Characterization of Geothermal Reservoirs and Modeling - Methods and Strategies to Obtain Thermal Properties with Matlab Reservoir Simulation Toolbox (MRST)

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Abstract

The characterization of geothermal reservoirs is very important in the field of geothermal energy. The article aims to model a reservoir using the characteristic quantities of the three phenomena (pressure, temperature and mechanical displacement), and to have a better knowledge and understanding of what is happening inside the simulation software of the tanks, and above all the advantage that the toolBox offers in terms of freedom of use in the MATLAB environment. Here the parameter studied is mainly the temperature. In our case, the MRST or Matlab Reservoir Simulation Toolbox tool served as a method to model this reservoir. By introducing the different parameters (pressure, temperature, and depth), after simulation we have a reservoir model with a temperature range between 130°C to 170°C as well as depths from 1300m to 3800m.

Keywords: *Reservoir modeling*, *Temperature estimation, Numerical simulation, Matlab toolbox MRST*

I. INTRODUCTION

Numerical simulations have become an important tool for the exploration and economic exploitation of geological reservoirs, because they allow a prognosis of the evolution of the deposit over time. But geothermal modeling gives reliable information concerning the temperature and the production rate only in case of representative characterization of the geometry and parameters of the model [1].
A reliable temperature forecast for a defined depth requires numerous parameters – above all knowledge of heat flow, effective conductivity and heat production in the targeted geological formation. We will develop methods to derive representative information for thermal properties from existing data [2].
The temperature at depth is characterized by two main parameters: amplitude and phase shift relative to the thermal signal at depth. This amplitude increases as the depth increases. Therefore, at depth, the temperature is higher than that at the surface. In this study, the heat transfer problem in geothermal reservoirs is modeled to be able to study the evolution of the temperature [3].

II. MRST TOOLBOX (Matlab Reservoir Simulation Toolbox)

Over the last decade, several studies carried out by the LSIA laboratory (The Simulation and Applied Informatics Laboratory) as part of the improvement and validation of new models and algorithms with a view to obtaining an appreciable toolbox, allowing other researchers to take advantage of MRST features to achieve a purely scientific goal (Figure 1).

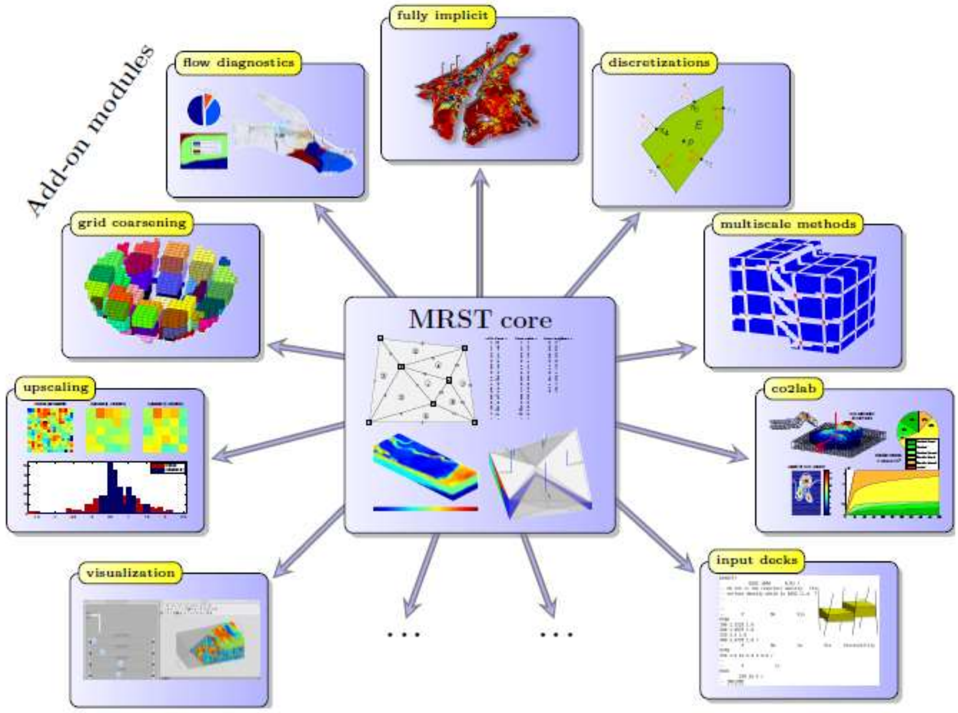

Figure 1: Main functionalities and modules integrated into the MRST toolbox [4]

For a good understanding of the problem of fluid flow through porous media, we found it useful to use the MRST toolbox which offers sufficient flexibility and even its functionalities under the MATLAB environment do not require in-depth computer training on which we considered in relation to our objective of having a better knowledge and understanding of what is happening inside the software, and especially the advantage that the toolBox offers in terms of freedom of use.

