	8

Table 2: Parameters for calculating kinetic rate constants of minerals. Note that: (1) all rate constants are listed for dissolution; (2) A is specific surface area, k_{25} is kinetic constant at 25°C, E_a is activation energy, and n is the exponent term (Eq. 4)

Mineral	A cm^2/g	Parameters for kinetic rate law				
		Neutral mechanism		Base mechanism		
		k_{25} $\text{mol}/\text{m}^2/\text{s}$	E_a KJ/mol	k_{25} $\text{mol}/\text{m}^2/\text{s}$	E_a KJ/mol	n(H ⁺)
Quartz	98	1.14×10^{-8}	32.8			
Low-albite	98	2.75×10^{-13}	69.8	$2.51 \text{E-}16$	71	-0.572
Anor-thite	98	2.75×10^{-13}	69.8	$2.51 \text{E-}16$	71	-0.572
K-feldspar	98	3.89×10^{-13}	38	$6.31 \text{E-}22$	94.1	-0.823
Chlorite	1516	3.02×10^{-13}	88			
Illite	1516	1.66×10^{-13}	35	$3.02 \text{E-}17$	58.9	-0.4

The uncertainty on the permeability specification doesn't affect modeling results of reactive transport and porosity enhancement (as long as pressure buildup at wellbore can be afforded) because a constant injection rate was specified in the present study. Conductive heat exchange with rocks of low permeability above and below this zone is an important process when injection temperature differs from the reservoir temperature. The confining layers are modeled as semi-infinite half spaces, and heat exchange is treated with a semi-analytical technique due to Vinsome and Westerveld (1980). Initial reservoir temperature is 210°C as indicated in Figure 6. An initial hydrostatic pressure of 20 MPa was assumed for about 2000 m depth. Hydrogeologic specifications of the 1-D radial flow problem are given in Table 3.

Table 3: Geometric and hydrogeologic specifications for 1-D radial flow problem

Reservoir properties:	
Permeability	$2.6 \times 10^{-12} \text{ m}^2$
Porosity	0.5
Rock grain density	2750 kg/m^3
Rock specific heat	$1000 \text{ J/kg}^\circ\text{C}$
Thermal conductivity	$2.4 \text{ W/m}^\circ\text{C}$
Initial and boundary conditions:	
Pressure	200 bar
Temperature	210 °C
Injection conditions (base case):	
Temperature	160°C
Rate	10 kg/s
Duration	12 hours

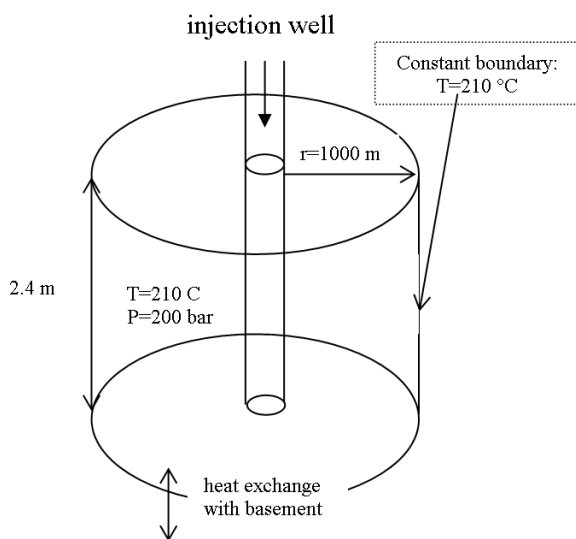


Figure 7: Simplified conceptual model for 1-D radial flow around a geothermal injection well.

Two injection temperatures of 120°C and 160°C were used (details will be discussed later). Injection water chemistry was the same as in the modeling of laboratory experiments, which was prepared by adding NTA agent and NaOH solution to steam condensate, and had a NTA³⁻ concentration of 0.1 mol/kgw, a Na⁺ concentration of 1.5 mol/kgw, and a pH of 11.5. The initial water chemistry is in equilibrium with the initial mineralogy at a reservoir temperature of 210°C. An injection rate of 10 kg/s was applied for a period of 12 hours. Reactive transport simulations were performed for a total time of one day, including a no-flow period after the 12-hour injection.

