Fluid-rock interaction in the context of underground hydrogen storage

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Given its promising prospects from an energy, political, and environmental standpoint, hydrogen is currently regarded as one of the most promising energy vectors for enabling a successful ecological transition. However, this success depends on the development of large-scale storage technologies capable of balancing mismatches between supply and demand. Among the most suitable storage methods are salt caverns and natural porous media, such as depleted hydrocarbon reservoirs or aquifers [fig 1]. In both configurations, mass exchanges occur between the stored hydrogen and the surrounding environment.

(a) (b)

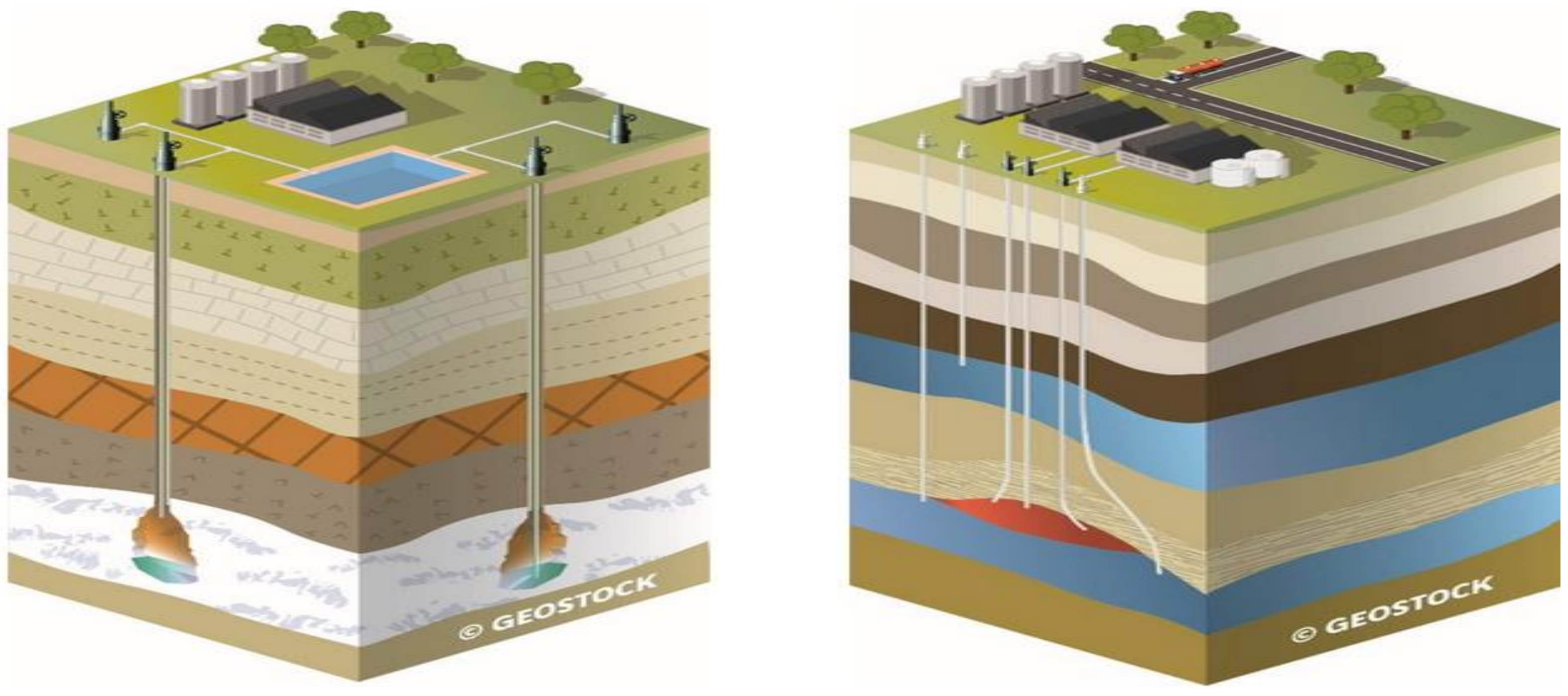

Figure 1: Storage in salt caverns (a), storage in aquifers or depleted hydrocarbon reservoirs (b) (source : Geostock).

