Large scale natural hydrothermal circulation at Soultz-sous-Forêts: a numerical 2D approach

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ABSTRACT

We develop a two dimensional numerical model for the Soultz-sous-Forêts reservoir, from an idealized cross section consisting of six homogenous horizontal layers. The nonlinear constitutive equations are those of homogenized saturated porous media involving THM (Thermo-Hydro-Mechanical) couplings. Most of materials properties (for brine and rocks) are taken dependent on temperature, pressure, or porosity. The entire set of constitutive equations is solved in transient regime with the finite element software *Code_Aster* to reach a stationary state of the reservoir. We show that a large scale natural convection can be obtained considering suitable boundary conditions, provided that the permeability of the reservoir exceeds a value close to 10^{-14} m^2. Convection cells are of the order of 1.3 km in width and we discuss several vertical profiles.

1. INTRODUCTION

The interest of obtaining a numerical and coupled model of a geothermal reservoir is fourfold:

- it allows the physical integration of laboratory measurements (rock physics), such as well logging, well head parameters, geological description, and geophysics field measurements. It shows how data are precious input parameters of the model, and gives them an utility of great importance.

- it provides a direct model based for geophysical inversion of field measurements: fluid flow, fluid pressure, temperature profile, seismicity monitoring, deformation of the ground surface (INSAR/GPS) related to reservoir modification, gravity or electromagnetic geophysical measurements.

- it provides the possibility to analyze the sensitivities of parameters involved in the hydrothermal circulation (or in other physical processes). This analysis can lead to the identification of material properties having the greatest influence on the model outputs, thus providing useful information for the planning of new experimental investigations.

- it can become a decision tool for drilling and trajectory planning, stimulation and exploitation.

This contribution is a step toward a THM model of the Soultz-sous-Forêts reservoir. At this stage, we show the existence of a large scale convective solution in the reservoir of Soultz-sous-Forêts, considering only the regional stratigraphy and known rheophysics properties of the rock matrix and the saturating brine. This solution is the starting point to proceed to a stability analysis of the reservoir when it is submitted to some mechanical, thermal or hydraulic perturbation specific of stimulation or production phases.

2. CONSTITUTIVE EQUATIONS

The constitutive equations used in this work are those of fluid saturated porous media with couplings between thermo-hydro-mechanical phenomena. The conservation equations driving the evolution of extensive quantities associated with all forms of energy are completed with relations between generalized stresses and deformations. In this work, the behavior of rock solid grains is assumed to be thermo-elastic and linear. The hydraulic and thermal phenomena are governed by the Darcy law and Fourier law respectively, and most rock properties (like the specific heat at constant stress $c_s^{\sigma}(T)$ or the thermal conductivity $\lambda(T,\varphi)$) are assumed to depend on the temperature T and/or porosity φ. The radioactivity of the rocks is taken into account through a heat source term appearing in the balance equation of enthalpy. To characterize as precisely as possible the convective movement of water and associated heat flow, the properties of water (specific mass $\rho_w(T,p_w)$, specific enthalpy $h_w(T,p_w)$ dynamic viscosity $\mu_w(T,p_w)$, thermal dilation $\alpha_w(T)$, and specific heat $c_w(T)$) are assumed to depend on the pressure and/or temperature. The entire set of material properties is extracted from the literature dealing with experimental investigations on brine and rocks, the brine being treated as a pure solution of NaCl characterized by a mass content of about 100 g.L^{-1}.

3. NUMERICAL ASPECTS

The governing equations are partially implemented and solved by using the finite element software *Code_Aster.* The associated mesh is composed of QUAD elements and materializes the six geological horizontal layers of the reservoir (10km in width, 5.5 km in height, see Figure 1 (a)). The boundary conditions of the problem are the following: the normal mechanical displacement vanishes (with no friction) on the left and lower boundaries of the domain, while the upper boundary is free of stress. The regional stress is provided on the right boundary. Regarding thermal aspects, a temperature is imposed on the upper and lower boundaries, and the thermal flow vanishes on lateral facets. For hydraulics, the flow vanishes on all boundaries except the upper one for which the water pressure equals the atmospheric pressure (see Figure 1 (b)). The simulation is carried out in two steps. At first, the boundary conditions and gravity are applied in a ``short'' period of about 100 years. In a second step, the code iterates with a time increment approximately equal to 1000 years until a stationary state is reached. A convergence indicator I_n is defined with the generalized displacements $X = \xi_x, \xi_y, \xi_z, P, T$ calculated for different time increments t_n.