MRST is an open source toolbox developed by the Norwegian research laboratory SINTEF. This tool intended for the petroleum field, was initiated using the MATLAB programming environment [4], it contains a set of algorithms which allow the reading, representation, processing and visualization of the inserted data, as well as modules for generating grid models, fluid models, and set the boundary conditions necessary for the simulation as shown in Figure 2.

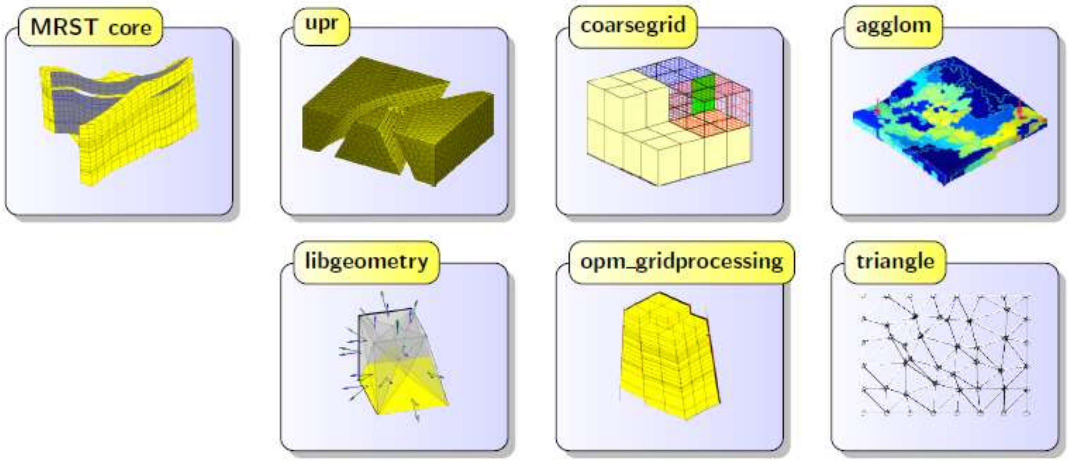

Figure 2: Grid generation and coarsening

The novelty resulting from our work, also a contribution to the development of a graphical interface under the MATLAB environment allowing better use of the modules integrated into the box, in order to simulate the dynamic model. Then we developed our own calculation program with MATLAB allowing us to calculate the reserves using the volumetric method. This graphical interface also makes it possible to import reservoir data in terms of geometry and petro-physical characteristics from the outputs of other software in order to use them in dynamic simulation under MATLAB.

III. MODELING THE GEOTHERMAL RESERVOIR

III. 1. Description of thermo-hydro-mechanical coupling

The modeling proposed in this study is based on the calculation of thermo-hydro-mechanical coupling. The thermo-hydro-mechanical coupling equations are developed within the framework of the linear thermo-poro-elastic approach described in the reference work [5]. The deep geothermal reservoir is assimilated on a large scale a porous medium entirely saturated by a single-phase brine. The assumption of local thermodynamic equilibrium is made. Thus the heat exchanges between the brine and the porous medium are assumed to be instantaneous. The mechanical deformations are assumed to be infinitesimal (Figure 3).