5.4 Simulation Setup

A total of four simulations were performed (Table 4). We started with a simulation using an injection water temperature of 160°C (base-case). Many chemical and thermophysical factors affect mineral dissolution and associated enhancement in formation porosity and permeability, including mineral abundance and distribution in the formation, and injection temperature and rate, and reaction kinetics. Therefore, in the second simulation, we used a lower temperature of 120°C. Other conditions and parameters are the same as in the base-case. In Simulation 3, the injection rate was increased to 30 kg/s from 10 kg/s in the base-case. In Simulation 4, the reaction rate constants for all mineral and chelating reactions were decreased by a factor of 5.

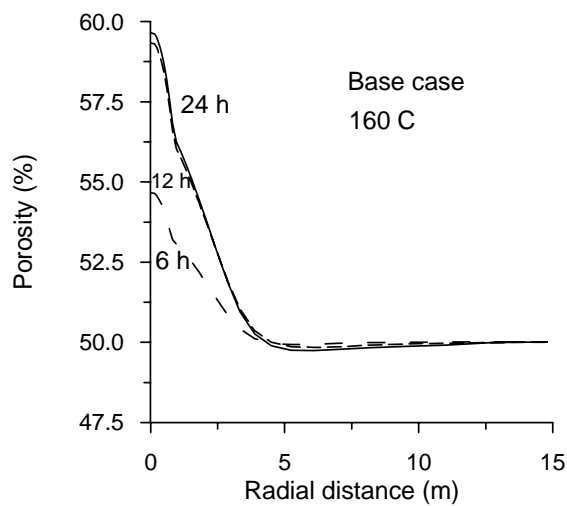
The evolution of reaction rate especially reactive surface area of a mineral is very complex, especially for multi-mineral systems, and is not quantitatively understood at present. The magnitudes of surface areas specified are highly uncertain. Aqueous solution interaction with the minerals in the field is generally expected to occur only at selective sites of the mineral surface, and the actual reactive surface area could be between one and three orders of magnitude less than the geometric surface area (Lasaga, 1995; Zerai et al. 2006). The difference is attributed to the fact that only part of the mineral surface is involved in the reaction due to coating or armoring, a small area exposed to water, and channeling of the reactive fluid flow. The reaction rate simulation may give some ideas on result sensitivity regarding these factors.

Table 4: List of simulations performed with different specifications

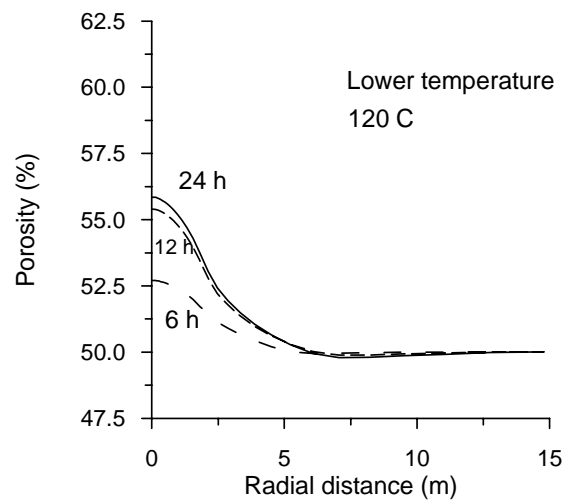
Simulation	Specification
1. Base-case	160°C injection
2. Low temperature	120 °C injection
3. Large injection rate	Injection rate increased by three times to 30 kg/s
4. Low reaction rate	Rate constant reduced by a factor of 5