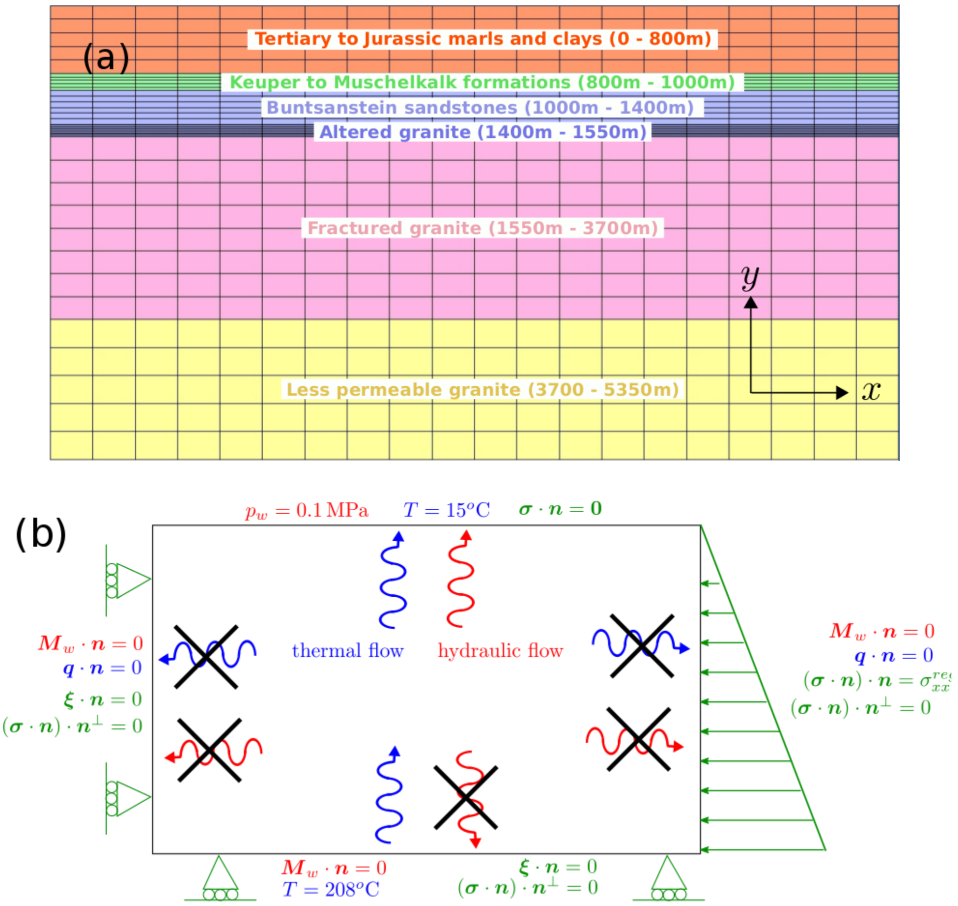

Figure 1: (a) Mesh and (b) boundary conditions used for the simulation.

Indeed, we will say that a stationary state is reached if:

$$I_n(X) = max_{nodes} \frac{[X_{n+1} - X_n]}{\Delta X_{max}} < 1$$

for m consecutive time increments, with ΔX_{max} the maximal uncertainty on the generalized displacement X. Once a stationary state is calculated, it is possible to export vertical temperature and stress profiles, as well as two dimensional fields of any quantities.

4. RESULTS

At this stage, the main results of our simulations are the following:

▪ A stationary convective solution at large scale is highlighted. The order of magnitude of the convective cell size in the reservoir is about 1.3km, a value being independent of the model width (Figure 2).

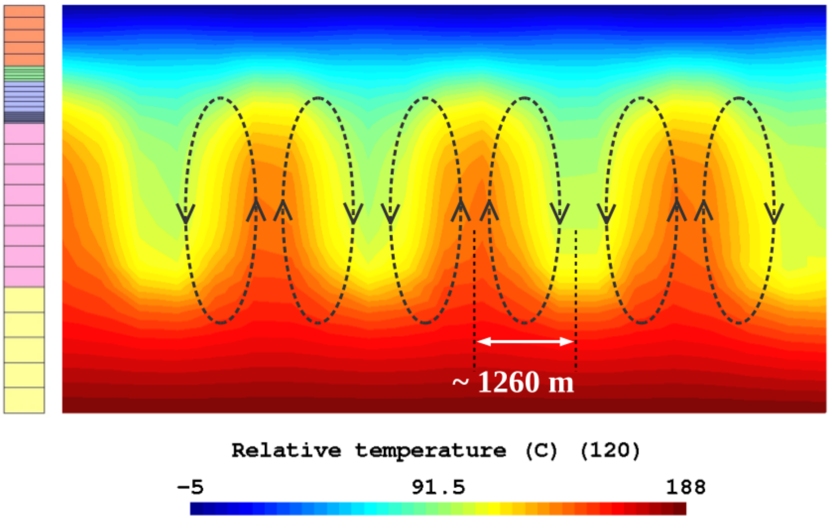

Figure 2: Map of relative temperature (real temperature minus 20°C). The colored vertical legend remind the width of geological layers.

