Modeling the evolution of mineralogy in the EGS geothermal system of Soultz-sous-Forêts*

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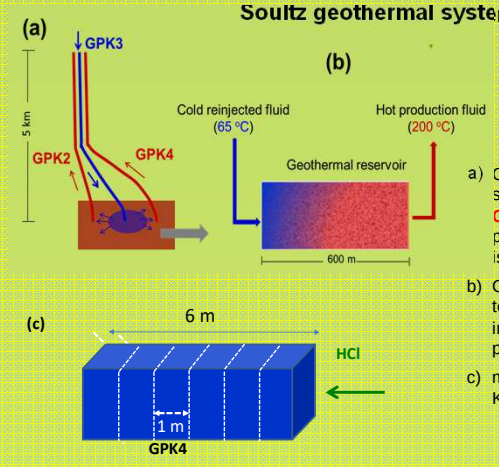
Abstract

- A modelling approach is considered to discuss different scenarios to actively stimulate the low-permeability granitic reservoir of Soultz-sous-Forêts, in terms of amount and duration of HCl solution injection.
- The approach used in this work is based on the geochemical code KIRMAT, which enables us to represent the geothermal reservoir using single-porosity and double-porosity models.
- The modelling results showed that chemical stimulation could significantly increase porosity and permeability; however, for both single and double-porosity models, the improved zones are very limited and are only present within a few meters of the reinjection well.

Soultz geothermal system



a) Cross-section of the Soultz system (Alsace, France); GPK2 and GPK4 are the production wells while GPK3 is the re-injection well.

b) Conceptual model shows the temperatures of the re-injection well (≈ 65°C) and the production well (≈ 200°C)

c) model domain used in KIRMAT simulations.

KIRMAT code

The KIRMAT code can describe the feedback effect of the chemical and mineralogical evolution of porosity and permeability due to dissolution and precipitation reactions.

- The intrinsic permeability k (m^2) is updated after each time step as follows:

$$k = C_0[\,\phi^{c-1}\left(\frac{\phi^3}{(1-\phi)^2 S^2}\right)]^2$$

where C_0, ϕ and S denote an experimental constant, the porosity of the porous medium and the grid cell surface in contact with the adjacent cell (m^2), respectively.

- The porosity at the time increment n is determined as follows:

$$\phi^n = 1 - \left[\frac{S\Delta x(1-\phi^{n-1}) + Bv^n}{S\Delta x}\right]$$

where ϕ^n and ϕ^{n-1} are the porosities at the time increments n and n-1, respectively; Δx is the cell length (m) and Bv^n is the absolute volume balance of all minerals at time increment n (m^3).

Single-porosity model

Main mineralogical compositions, corresponding volume fractions and the estimated reactive surface areas of the Soultz granite on the assumption that the fresh granite contains 90% of the volume fraction and the rest is vein alteration.

Minerals	Structural formula	Volume fraction (%)	Reactive surface area ($m^2\ kg^{-1}H_2O$)
Quartz	SiO_2	25.87	308.30
K-Feldspar	$KAlSi_3O_8$	22.63	7457.55
Albite	$NaAlSi_3O_8$	36.25	8262.75
Anorthite	$Ca(Al_2Si_2)O_8$	2.00	124.21
K-Muscovite	$KAl_3(AlSi_3)O_{10}(OH)_2$	2.82	631.77
Annite	$KFe_3(AlSi_3)O_{10}(OH)_2$	2.82	740.82
Phlogopite	$KMg_3(AlSi_3)O_{10}(OH)_2$	2.82	622.69
Calcite	$CaCO_3$	0.46	112.19
Mg-Illite	$K_{0.85}Mg_{0.25}Al_{2.35}Si_{3.4}O_{10}(OH)_2$	0.87	6375.75
Fe-Illite	$K_{0.85}Fe_{0.25}Al_{2.35}Si_{3.4}O_{10}(OH)_2$	0.87	6687.79
Al-Illite	$K_{0.85}Al_{2.85}Si_{3.15}O_{10}(OH)_2$	0.87	6611.52
Smectite	$[Ca_{0.009}Na_{0.409}K_{0.024}][(Si_{3.738}Al_{0.262}][Al_{1.598}Fe_{0.209}Mg_{0.214}]O_{10}(OH)_2$	0.97	5484.20
Dolomite	$CaMg(CO_3)_2$	0.08	20.71
Chamosite	$Fe_5Al(AlSi_3)O_{10}(OH)_8$	0.33	13.72
Clinochlore	$Mg_5Al(AlSi_3)O_{10}(OH)_8$	0.33	10.79

Physical properties	
Porosity	5 %
Permeability	10^{-16} m²

Double-porosity model

The tested ratio of surface contact and volume contact between fractured and matrix zones **(α/e)** are 1000 and 10000