6. RESULTS AND DISCUSSION

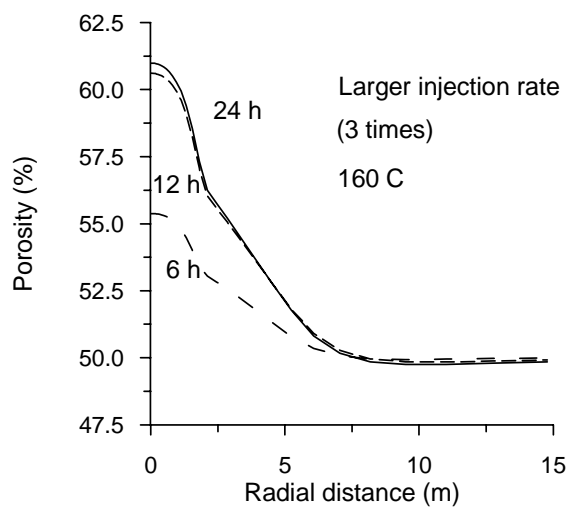
Injection of the high pH solution with chelating agent (NTA) results in increases in porosity along the flow path close to the injection well. Porosity profiles at different times obtained for four cases are presented in Figure 8. Increases in porosity are mainly caused by dissolution of calcite, low-albite and anorthite (Figures 9, 11, and 12).



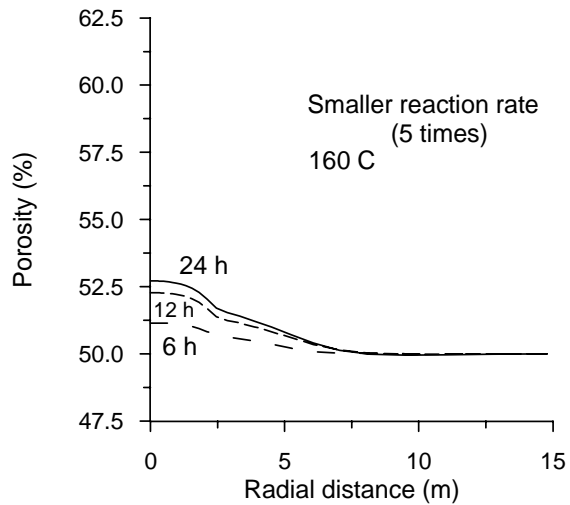
(8a) Case 1: Base case



(8b) Case 2: Lower Temperature



(8c) Case 3: Larger injection rate



(8d) Case 4: Smaller reaction rate

Figure 8: Porosity profiles at different times obtained for the four cases (Initial porosity of the fracture domain is 50%).

In the base-case with an injection temperature of 160°C, the porosity increases to 60% from an initial value of 50% close to the injection point; enhancement of porosity extends to a radial distance of about 5 m (Figure 8a). A low temperature injection (120°C) results in a smaller porosity increase (to 56%) close to the injection point, but a longer extent to a radial distance of about 7 m (Figure 8b). For Case 3 with injection rate increased by three times, the porosity increases to 61% close to the injection point, and the enhancement extends to a longer distance of about 8 m (Figure 8c). Reduction of reaction rate (Case 4) results in less dissolution close to injection point and larger extent along the flow path (compare Figure 8d to 8a), indicating that smaller reaction rates may be more effective for chemical stimulation.

Next we discuss the dissolution of individual minerals along the flow path. A decrease in injection temperature from 160 to 120°C results in no significant changes in the calcite dissolution pattern, with a maximum dissolution of 3.6% close to the injection point (compare Figure 9b to 9a).

Larger injection rate produces slightly higher calcite dissolution (4.5%) close to the injection point, and the dissolution extends to a much longer distance of more than 5 m (Figure 9c). For the first three cases, small amounts of precipitation occur at the moving thermal front because an increase in temperature causes decrease in calcite solubility. A reduction in reaction rate causes a reduction of calcite dissolution (1%) close to the injection point, dissolution extends to a larger distance of about 6 m, and no precipitation of calcite occurs at the moving thermal front (Figure 9d). For all four cases, the amounts of quartz dissolution are very small because of small reaction rate (Figure 10). Generally low-albite dissolves close to the injection point due to high pH, but precipitates along the flow path because of lowered pH and high injected Na^+ concentration (Figure 11). Anorthite dissolves along the flow path because of low Ca^{2+} concentration (Figure 12). K-feldspar, chlorite, and illite all dissolve close to the injection point and precipitate later along the flow path, but the amounts of their dissolution and precipitation are very small.