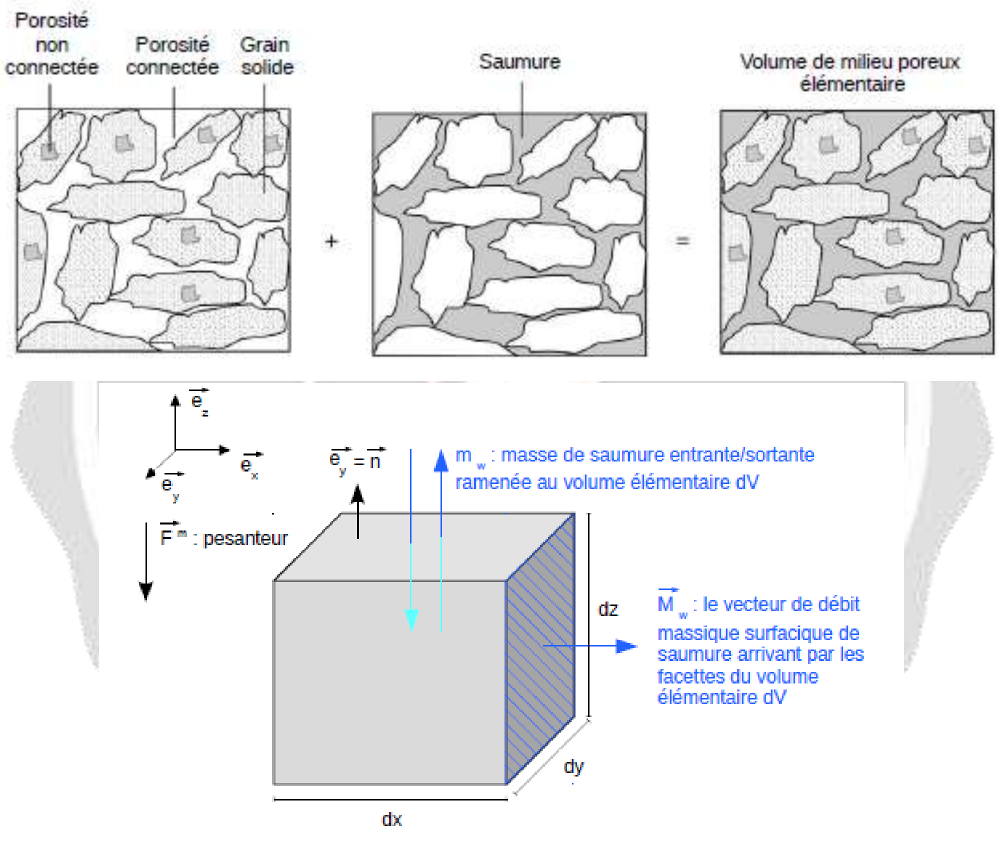

Figure 3: Representative elementary volume

Three aspects of coupling, hydraulic, thermal and mechanical, are considered within the model. The characteristic quantities of the three phenomena are summarized in Figure 4. For each of these aspects, three types of physical quantities have been differentiated:

- Generalized displacements (pressure, temperature and mechanical displacement).
- Generalized deformations (ie the gradients of generalized displacements)
- Generalized constraints (ie thermodynamic duals of generalized deformations).

	Mécanique	Hydraulique	Thermique
Déplacement	Déplacement mécanique ξ	Pression de fluide p_w	Température T
Déformation	Déformation linéaire $\epsilon = \text{sym}(\nabla\xi)$	∇p_w	∇T
Contrainte	Tenseur de contrainte de Cauchy σ	Flux hydraulique M_w	Flux de chaleur q

Figure 4: Summary of generalized thermodynamic variables

III.2. Conservation law used for simulation

For each aspect of the coupling, the conservation laws are defined. For the hydraulic aspect, the conservation equation (1) results from a mass balance of the incoming brine (or outgoing depending on the chosen convention) of an elementary volume dV in an instant dt. The quantity of incoming (or outgoing) water mass is compensated by the surface mass flow of brine, expressed by the vector M_ω

$$\frac{\partial m_w}{\partial t} + \nabla . M_w = 0 \quad (1)$$

With :
- m_ω the mass of incoming brine reduced to a volume dV of porous medium, in $kg.m^{-3}$
- M_ω the surface mass flow vector in brine in $kg.m^{-2}.s^{-1}$

The same goes for the thermal energy conservation equation (2). However, there are added different terms relating to the multiple modes of heat transfer. Thus, the quantity Q represents the variation of internal energy per unit volume outside of any conduction or convection. The quantity q expresses the norm of the conductive heat flow vector. We also note the presence of a source term note θ_{rad} linked to the contribution of thermal energy by radioactive heat sources present in the rocks.
Note, the hydro-thermal coupling is already highlighted by the appearance, in the two conservation equations (1) and (2), of the quantities M_ω and m_ω.

$$M_w.\mathbf{F^m} + \theta_{rad} = h_w^m \frac{\partial m_w}{\partial t} + \frac{\partial Q}{\partial t} + \nabla.(h_w^m.M_w) + \nabla.\mathbf{q} \quad (2)$$

