Thermo-Hydro-Mechanical Impacts of CO_2 storage: A Synthetic Study on Sleipner CO_2 Injection Site, Norwegian North Sea

Introduction

The effects of thermo-hydro-mechanical coupling have been a concern for the integrity of the caprock during CO_2 injection operations. The previous studies suggest that if a strong contrast in thermal conductivity exists between a caprock and the reservoir unit, thermal shock can propagate faster than pore pressure diffusion (Bjørnarå et al. 2021). In this situation, the thermal contraction can lead to fracturing of the caprock and potential leakage. The caprock-reservoir interface may deform plastically due to thermal stress. The thermal-induced stresses are driven by variation of both hydraulic and thermophysical parameters of both the cap and reservoir rocks. The additional shear stress is caused by the pore pressure changes and depends on the Poisson ratio of the caprock.

On the Norwegian Continental Shelf (NCS), the main caprock units are Late Jurassic shales that may exhibit both brittle and ductile behavior under stress loading, depending on geological conditions and mineral composition. The total organic carbon (TOC) content can improve caprock properties by filling the pores and making the shale more ductile under mechanical loading. At the same time, the increased temperature may lead to maturation, the expulsion of hydrocarbons, fracturing and an increase in permeability. Cooling the caprock can shrink the pores, reducing permeability, but may also lead to embrittlement of the shale and facilitate fracturing with excessive cooling. However, there is a lack of observational constraints on the thermomechanical processes occurring in the subsurface. The existing mechanical models are predominantly simplified and assume laterally uniform properties, which may not be representative of in-situ conditions. Drilling into the CO_2 plume is associated with risks, and there are only a few cases where the injection is accompanied by downhole monitoring. There is also a limitation in reproducing the in-situ conditions in the laboratory; however, some research has been done towards the assessment of both thermal and mechanical responses of shales (Bjørnarå et al. 2021).

Among the remaining questions is how mechanical heterogeneity and thermo-hydro-mechanical coupling may assist the vertical migration of the plume. The problem can be challenging due to the lack of physical constraints on the in-situ condition mentioned above. On the other hand, resolving multiphysics coupling requires robust numerical algorithms and high-performance computing (Raess et al. 2019; Kiss et al. 2024). Two CCS projects (Sleipner and Snøhvit) on the NCS are monitored using high-resolution time-lapse 3D seismic data. These data have been used to track both upward migration of injected cold CO_2 and the sideways propagation of the plume along the caprock-reservoir interface. The seismic reflection amplitude anomalies have been linked to gas saturation of the pore fluid and verified through rock-physics-based modelling of the acoustic impedance (Chadwick et al. 2019).

In this study, we performed coupled thermo-hydro-mechanical simulations of CO_2 injection using industry-standard software. The simulation results are used for synthetic seismic modelling to investigate the seismic expression of competing thermal and saturation effects on the mechanical properties during CCS operations. The modelling workflow shows potential for history-matching studies using time-lapse seismic data in similar CO_2 storage operations.

Method

To analyze the complex interactions of thermo-hydro-mechanical (THM) processes on subsurface CO_2 injection, we define a Sleipner-inspired 3D model for regional-scale simulations. A simple workflow utilized in this study is shown in Figure 1a. The model grid covers a 3D volume with a lateral extent of 0.1 km by 0.2 km and extends from a depth of 800 m to about 1000 m (Figure 1b). As initial conditions, we use no flow boundaries for Darcy fluxes and zero displacement for mechanics. A constant lithostatic stress was set at the lower boundary of the model, and temperature-insulated boundary conditions were implemented. A variable water chemistry was assumed, and dissolution of CO_2 in water was implemented using Henry's law. The model incorporates two primary rock types: high-permeability reservoir facies representing Utsira sandstone and low-permeability facies representing Nordland shale caprock. The material properties and model parameters are partially obtained from an open dataset (Equinor, 2018) or inferred from correlation with porosity. The model simulates the injection of cold CO_2 (10°C) into the saline aquifer at reservoir temperature 40°C and 100°C at an injection rate of 1 Mt/yr over five years. The temperature scenarios in this study are hypothetical and do not reflect actual Sleipner conditions, where CO_2 arrives at approximately 48.1 °C (Alnes et al. 2011). The use of a lower injection temperature (10 °C) is intended to investigate thermal effects under controlled, non-representative conditions. The simulations were performed using tNavigator2025 (v25.4), which solves the fully coupled equations of mass, momentum, and energy balance, accounting for two-phase fluid flow (CO_2 and brine), solid rock deformation, and non-isothermal effects.