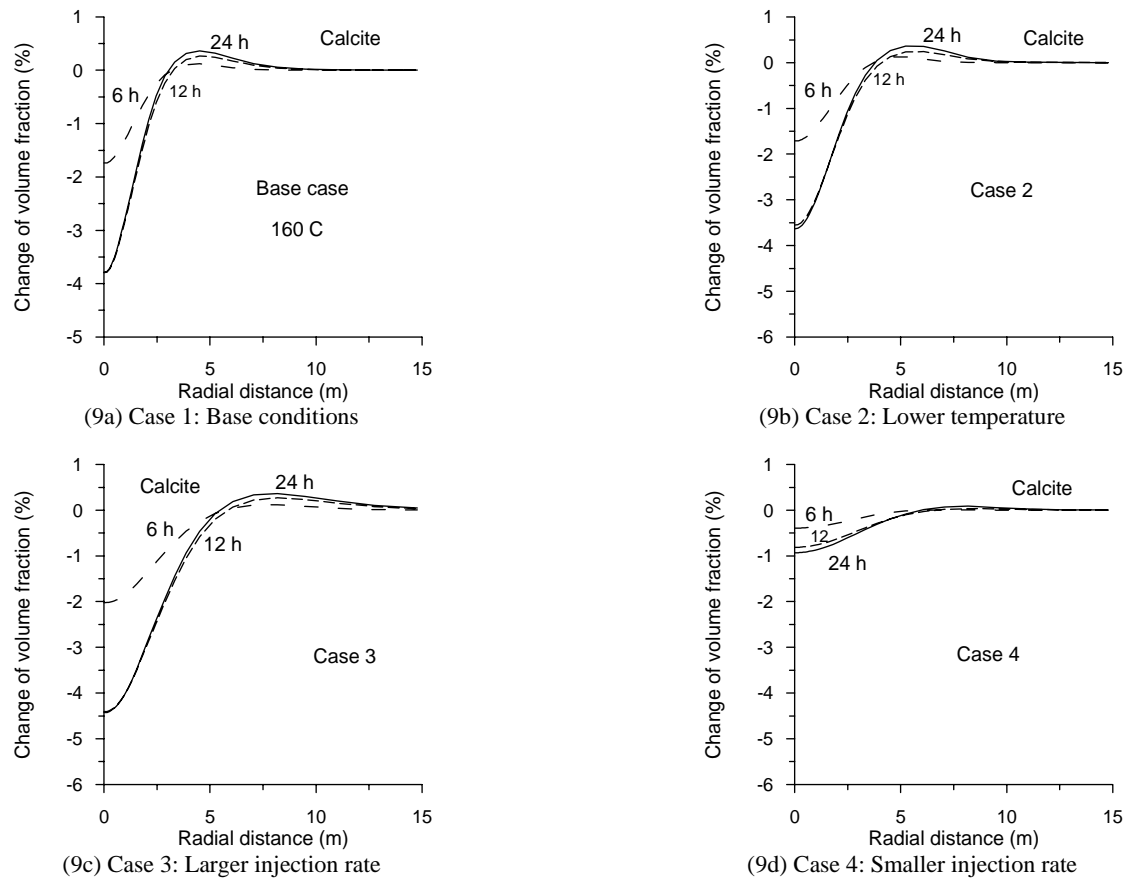


Figure 9: Changes of calcite abundance (in percentage of volume fraction, negative values indicate dissolution, positive precipitation) at different times for the four cases.