With the same notations as equation (1):
- F^m, the mass force density in $N.kg^{-1}$, here only the gravity field is taken into account,
- θ_{rad}, the source term corresponding to the thermal energy emitted by the radioactivity of rocks in Wm^{-3},hmw, the specific enthalpy of the brine in $J.kg^{-1}$,
- Q, the non-convective or conductive heat in Jm^{-3},
- q, the heat flow vector emitted by conduction in $Jm^{-2}.s^{-1}$

III.3. Flow-force relationships

The balance equations written previously allow the calculation of generalized displacements. However, these equations must be associated with other relationships between deformations and stresses in order to deduce the generalized stresses. These relationships are called flow-force relationships. Those characterizing the thermal and hydraulic aspect are respectively better known under the name of Fourier's law (3) and Darcy's law (4):

$$\mathbf{q} = -\lambda \nabla T \quad (3)$$

With the same notations as equation (2) and λ, the thermal conductivity in$W.m^{-1}.K^{-1}$

$$M_w = \frac{\rho_w K_{int}}{\mu_w}(-\nabla p_w + \rho_w.\mathbf{F^m}) \quad (4)$$

With :
- K_{int} being the permeability of the rock in m2,
- μ_ω, the dynamic viscosity in Pa.s,
- ρ_ω the density in kg.m^{-3} and
- p_ω, the fluid pressure in Pa.

For the mechanical aspect of the model, the behavior of the porous matrix is assumed to be linear thermo-poro-elastic. The effective Cauchy stress is then linked to a temperature variation. Indeed, Hooke's law takes into account the phenomenon of linear expansion through the coefficient of thermal expansion note α_o of:

$$d\boldsymbol{\sigma}' = \mathbb{C} : (d\boldsymbol{\epsilon} - \alpha_0\, dT\, \mathbf{1}) \quad (5)$$

with :
- C: the elasticity tensor drains in Pa,
- ϵ : Mechanical deformation
- 1: the unit matrix.

IV. DATA ANALYSIS AND SIMULATION

IV.1. Mixture of homogenized properties

In a deep geothermal reservoir, the properties of the porous medium evolve when its pressure and temperature conditions experience strong variations. In the area that interests us, temperatures are between 10°C and 220°C and fluid pressures vary between 0.1 MPa and 56 MPa. To take these changes into account, thermal conduction is described according to a classic mixing law involving porosity.

$$\lambda_{sec}(T) = (1-\phi_0)\lambda_s(T) + \phi_0\lambda_{air}(T) \quad (6)$$

With λ_s (respectively, λ_{air}) the thermal conductivity of solid grains (respectively, air).
The thermal conductivity of the air is assumed to be negligible. Consequently, the thermal conductivity of the solid grains is then expressed as follows:

$$\lambda_s(T) = \frac{\lambda_{sec}(T)}{1-\phi_0}. \quad (7)$$

The thermal conductivity of the dry medium is assumed to depend linearly on the temperature:

$$\lambda_{sec}(T) = a_{\lambda_{sec}} + b_{\lambda_{sec}} T \quad (8)$$

With $a_{\lambda sec}$ and $b_{\lambda sec}$ of empirical constants obtained from experimental data. Finally, the homogenized thermal conductivity of the saturated medium is described by the same type of mixing law.

Table 1: Summary of relationships between brine properties and fluid temperature and/or pressure with experimental coefficients associated with Itasy [6] results