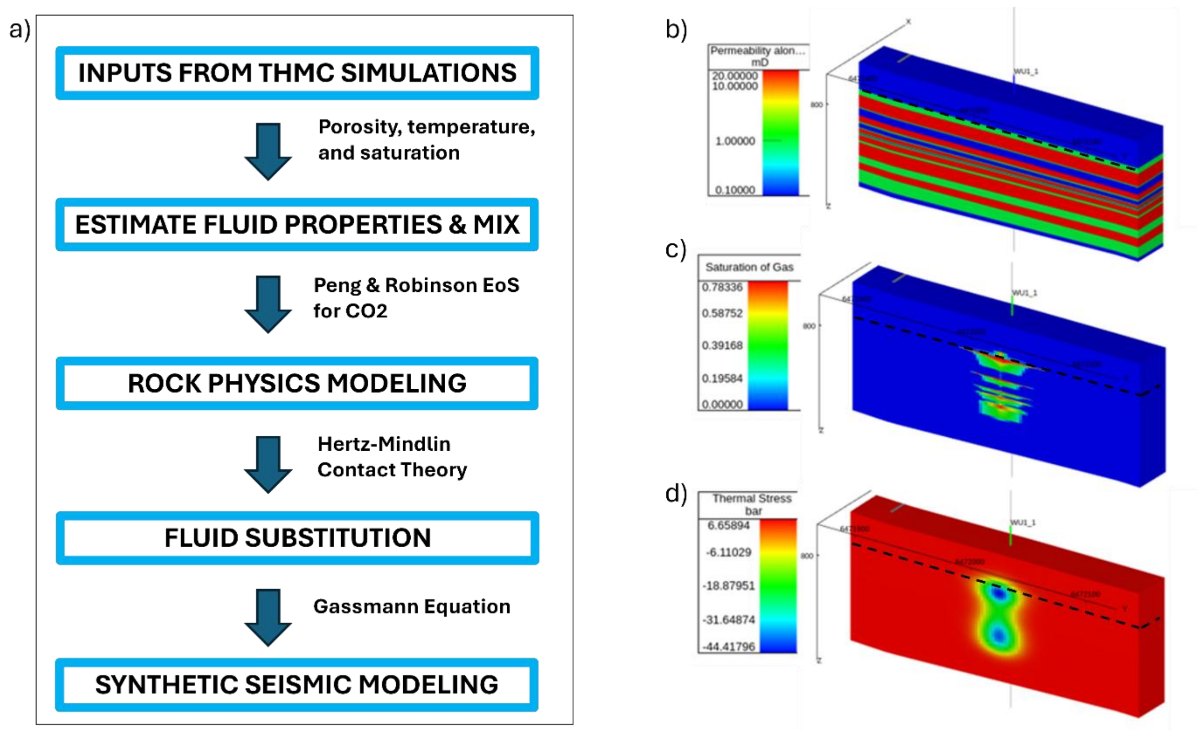

Figure 1 *a) Workflow for coupled THM simulation and seismic modelling. b) Model geometry with permeability. c) Gas saturation after 5 years of injection (reservoir temperature 100 °C. d) Thermal stress due to cold* CO_2 *injection. The dashed line indicates the reservoir-caprock interface.*

After the injection simulation, we developed a rock-physics-based workflow to estimate the effects of saturation, pressure, and temperature on seismic data. We use porosity, saturation, temperature and pressure outputs from simulation results as inputs to our rock physics forward modelling. First, we use the Hertz-Mindlin theory (Mindlin 1949) to estimate the bulk and shear moduli of the dry Utsira sand in the Sleipner field. For the fluid properties, we use Batzle and Wang (1992) for the brine phase and the Peng and Robinson equation of state (1976) for CO_2 properties inside the porous medium. We then used Gassmann fluid substitution to see the effect of gas saturation on elastic and seismic properties. After estimating the acoustic impedance of the reservoir and cap rocks using rock physics theory across different simulation scenarios, we compute normal-incidence reflection coefficients. Following that, the reflection coefficient matrix is convolved with a 57-Hz zero-phase Ricker wavelet representative of the real seismic data at the Sleipner CO_2 storage site.

Results and discussion

We present results for five years of CO_2 injection. Migration of CO_2 along the thin shale layers within the reservoir is significantly faster than the advancement of the thermal diffusion front. The temperature perturbation is most pronounced near the injection well. Over the five years, the thermal anomaly gradually expands and begins to influence the shale unit (Figures 1c & d). Assuming thermophysical parameters characteristic of Sleipner, the thermal anomaly decreases from approximately 25°C to 5°C during the injection period. The resulting contraction stresses induced by cooling range between 2 and 4 MPa (Figure 1d). The corresponding shear stresses do not exceed the Griffith yield stress in our simulations.

The calculated Vp/Vs ratios, based on mechanical properties and fluid saturations at reservoir pressure–temperature conditions, follow the expected mixture line for a gas–brine-saturated quartz sand model, providing verification of the chosen rock-physics approach. After five years of injection, the resulting acoustic impedances are approximately 50% lower than in the base synthetic survey prior to injection. The acoustic impedance anomalies correlate with the saturation front (Figure 2). The thermal plume further influences the acoustic impedances and the seismic response in the central region near the injection well. The estimated magnitude of the time-lapse seismic anomaly due to thermal effects is 5–10%, depending on the pressure–temperature conditions.

The strongest influence on seismic waveforms occurs at lower temperatures (approximately 20–50 °C) and pressures of 10–20 MPa, corresponding to the transition of CO_2 from the liquid to supercritical state (Figure 2). This effect may be detectable in high-resolution time-lapse seismic data. However, increased pore pressure due to injection dissipates rapidly in the high-permeability reservoir.

