# Improving prospectivity by numerical modeling of hydrothermal processes

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***Abstract* — The formation of "hydrothermal resources", a term including mineral and geothermal resources, is the result of thermal, hydraulic, mechanical and chemical processes. Accounting for all of them (THMC modeling) is not an easy task since a large number of variables are unknown. However, when only hydraulic and thermal processes are selected, numerical tools such as the "Rock Alteration Index" can be used to predict locations of the most probable mineralized zones. As an example, 3D numerical models of the Tighza pluton (Morocco) demonstrate that computed mineralized zones correspond to those found in the field. Using geological, petrophysical data and measured temperatures, numerical simulation of the Soultz-sous-Forêts geothermal system (France) helped to understand how fluid circulation in the shallow crust is controlled. Besides reproducing temperature profiles, the obtained numerical models were also used to predict the depth and the temperature of a previously suspected anomaly (Rittershoffen area). It turned out that this anomaly (160°C at a depth of 2500m) was confirmed at the same time by temperature measurements in a borehole. Numerical modeling of hydrothermal processes should thus be considered as a predictive tool in exploration strategies.**

## I. Introduction

Hydrothermal ore deposits and geothermal systems obey to identical physical processes: in both cases, crustal fluids circulate through permeable zones of the Earth's crust and exchange heat and mass with the host rocks. When sufficiently hot, deep fluids can reach shallow depths, creating geothermal anomalies that can be exploited. After having exchanged mass (metals) with the host rocks, hot fluids can be efficiently cooled within structural traps and finally form ore deposits in tens to hundreds of thousand years.

While geothermal systems correspond to present-day active hydrothermal reservoirs, mineralized bodies testify of a hydrothermal activity in the past. For present-day active geothermal systems, a number of geophysical tools help to understand how crustal fluids circulate and where interesting geothermal anomalies could be located [1-2]. This is not the case for ore deposits formed millions years ago by a today extinct hydrothermal system. To understand how hydrothermal ore deposits were emplaced, numerical simulation of physical processes - constrained by geological data and petrophysical properties – can be helpful. In addition to the "simulation character" of numerical modeling, one may also use numerical results to "predict" the highest probable zones of mineralization. This work aims at convincing geoscientists that numerical modeling of hydrothermal processes should not be discarded when exploration methods are examined.

## II. Coupled equations

Fluid circulation in the permeable zones of the Earth's crust can be driven by pressure gradients and/or by buoyancy, as illustrated by Darcy law, which includes these two terms in the fluid velocity $\vec{u}$ :

$$\vec{u} = -\frac{k}{\mu}(\vec{\nabla}p - \rho_L \vec{g}) \tag{1}$$

where $k$ is permeability (m²), $\mu$ is the fluid dynamic viscosity (Pa.s), $p$ is pressure, $\rho_L$ the fluid density (kg.m$^{-3}$) and $\vec{g}$ is acceleration of gravity (m.s$^{-2}$). In presence of topography, the lateral pressure gradient imposes a "topography-driven" flow. Fluid density being temperature-dependent, one may also observe thermal convection if the required physical conditions are present. In that case, fluid flow is "density-driven". To account for heat transfer between the circulating fluid and the host rocks, Darcy law has to be coupled with the heat equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla\left(\lambda \cdot \vec{\nabla}T\right) - \rho_L C_L \vec{u} \cdot \vec{\nabla}T \tag{2}$$

where $\rho$ (kg.m$^{-3}$) is rock density, $C_p$ (J.kg$^{-1}$.K$^{-1}$) is the heat capacity of the saturated medium, T (K) is temperature, t (s) is time and $\lambda$ (W.m$^{-1}$.K$^{-1}$) is thermal conductivity of the saturated medium, defined by thermal conductivity $\lambda_S$ of the solid rock, and thermal conductivity of the fluid $\lambda_L$ (see [3] for the specific role of porosity in the saturated medium properties). The advective term (second term on the right) includes the heat capacity of the fluid ($C_L$) and the same fluid velocity as defined in (1). Because fluid is supposed incompressible, the mass conservation writes:

$$\nabla \cdot \vec{u} = 0 \tag{3}$$

By coupling these three equations, many hydrothermal systems can be numerically studied, as soon as boundary and initial conditions are well constrained, and for sufficiently known petrophysical properties. The coupling applies not only with the fluid velocity which appears in the three equations, but also with temperature which controls both fluid density and viscosity.

Among the numerous physical properties which have to be assigned a value, permeability corresponds to the most critical unknown parameter. However, recent studies [4] emphasize that permeability values – which have to be considered as time-dependent – may be much higher than they were supposed in the past decades. One first consequence is that fluid flow in the crust may be much more present than usually thought. Another consequence is that thermal convection may be easily triggered.

## III. MINERALIZED ZONES

One way to illustrate potential zones for mineralization consists in looking at zones where the cooling rate is important. This cooling rate was called “rate of mineralization” by Phillips [5] and corresponds to negative values of the “Rock Alteration Index”, defined by:

$$RAI = \vec{u} \cdot \nabla T \tag{4}$$

For negative values of the RAI, the fluid moves toward low temperatures, and if the fluid velocity is greater than $10^{-10}$ m.s$^{-1}$, then potential zones of mineralization can be delineated (see [6] for details). Several other teams [7-9] used different criteria, but it turned out that the RAI tool was quite useful to better understand the formation of hydrothermal ore deposits. Figure 1 shows the reproduction of mineralized zones, 30 kyrs after the beginning of reservoir cooling. Other similar impressive results with 2d numerical models of plutonic bodies in presence or not of apexes or faults were also obtained [6].