Setting	Expression	Coefficient
μ_w (Pa s)	$\mu_w^{\infty} + \Delta\mu_w^{\infty} \exp(\beta(T - T_{ref}))$	μ_ω^∞ =1.9 10-4 Steps $\Delta\mu_\omega^\infty$ =6.2 10-6Steps β =- 0.02 K-1 T_{ref} =406.4K
c_w^p (J kg^{-1} K^{-1})	$a_{c_w^p} + b_{c_w^p}(T - T^1) + c_{c_w^p}(T - T^1)^2$	$a_{c_\omega^p}$ =3.7 JKg-1K-1 $b_{c_\omega^p}$ =0.4 JKg-1K-1 $c_{c_\omega^p}$ =4.6 10-3JKg-1K-1 T^1= 273.15K
α_w (K^{-1})	$a_{\alpha_w} + 2b_{\alpha_w}(T - T^0) + 3c_{\alpha_w}(T - T^0)^2$	a_{α_ω} =1.3 10-3 K-1 b_{α_ω} =4.3 10-3 K-2 c_{α_ω} =2.3 10-3 K-3 T^0= 278K
ρ_w (kg m^{-3})	$\rho_w^0 \exp\left[\frac{p_w - p_w^0}{K_w} - 3(a_{\alpha_w}(T - T^0) + b_{\alpha_w}(T - T^0)^2 + c_{\alpha_w}(T - T^0)^3)\right]$	ρ_ω^0 =1.07Kg m3 p_ω^0 =0.2 MPa
λ_w (W m^{-1} K^{-1})	$a_{\lambda_w}\left[1 - b_{\lambda_w}\exp(-c_{\lambda_w}(T - T^1)\right]$	a_{λ_ω} =0.7Wm-1K-1 b_{λ_ω} =0.2 c_{λ_ω} =0.02 K-1

IV.2. GUI Overview

The advantage of using MRST is that everyone can contribute to its improvement by integrating new features not yet implemented. This therefore makes it a rapidly and constantly evolving software. The aim of this section is to present our contribution to the development of a graphical interface (GUI - Guide User Interface) under the

MATLAB environment, which simplifies the handling of the software and also allows better use of the integrated modules of the MRST toolbox, in order to calculate the reserves in place and subsequently simulate the dynamic model. The following Figure 5 shows some of these graphs.