	Matrix			Fracture	
Minerals	Volume fraction (%)	Reactive surface area ($m^2\ kg^{-1}H_2O$)	Minerals	Volume fraction (%)	Reactive surface area ($m^2\ kg^{-1}H_2O$)
Quartz	24.2	288.40	Quartz	40.9	487.42
K-Feldspar	23.6	7777.20	K-Feldspar	13.9	4580.64
Albite	40.5	9231.49	Calcite	3.9	951.17
Anorthite	2	124.21	Mg-Illite	8.7	63757.49
Muscovite	3.13	701.22	Fe-Illite	8.7	66877.88
Annite	3.13	822.26	Al-Illite	8.7	66115.20
Phlogopite	3.13	691.15	Smectite	9.7	54841.96
Calcite	0.3	73.17	Dolomite	0.8	207.06
			Chamosite	2.4	137.19
			Clinochlore	2.4	107.86

Physical properties		Physical properties	
Porosity	10%	Porosity	1%
Permeability	10^{-16} m²	Permeability	10^{-14} m²

Double-porosity medium

The mass balance equations of reactive transport:

- in a fractured medium:

$$\frac{\partial}{\partial t}\left(\phi^f \Psi_j^f\right) = \phi^f D\left(\frac{\partial^2 \Psi_j^f}{\partial x^2}\right) - U\frac{\partial \Psi_j^f}{\partial x} + \varphi_j^f + \frac{\alpha}{e}\phi^f D_{diff}\left(\Psi_j^m - \Psi_j^f\right)$$

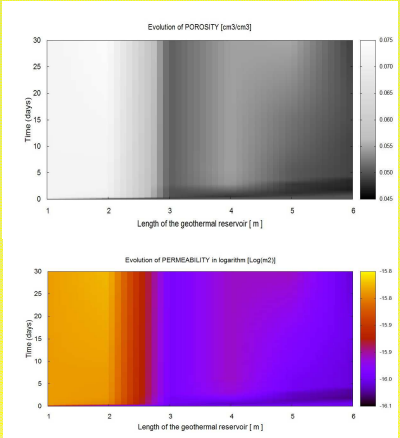
- in the matrix, where it is assumed that no flow and no mass transport take place:

$$\frac{\partial}{\partial t}\left(\phi^m \Psi_j^m\right) = \varphi_j^m - \frac{\alpha}{e}\phi^m D_{diff}\left(\Psi_j^m - \Psi_j^f\right) \quad (j = 1, \ldots, N)$$

where Ψ_j^f and Ψ_j^m are the dissolved global concentrations of primary species j in fractured medium and matrix, respectively (mol.L^{-3}); ϕ^f and ϕ^m are the porosity of fractured medium and matrix, respectively; D is the effective hydrodynamic dispersion coefficient ($L^2.T^{-1}$) in fractures; D_{diff} is the diffusion coefficient ($L^2.T^{-1}$) in matrix; U is the Darcy velocity ($L.T^{-1}$); φ_j^f and φ_j^m are the sink terms corresponding to the geochemical fluxes in fractured medium and matrix, respectively (mole.$L^{-3}.T^{-1}$); **α** is the surface contact between fractured medium and matrix (L^2); ***e*** is the volume contact between fractured medium and matrix (L^3).

Reference case

Single-porosity model
HCl concentration: 0.2% (pH =0.74)
injection duration: 2 days with a Darcy velocity of 1 $m.h^{-1}$



Sensitivity study cases

Case 1: change of the Darcy velocity, where the Darcy velocities are equal to 0.1 $m.h^{-1}$, 0.2 $m.h^{-1}$ and 2 $m.h^{-1}$: similar to those of the reference case

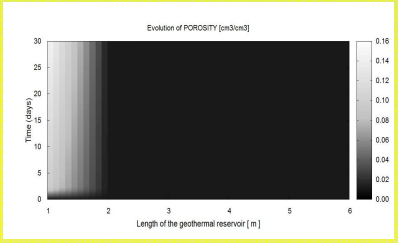
Case 2: increase of the injection duration by a factor 2: similar to the reference case

Case 3: increase of the acid concentration, pH=0: from 2 to 6 meters away from the injection well, the porosity decreases drastically

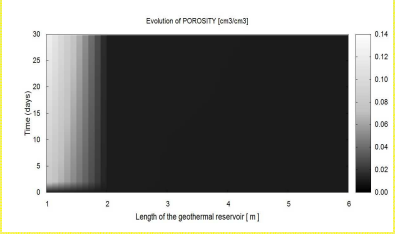
Case 4: increase of the initial amount of calcite in the reservoir, (2%): induces higher porosity

Double-porosity model

α/e = 1000



α/e = 10000



Conclusions

- The reference case shows an increase in porosity resulting from a strong dissolution of the primary minerals such as calcite and anorthite in the zone around the acid-injected well, but precipitation of secondary minerals such as beidellite, which leads to a porosity decrease in the rest of the system
- The sensitivity study cases show no significant improvements, except for Case 4 when there is more calcite in the system, which is more affected by dissolution
- The comparison of the modelling results from the single porosity and double porosity models confirm that the impacted zone is limited to a few metres around the acid-injected well.

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