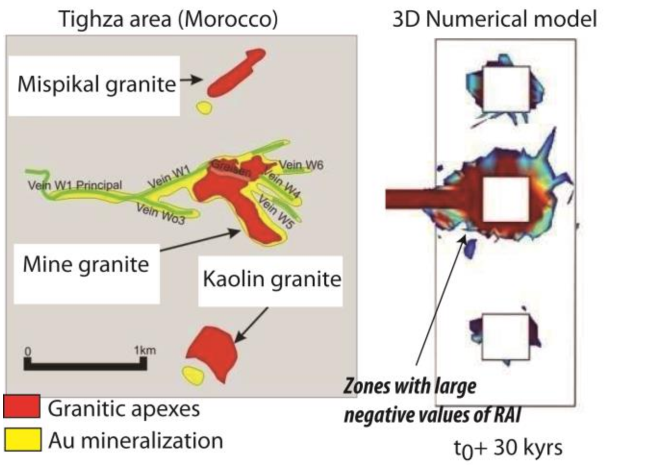


*Figure 1 – Case of an Intrusion-Related Gold Deposit (Tighza district, Morocco), where three apexes (squares on the right) are connected at depth to a large batholith (rectangle). Comparison between Au-mineralization (left, yellow areas) and zones where the computed RAI shows large negative values (red zones on the right). After [10] and [11].*

## IV. ZONES OF UPWELLINGS

Crustal fluids can circulate through permeable zones. Permeability has been studied by numerous teams and it is widely agreed that it is a depth-dependent parameter, with high values in the first kilometers [e.g. 12]. Consequently, cold meteoric fluids can circulate more easily than deep and hot fluids located in a less permeable part of the crust. In other words, cooling of the crust from above, by meteoric fluids, is probably more efficient than warming from below by metamorphic or magmatic fluids. While the cooling effect could be pervasive in the upper kilometers, hot upwelling fluids might be focused in fractured zones or in anomalously permeable aquifers. When permeability is depth-dependent, it has been shown that convective wavelength increases, the number of upwellings decreases, and the size of the upwelling is also reduced [3].

In the Upper Rhine Graben (France and Germany), the number of hot upwellings forming interesting geothermal anomalies (Soultz-sous-Forêts, Rittershoffen, Laudau, Insheim, etc) is limited. The 3D structure of hydrothermal convection within the permeable granitic basement is probably controlled by permeability structure and by topography of the basement-sediment interface [3]. Figure 2 illustrates a 2D numerical simulation of what could happen in the Soultz-sous-Forêts area.

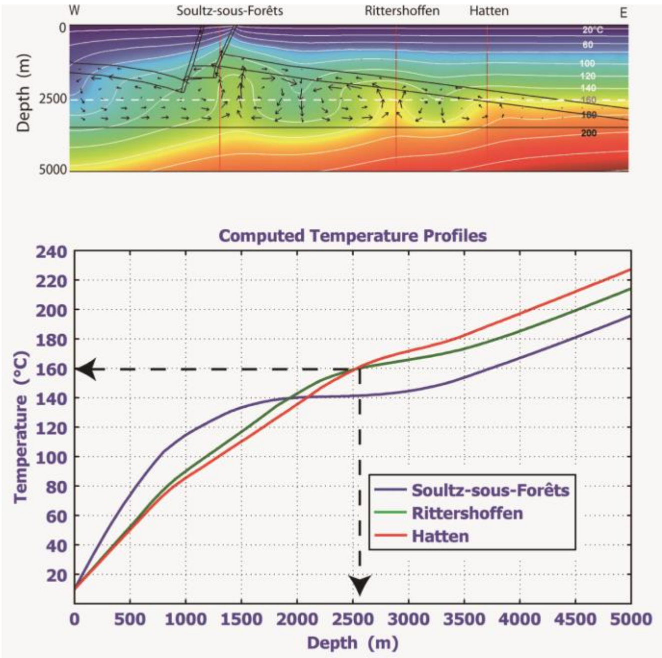


*Figure 2 – Numerical simulation of hydrothermal convection in the Upper Rhine Graben. The 2D west-east section crosses the Soultz-sous-Forêts thermal anomaly. Permeability values are chosen to reproduce the measured temperature profile. For the two other anomalies (Rittershoffen and Hatten), higher temperatures at a depth of 2000-2500m are predicted.*

The numerical temperature profile reproduces temperature measurements within the GPK2 borehole. In addition, a second thermal anomaly 7 km eastwards is predicted. This latter indicates higher temperatures (160°C) at shallower depth (2500m) than at Soultz-sous-Forêts. Four years ago, the GRT1 borehole at Rittershoffen (7 km west of Soultz-sous-Forêts) confirmed the existence of a thermal anomaly of 160°C at a depth of 2500m [13]. According to the model, another identical positive thermal anomaly would be present at Hatten, 3 km east of Rittershoffen.

## V. CONCLUSION

Numerical modeling of hydrothermal processes can be used as a predictive tool, as soon as petrophysical properties are available. Once a given numerical model is able to reproduce field and measured data (by, e.g., adapting permeability values), it can be used to predict locations of hidden or not suspected targets. Additional numerical tools such as the RAI , or other modified versions of this index, can help to delineate at a given time the most probable mineralized zones.

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