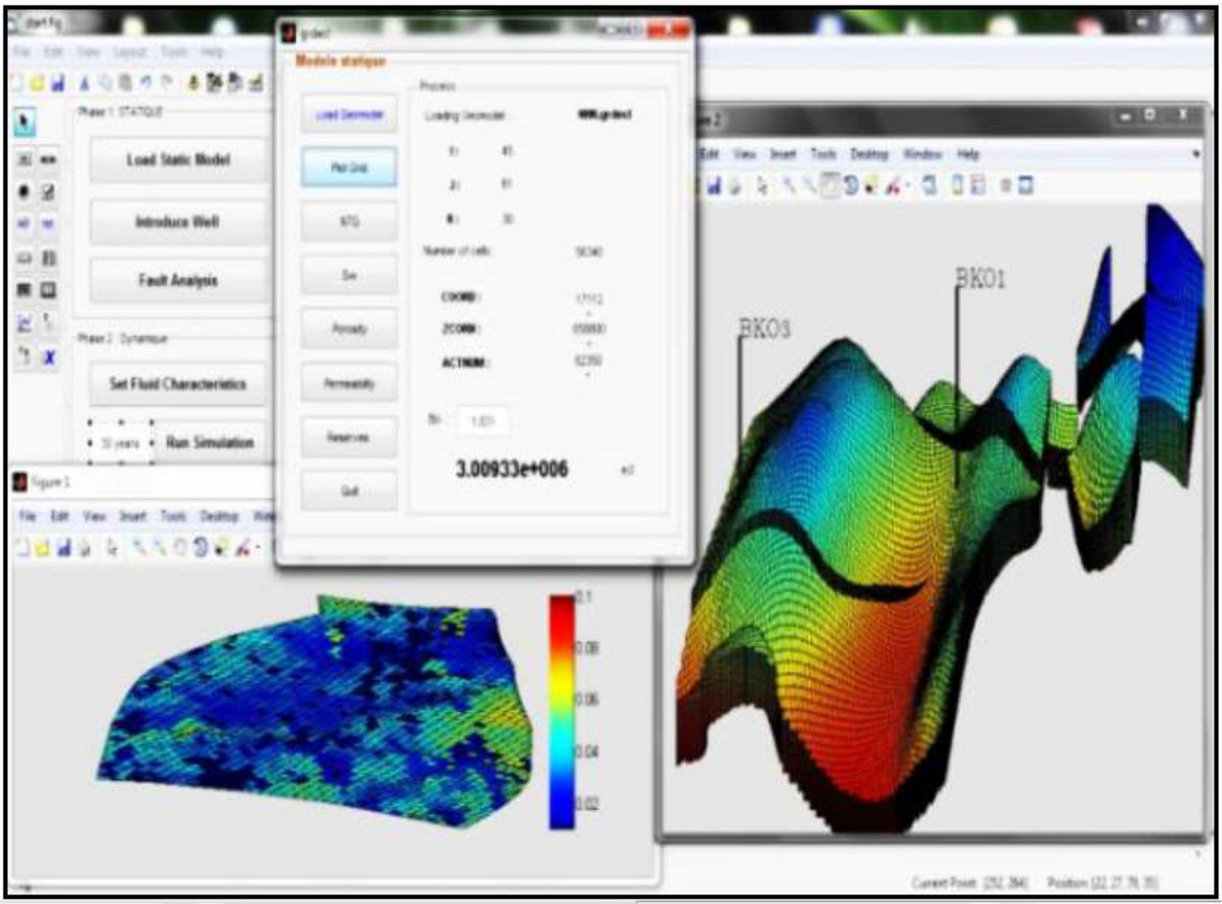

Figure 5: Some graphics of the interface developed using the MRST MATLAB toolbox

The graphical interface is visually composed of several buttons allowing firstly to load the static model, then to fill the geometric grid with the petro-physical properties (porosity, permeability, saturation, etc.). Figure 6 briefly describes an overview of the GUI.

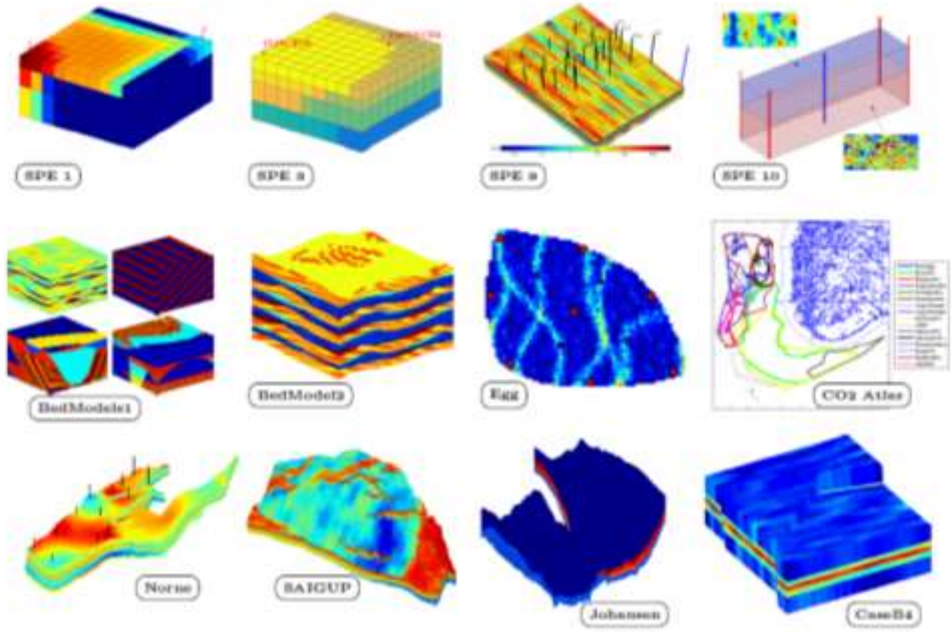

Figure 6: GUI overview.

V. RESULTS AND INTERPRETATIONS

After the software manipulation, we obtained the following results:

V.1. Horizontal Permeability

Based on the subsurface geological model made available to us and the initial parameters determined, a 3D permeability model with dimensions (22.5 x 24.3 x 5 km) and a smaller model for the reservoir in the targeted stratigraphic level where been developed.