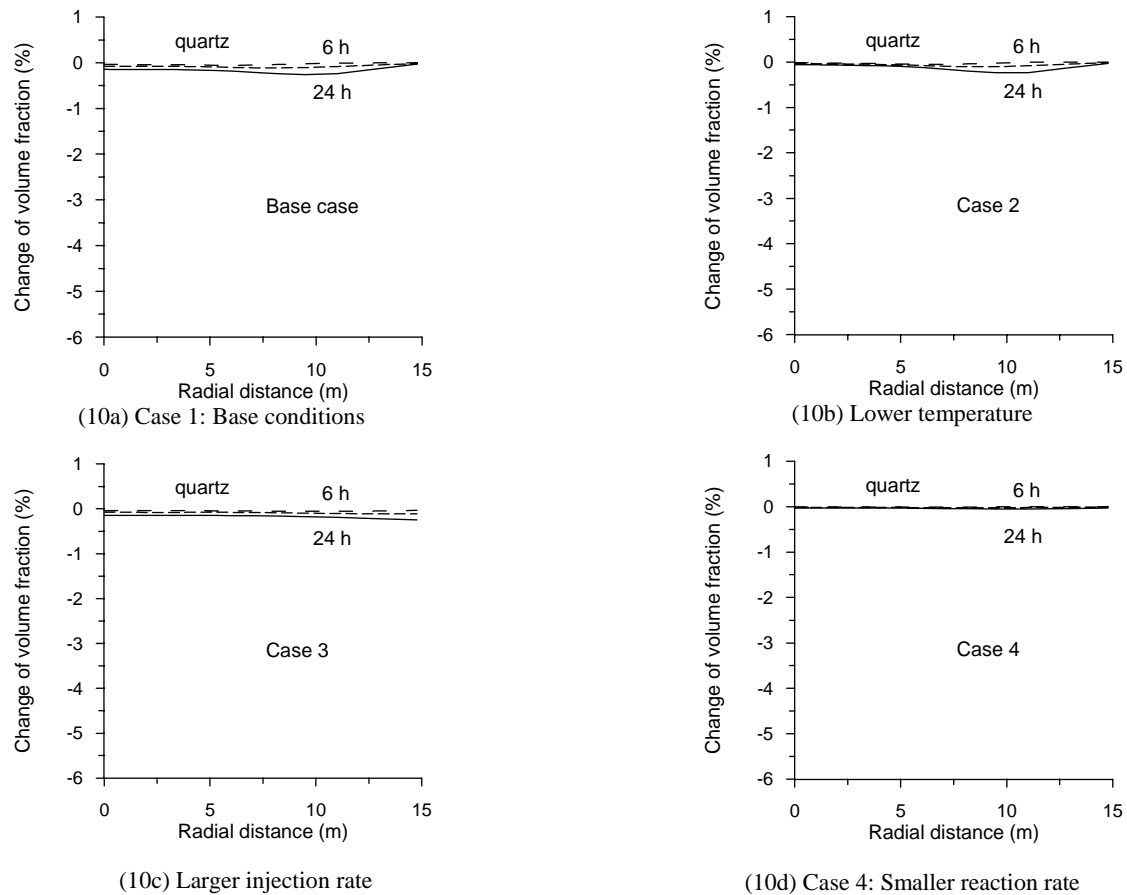


Figure 10: Changes of quartz abundance (in percentage of volume fraction) at different times for the four cases.