Problematic

Mass exchanges manifest as gas dissolution in the aqueous solution and its humidification. The specific properties of hydrogen raise concerns about the potential for gas migration into the salt formation or the substrate of the porous reservoir, especially in the event of damage caused by storage operations. Chemical reactivity may lead to the release of other gases such as hydrogen sulfide (H_2S) [fig 2]. The presence of such gas mixtures, especially under high-pressure and high-temperature conditions, introduces further uncertainties, as their behavior is not yet well understood.

(a)

(b)

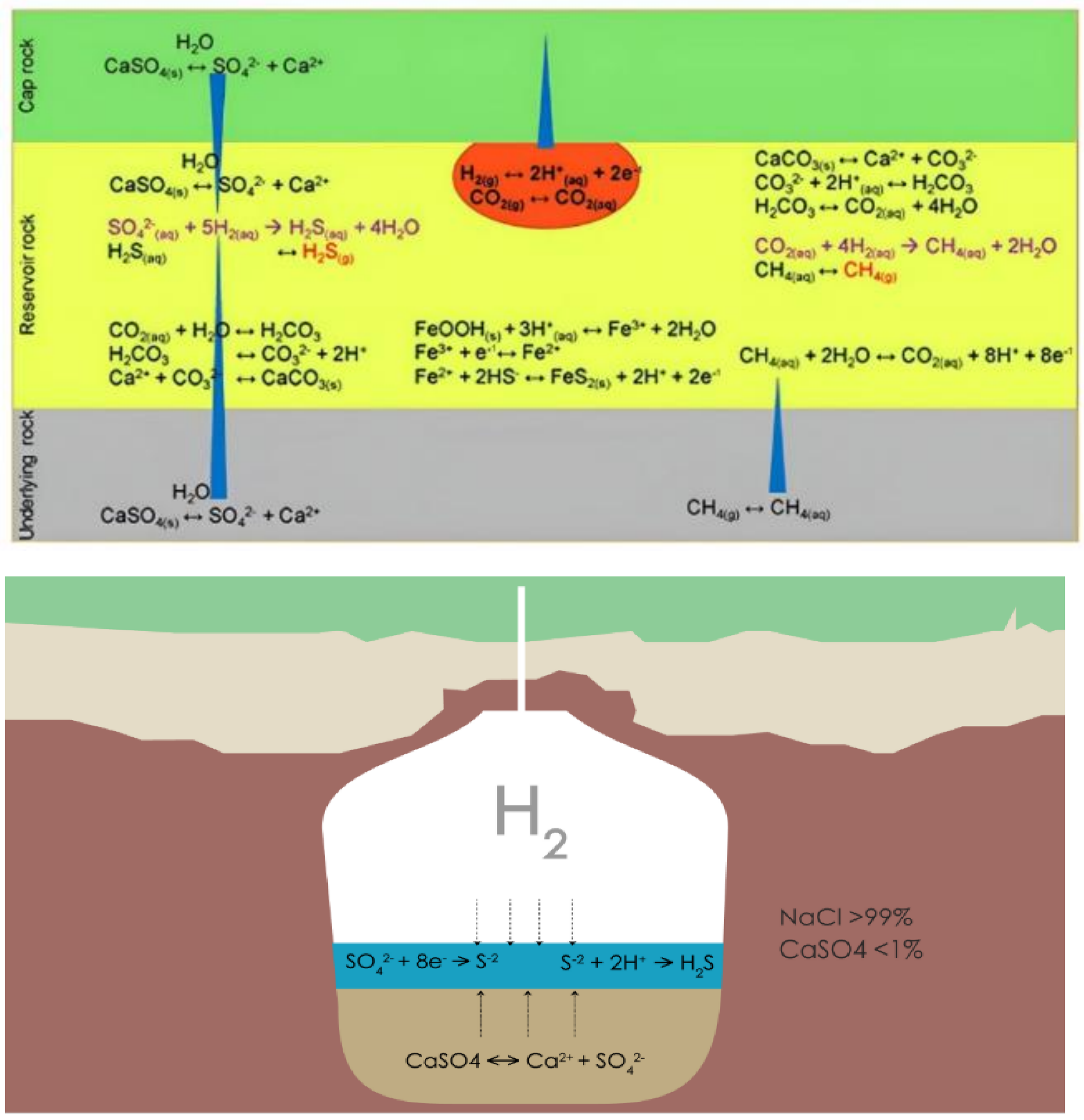

Figure 2: Potential geochemical reactions in a depleted gas reservoir (a) and salt cavern (b) used for hydrogen storage (Duartey K.O. et al., 2023) (Laban, Maarten Pieter,2020)

Key Interactions in hydrogen underground storage

The following interactions will be investigated between hydrogen and its storage environment in a salt cavern or natural porous media:

- Hydrogen dissolution in the aqueous solution present in the storage reservoir.
- Humidification of hydrogen through contact with the aqueous phase.
- Permeation of hydrogen into the salt or rock matrix of the storage formation.
- Chemical reactions potentially leading to the formation of secondary gases such as hydrogen sulfide (H_2S), resulting in a hydrogen-rich gas mixture with complex thermodynamic behavior.

Methodology

The methodology begins with exploratory modeling based on a simplified analytical model of the equilibria and kinetics of dissolution, diffusion, and sulfate-reductive reactions, in order to identify the most influential parameters. On this basis, targeted experimental tests are designed to measure these parameters (H_2 solubility in synthetic brines, gas humidification, sulfate-reduction kinetics in the presence of mineral catalysts), all with real-time monitoring (pressure, temperature, chromatographic gas analysis, and pH) and repeated runs to ensure data robustness