A periodic pair of cells is then 2.6 km wide. We insist on the fact that the uniqueness of this solution can in no way be guaranteed. Furthermore, the way the initial conditions influence the final result of the simulation is a difficult task accounting for the strong non-linearity of the constitutive equations. The unicity of this solution, its stability, and the way initial conditions may influence the final results will be analyzed in a future work.

▪ The order of magnitude of the maximal vertical Darcy velocity is 20 $cm.year^{-1}$ (see Figure 3 (f)), a value confirmed by previous works found in the literature, Guillou-Frottier et al. (2013).

▪ The field of water pressure keeps globally linear with depth (Figure 3(d)), and the influence of thermo-hydraulic coupling on the vertical stress state of the reservoir is rather low (Figure 3 (e)).

▪ The large scale convection is triggered with a permeability in the five upper geological layers of about 10^{-14} m^2, the permeability in the lowest layer being kept constant and equal to 10^{-18} m^2

▪ The vertical profiles of total stress (Figure 4), calculated for different values of the horizontal coordinate x , show that the hydraulic stress σ_p keeps relatively small (less than 25%) relative to total stresses whatever the position of the vertical profile. We conclude that effective stress and total stress are approximately the same in this model. Furthermore, the shear stress σ_{hv} corresponding to the shear associated with the horizontal and vertical directions is negligible. It is then possible to claim that the total Cauchy stress tensor keeps diagonal. In addition, the vertical stress σ_v remains close to the initial lithostatic stress $\sigma_{litho}=r_0 g y$ (with r_0 the initial homogenized specific mass, g the gravity and y the vertical space coordinate), showing that thermo-hydraulic phenomena do not have a great impact on the vertical stress state in the reservoir.

Of course, this conclusions obtained in two dimensions and with the assumption of plane strains could be different with a three dimensional model including the main faults present in the reservoir.

REFERENCES

Coussy, O.: Poromechanics. John Wiley & Sons, 2004.

Guillou-Frottier, L. and Carré, C. and Bourgine, B. and Bouchot, V. and Genter, A.: Structure of hydrothermal convection in the Upper Rhine Graben as inferred from corrected temperature data and basin-scale numerical models, *Journal of Volcanology and Geothermal Research*, **256**, (2013), 29–49.

Kohl, T. and Mégel, T.: Predictive modeling of reservoir response to hydraulic stimulations at the European EGS site Soultz-sous-Forêts, *International Journal of Rock Mechanics and Mining Science*, **44**, (2007), 1118–1131.

Kohl, T. and Bächler, D. and Rybach, T.: Steps towards a comprehensive thermo-hydraulic analysis of the HDR test site Soultz-sous-Forêts, *Proceedings World Geothermal Congress*, (2000).

Magnenet, V. and Fond, C. and Genter, A. and Schmittbuhl, J.: Two dimensional THM modelling of the large scale natural hydrothermal circulation at Soultz-sous-Forêts (Alsace), *Geothermal Energy*, revised, (2014).