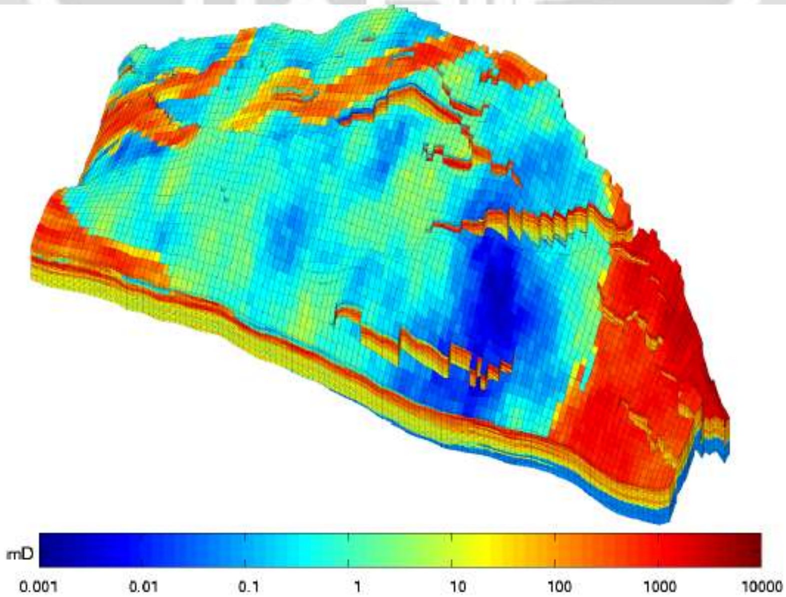

Figure 7: Horizontal permeability

The example presented shows that careful research and interpretation can determine representative initial parameters for compiling digital geothermal models. The results show the feasibility of reliable prognostics using appropriate models calibrated on permeability (Figure 7).

V.2. Vertical Permeability

Effective porosities are the main parameters governing thermal advection since they influence the effective groundwater velocity.

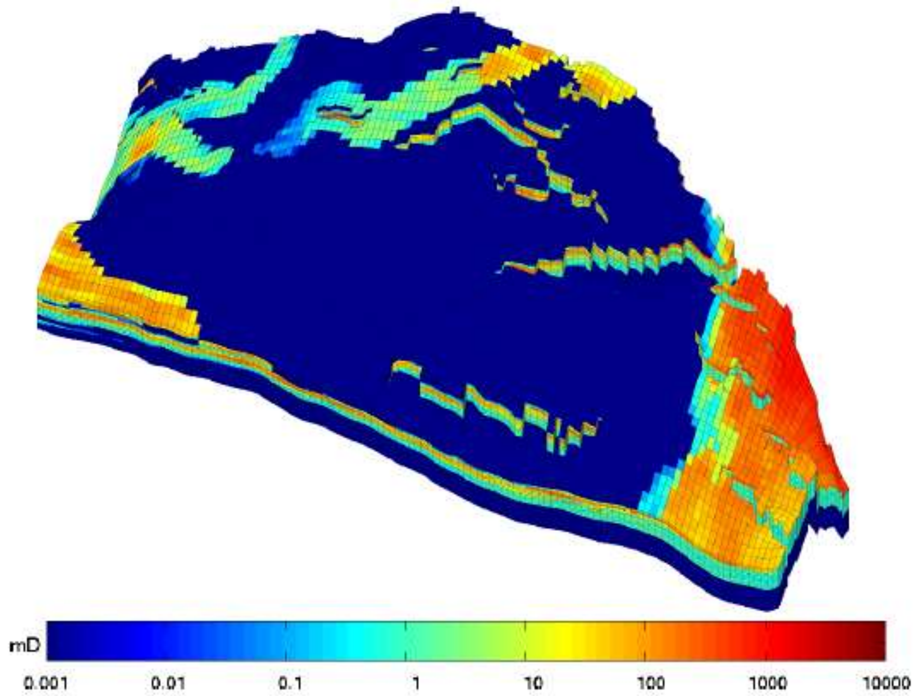

Figure 8: vertical permeability

The longitudinal and transverse thermal dispersivities govern the dispersivity. These longitudinal (Figure 7) and transverse (Figure 8) thermomechanical dispersivity coefficients are very sensitive to scale effects like the mechanical dispersivity coefficients for the transfer of solutes.

V.3. Hydro-thermal Convection Through the Sediment

From these results, we can proceed to the dynamic simulation of the reservoir, since from a practical point of view, the latter contains fewer cells, which subsequently allows us to simulate the dynamic model more quickly via MRST.