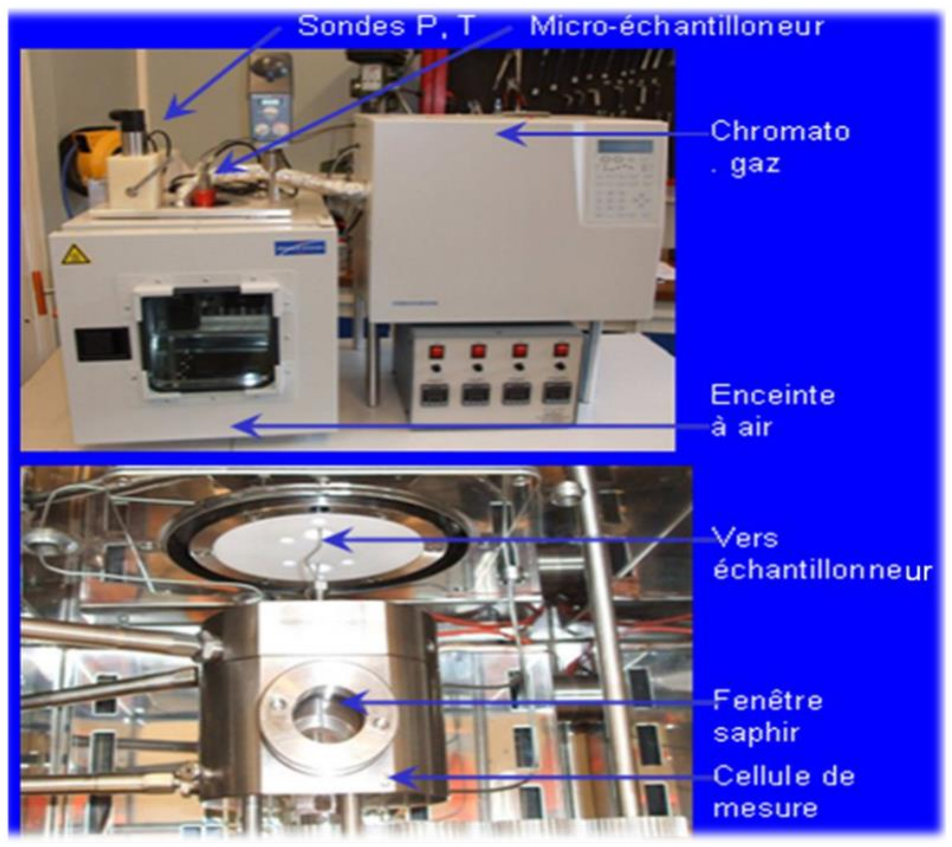

Figure 3: Equilibrium dissolution cell for a gas in an aqueous solution

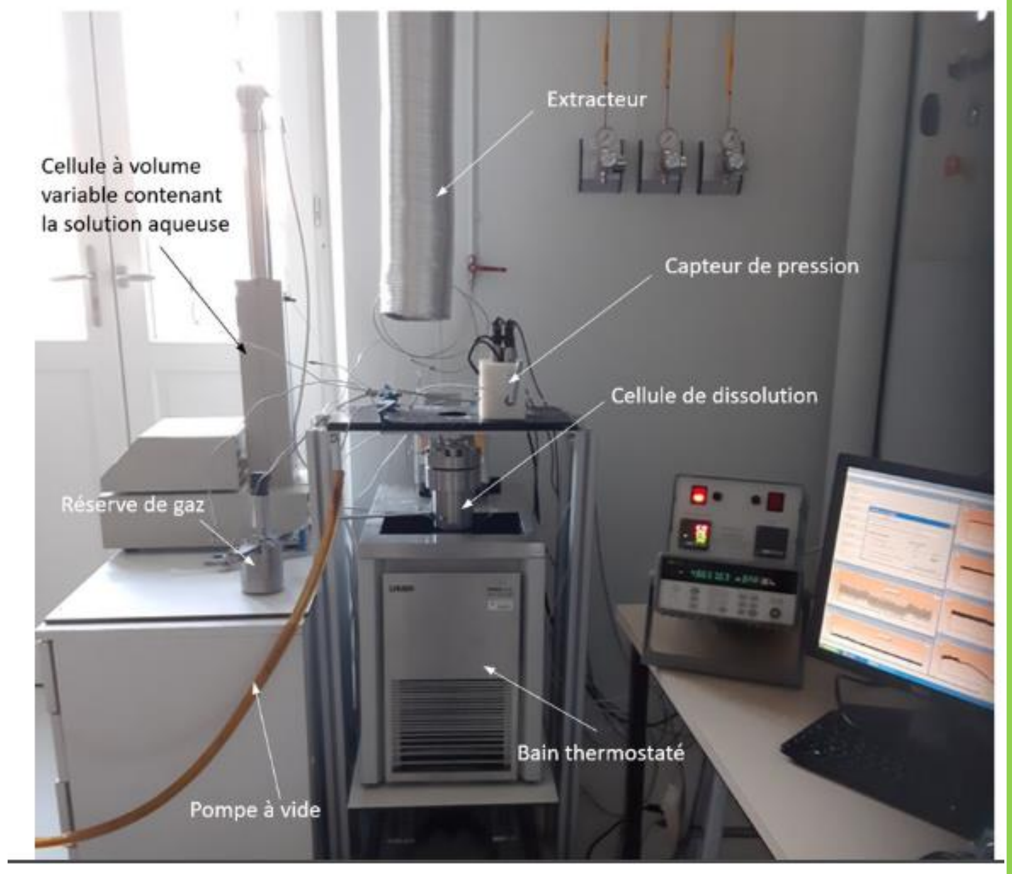

Figure 4: Experimental setup for studying the gas dissolution kinetics in an aqueous solution

Figures 3 4 & 5 show some illustrations providing an overview of the main experimental setups that will be used.

The initial results then feed into refined modeling, where the rheological laws (solubility, diffusion, permeation, kinetic constants) are adjusted.