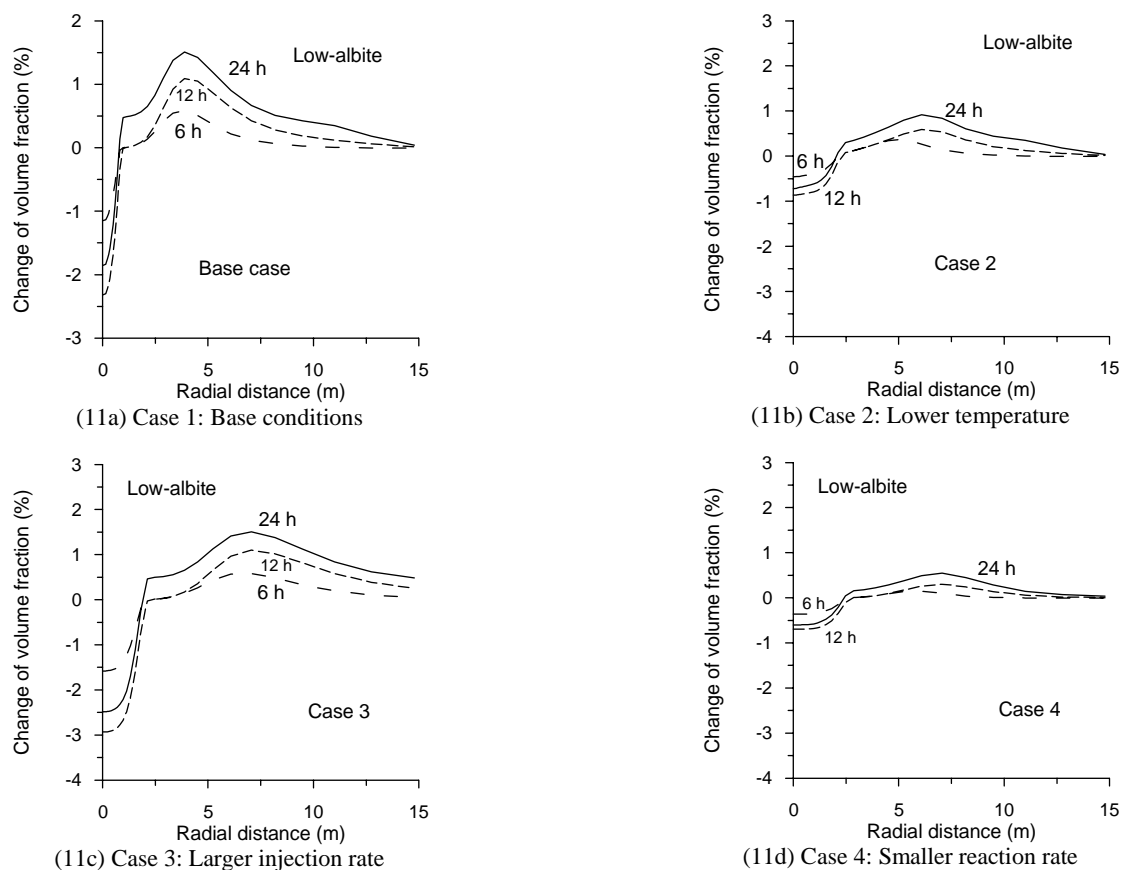


Figure 11: Changes of low-albite abundance (in percentage of volume fraction, negative values indicate dissolution, positive precipitation) at different times for the four cases.