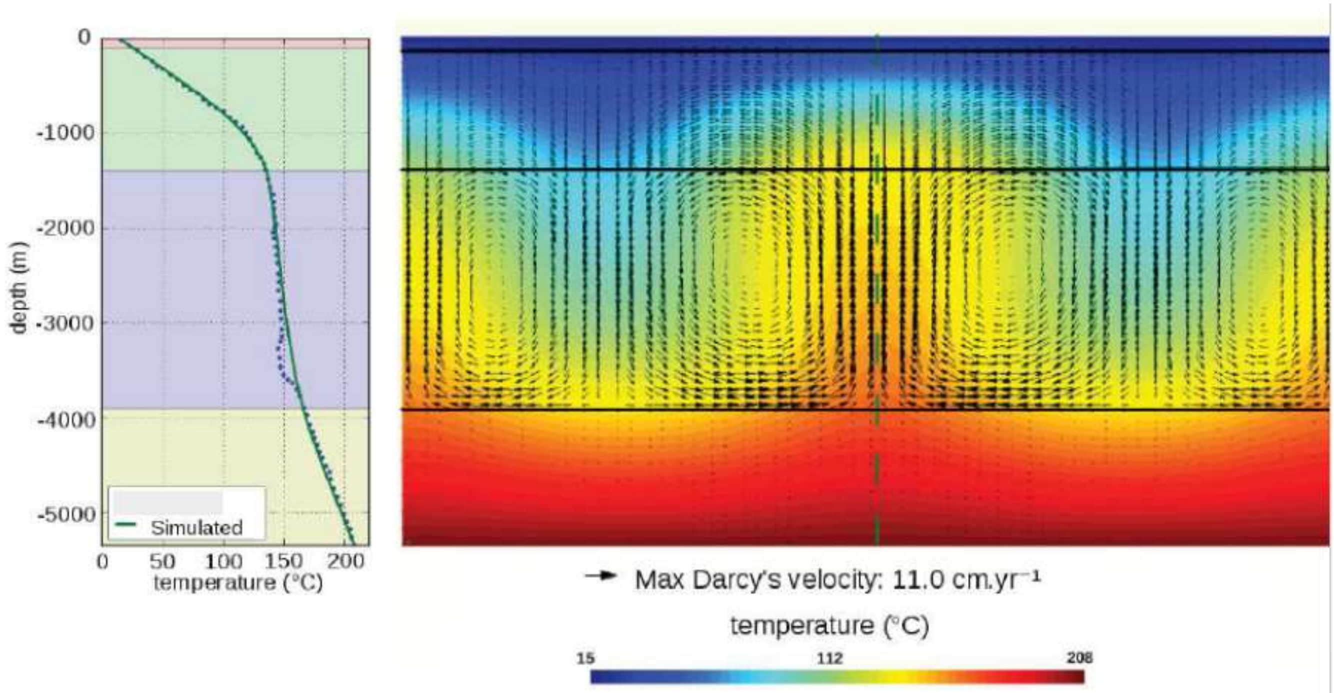

Figure 9: hydro-thermal convection through the sediment

The temperature field is the subject of a polynomial interpolation whose number of terms is equal to the number of nodes in our element (Discretization of the reservoir). The constitutive equation system, involving the pressure and temperature field, is transformed into a discretized system. In the reservoir there is hydrothermalism composed of complex fault networks; the fluid movement associated with heat transfer forms hydrothermal circulation (Figure 9).

VI. DISCUSSION

Thanks to the model obtained, the presence of lateral variations in temperatures at depth could suggest the presence of groundwater. In porous rocks, pore connectivity is important for fluid flow. Therefore, it is necessary to determine the petrophysical parameters like porosity and permeability of rocks. The empty spaces filled with water at depth mean that surface water bodies can circulate and descend into the groundwater from discontinuities such as faults. These interpretations suggest the presence of aquiferous rocks.
The basement modeling is carried out by the MATLAB environment developed by the MRST toolbox.
Taking into account the geothermal gradient of the order of 3°C/km, the interpretation and modeling using the different equations showed the possibility of the existence of geothermal reservoirs characterized by temperature variations ranging from 1300°C to 1700°C corresponding at depths between 1300m and 3800m (figure 9).
This figure 9 visibly shows the hydrothermal convection in the reservoir, suggesting a certain permeability of the layers at depth. It is universally accepted that this convection is characteristic of the lower crust and upper mantle.

VII. CONCLUSION

The available reservoir engineering data makes it possible to satisfactorily characterize the fluid and reservoir of the deposit and to generate the data necessary for the dynamic simulation (Data Initialization). This consisted of constructing a geothermal properties model consistent with the geology and constrained by all available quantitative data.
A good characterization of a reservoir is an essential preliminary step to the optimization of exploitation planning with which enormous economic issues are associated. In the case of conventional geothermal

reservoirs, throughout the life of the reservoir, this model evolves and makes it possible, for example, to estimate the quantity of steam that will be produced or to plan the location of new production wells.

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