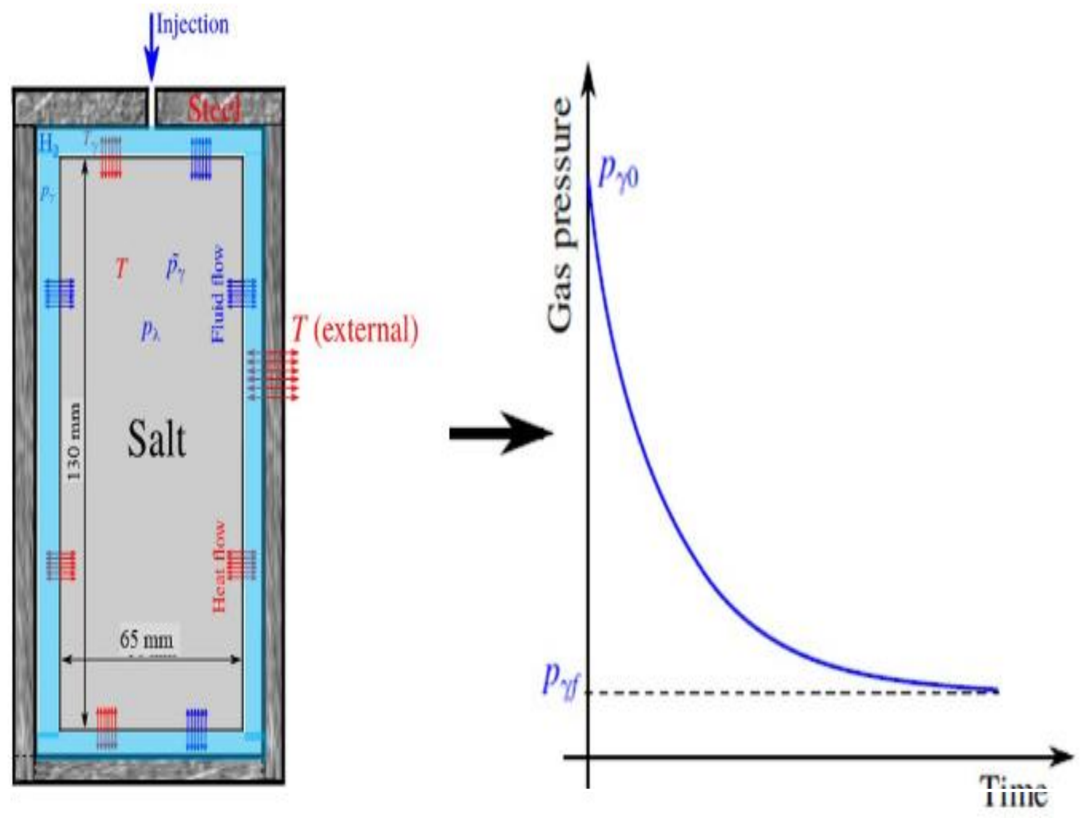

Figure 5: Gas permeation test in an intact or damaged rock sample

Finally, these calibrated laws are implemented in the DEMETHER code (salt-cavern thermodynamics) [fig 7] and the PHIMEF code (2D/3D thermo-hydro-mechanical simulations) [fig 8], then validated by comparing the predictions (gas composition, cavern deformations) with in situ data, in an iterative cycle aimed at reducing uncertainty and maximizing predictive reliability for underground hydrogen storage.