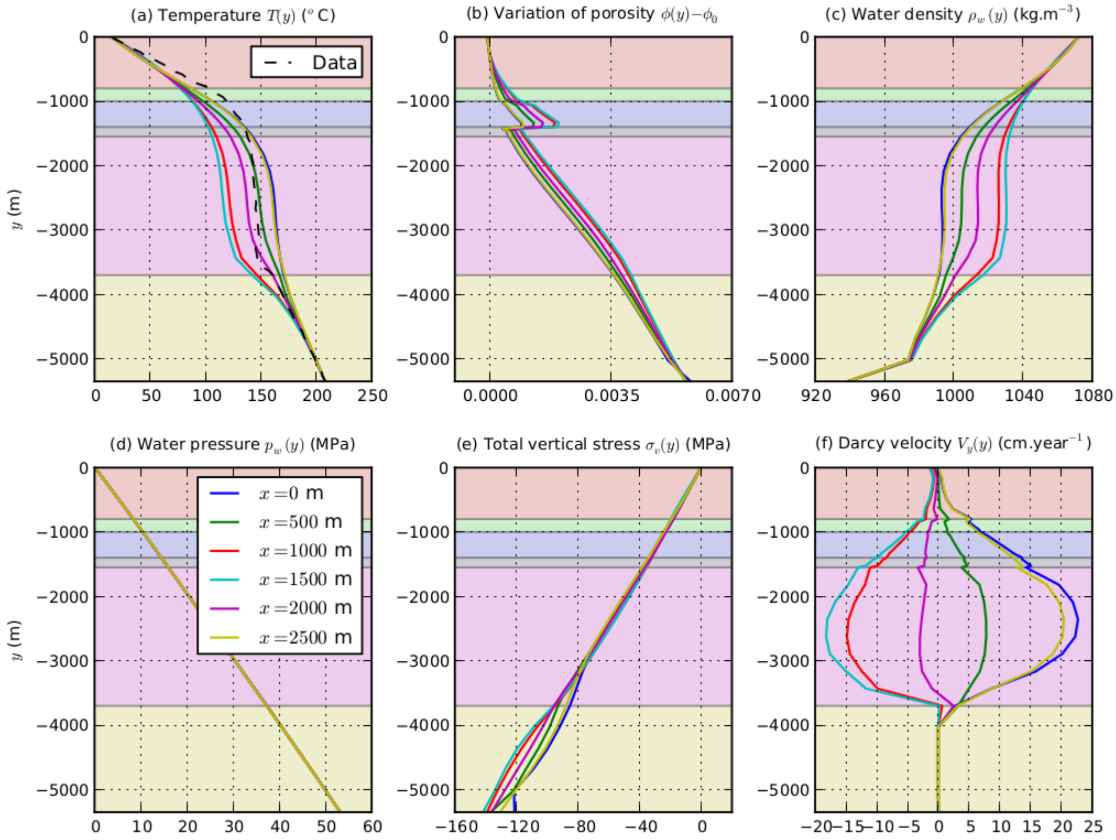

Figure 3: Vertical profiles calculated every 500m in a convective cell.

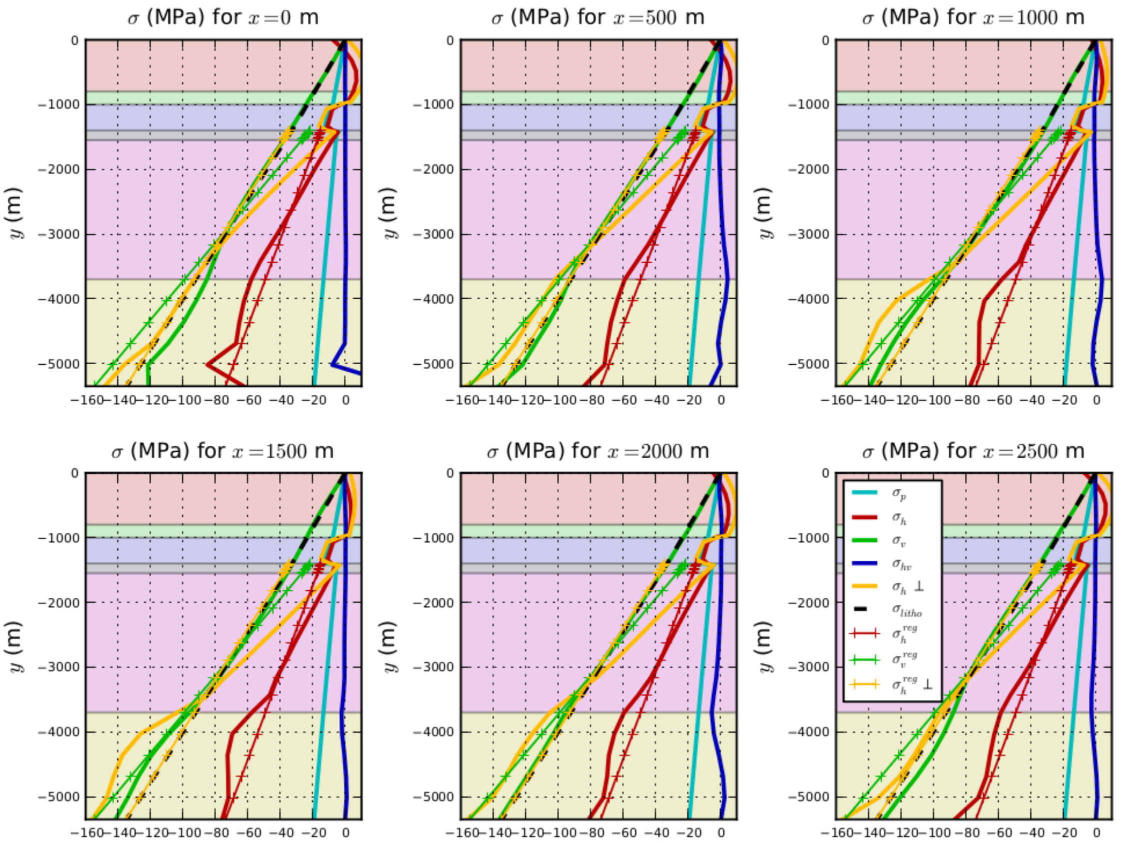

Figure 4: Stress profiles in a convective cell, calculated every 500m.