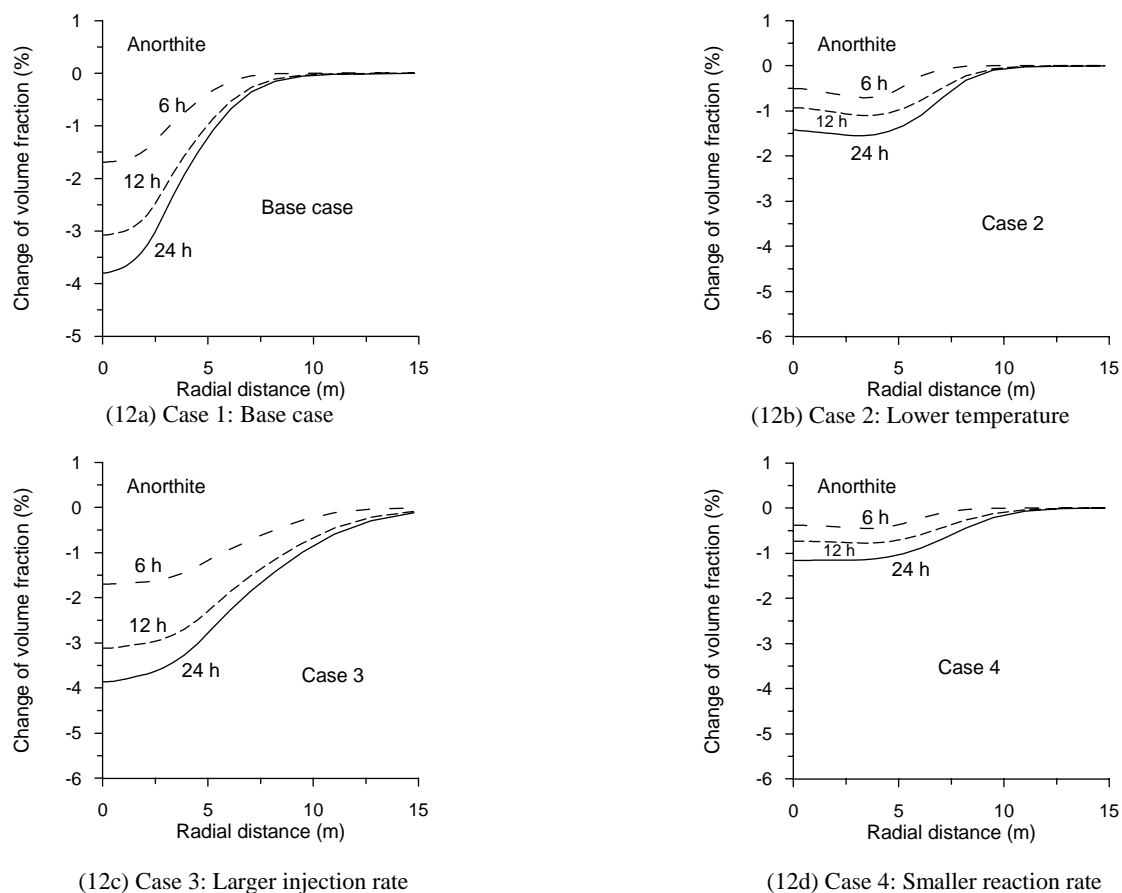


Figure 12: Dissolution of anorthite (in percentage of volume fraction) at different times for the four cases.

Next we examine profiles of temperature, aqueous concentrations, and pH distribution (Figure 13) for the base-case simulation. Temperature reaches the initial value of 210°C after 12 hours at a distance of about 13 m for the 10 kg/s injection rate (Figure 13a). NTA^{3-} concentration increases during the 12-hour injection period (Figure 13b). After injection stops, NTA^{3-} is continuously complexing with Ca^{2+} and driving calcite dissolution, its concentration decreases, and it is used up at 24 hours. Total dissolved carbon concentrations (mainly CO_3^{2-}) increase gradually along the flow path because of calcite dissolution (Figure 13c), and reach a maximum at the calcite dissolution front. The distribution of pH is controlled by the injection pH, consumption of OH^- by silica/silicate mineral dissolution, and transport processes (Figure 13d).

7. SUMMARY AND CONCLUSIONS

Dissolution of silica and calcite minerals in the presence of a chelating agent (NTA) at high pH has been successfully demonstrated in the laboratory using a high-temperature flow reactor. The mineral dissolution and associated porosity enhancement in the laboratory experiment has been reproduced by reactive transport modeling using TOUGHREACT, resulting in calibrated parameters for a dissolution model of calcite and silica minerals. The chemical stimulation method together with calibrated parameters has been applied by numerical modeling to a field geothermal injection well system. Parameters

applicable to crystalline quartz monzodiorite rock unit at the site the Desert Peak EGS site were used. The following conclusions can be drawn from the numerical experiments.