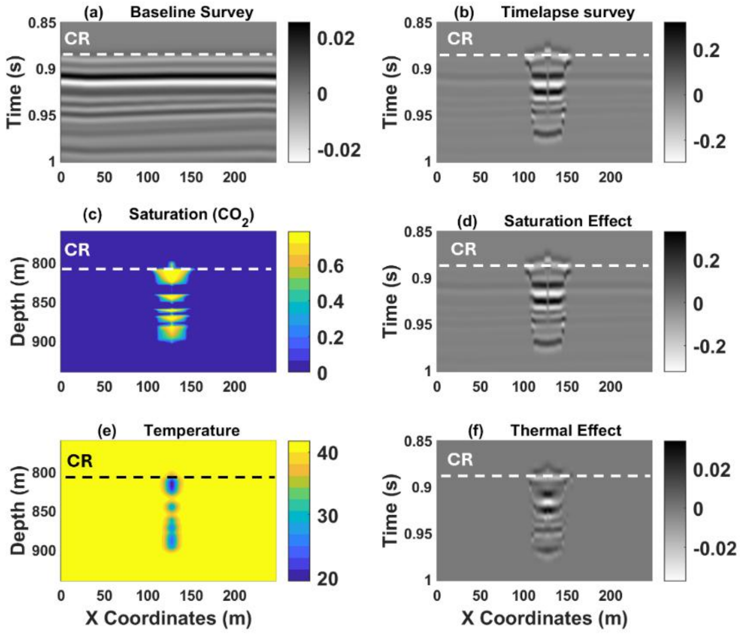

__Figure 2__ a) Synthetic seismogram before injection. b) Synthetic seismogram after injection (reservoir temperature 40^{o}C). c) Saturation from simulation results. d) Saturation effect on seismic. e) Temperature anomaly results from simulation. f) Thermal effect on seismic. The dashed line indicates the reservoir-caprock interface (CR).

Conclusions

We present a workflow for combining thermo-hydro-mechanical (THM) simulations with seismic modelling for the application of CO_2 storage monitoring. We show that a cold CO_2 plume affects normal-incident seismic reflection waveforms mainly through gas saturation, with a smaller effect from cooling. With this contribution, we aim to establish a framework for time-lapse seismic data analysis of the thermo-mechanical state of the subsurface during geological CO_2 storage operations. An in-depth understanding of the balance between thermal and hydro-mechanical effects is crucial for ensuring the safety and efficiency of CO_2 storage projects.

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References

Alnes, H., Eiken, O., Nooner, S., Sasagawa, G., Stenvold, T., Zumberge, M. [2011]. Results from Sleipner gravity monitoring: updated density and temperature distribution of the CO2 plume. *Energy Procedia,* **4**: 5504–5511.

Batzle, M. and Wang, Z. [1992]. Seismic properties of pore fluids. *Geophysics*, **57**(11), 1396–1408.

Bjørnarå, T.I., Park, J. and Marin-Moreno, H.M. [2021]. Geomechanical integrity and non-isothermal effects in CO2 storage. In: *Proceedings of the 15th Greenhouse Gas Control Technologies Conference*, Abu Dhabi, 15–18 March 2021.

Chacín, M.M., Cabrera, A.C., Barandiaran, L., Martinez, E.I., Carol, I., Garolera, D. and Iglesias, J.A. [2025]. Value of Thermal-Hydro-Mechanical Full Coupling in CO2 Geological Storage Projects Under Near-Wellbore Conditions. In: *World CCUS Conference 2025*, **1**. European Association of Geoscientists & Engineers, 1-3.

Chadwick, R. A., Williams, G. A. and Falcon-Suarez, I. [2019]. Forensic mapping of seismic velocity heterogeneity in a CO2 layer at the Sleipner CO2 storage operation, North Sea, using time-lapse seismics. *International Journal of Greenhouse Gas Control*, **90**, 102793.

Equinor [2018]. Northern lights data package for use in external R&D projects, released March 2018.

Kiss, D., Yarushina, V., Kaus, B. and Minakov, A. [2024]. Thermo-Hydromechanical modelling of poro-(visco-) elasto-plastic reservoir processes using GPUs in Julia. *European Geosciences Union General Assembly 2024 (EGU24)*, 16070.

Mindlin, R.D. [1949]. Compliance of Elastic Bodies in Contact. *Journal of Applied Mechanics*, **16**(3), 259–268.

Peng, D.Y. and Robinson, D.B. [1976]. New two-constant equation of state. *Industrial & Engineering Chemistry Fundamentals*, **15**(1), 59–64.

Räss, L., Duretz, T. and Podladchikov, Y. Y. [2019]. Resolving hydromechanical coupling in two and three dimensions: spontaneous channeling of porous fluids owing to decompaction weakening. *Geophysical Journal International*, **218**(3), 1591-1616.

Thompson, N., Andrews, J.S. and Bjørnarå, T.I. [2021]. Assessing Potential Thermo-Mechanical Impacts on Caprock Due to CO2 Injection—A Case Study from Northern Lights CCS. *Energies*, **14** (16), 5054.