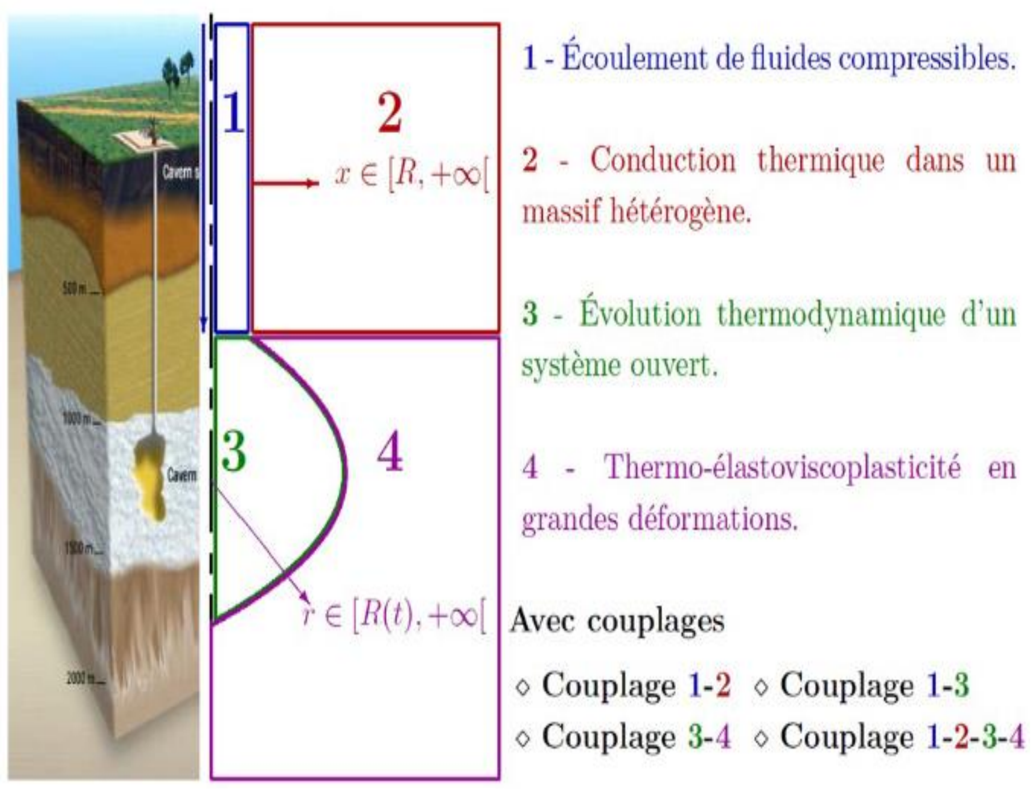

Figure 7: DEMETHER software and coupled multiphysics phenomena

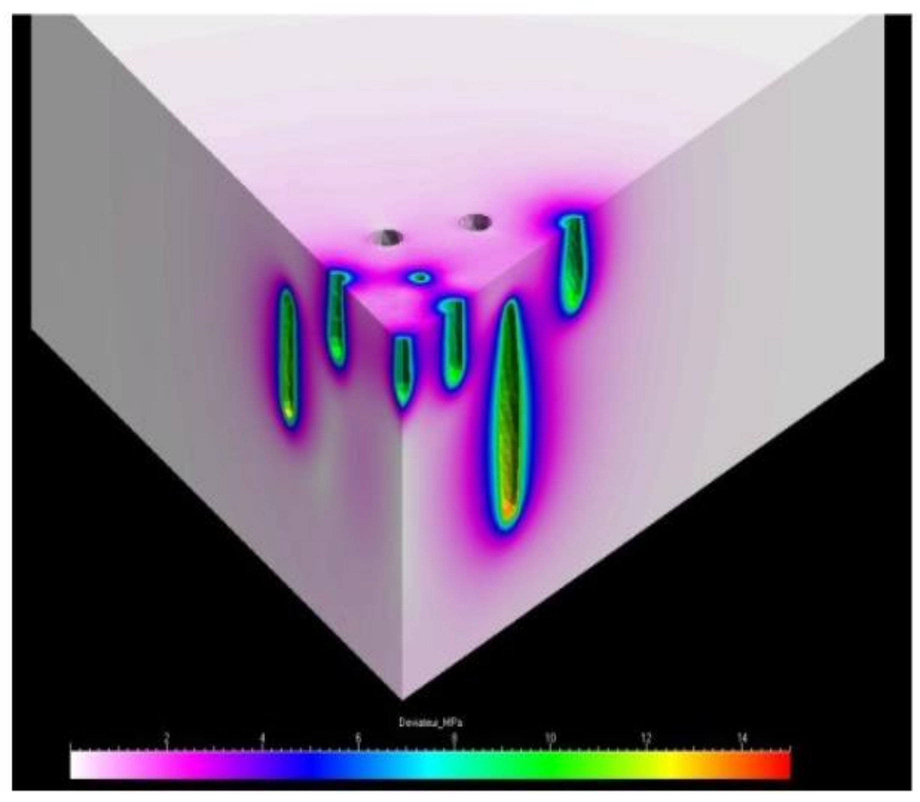

Figure 8 : Simulation with PHIMEF of Natural Gas Storage in Salt Caverns