The injection of a high pH chelating solution (NTA) results in dissolution of both calcite and plagioclase minerals, while avoids precipitation of calcite at high temperature conditions. Consequently reservoir porosity and permeability can be enhanced in a region extending several meters around the injection well. A lower temperature injection results in a smaller porosity increase close to the injection point, but a longer extent to a radial distance. Increase in injection rate causes a larger extent of mineral dissolution, favorable for chemical stimulation. Decrease in reaction rate results in less aggressive dissolution close to injection point and larger extent along the flow path. More detailed investigations will be conducted in the future when data will become available from field EGS demonstration projects.

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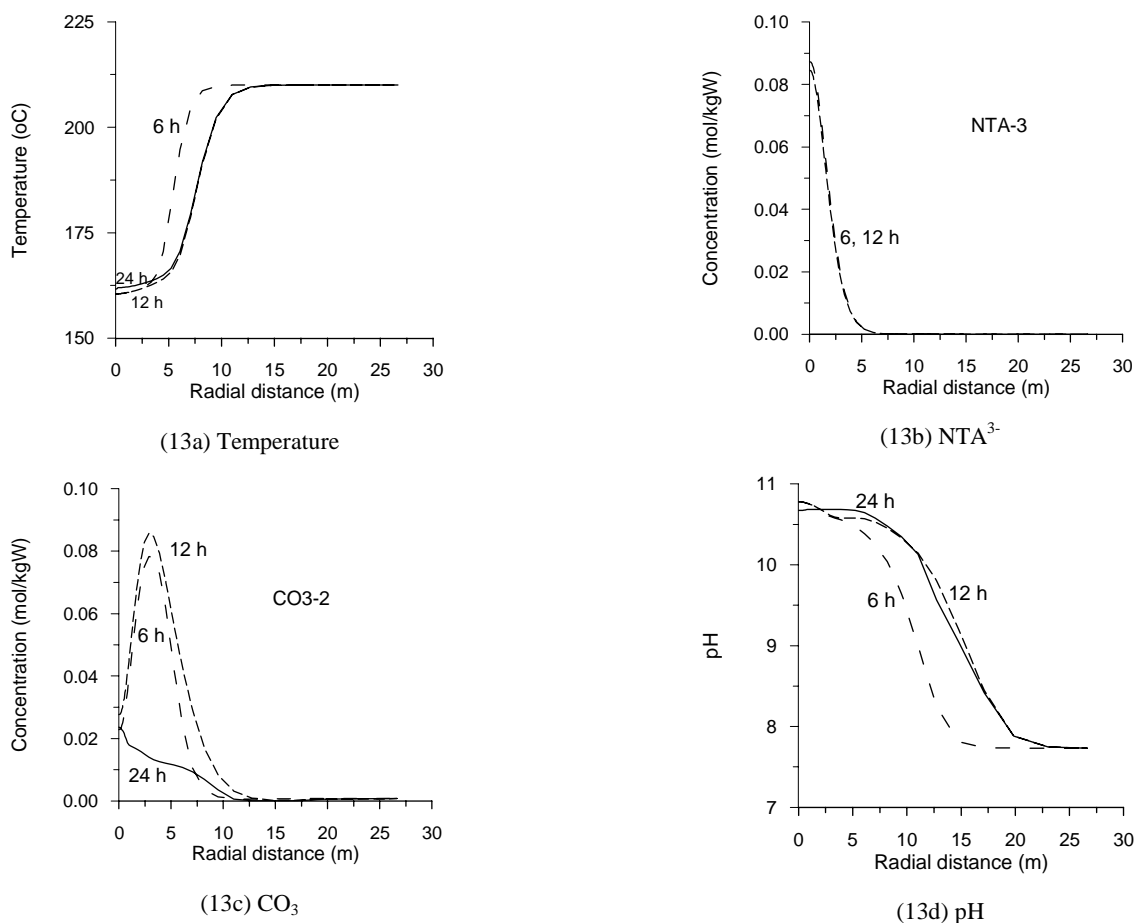


Figure 13: Profiles of temperature, NTA^{3-} , dissolved carbon concentrations, and pH at different times obtained for the base-case with an injection temperature of 160°C.

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