Introduction

Carbon capture and storage (CCS) is a critical strategy for mitigating anthropogenic carbon dioxide (CO_2) emissions, contributing to the stabilization of atmospheric greenhouse gas concentrations. Among CCS approaches, geological CO_2 sequestration has emerged as a viable long-term solution, involving the capture of CO_2 from industrial sources, its transportation, and subsequent injection into deep subsurface geological formations for permanent storage.

Several geological formations are suitable for CO_2 sequestration, including deep saline aquifers, depleted hydrocarbon reservoirs, and unmineable coal seams. Among these, saline aquifers offer the largest storage capacity due to their widespread distribution and extensive pore volume. Effective sequestration requires comprehensive geological, hydrogeological, geochemical, and geomechanical characterization of the storage site to assess its suitability and long-term containment potential. The primary focus is on the reservoir and its sealing formations, particularly the caprock, which serves as the main barrier to CO_2 migration. However, an integrated assessment of the overlying strata and caprock is also essential because if CO_2 leaked it would migrate through them.

The Sleipner project, located in the Norwegian North Sea, represents the world's first large-scale CO_2 sequestration initiative in a deep saline aquifer, the Utsira Formation. Since its inception in 1996, Sleipner has served as a global benchmark for CCS research, demonstrating the feasibility of safely storing CO_2 in high-permeability sandstone formations. A defining feature of the project is the extensive use of 4D time-lapse seismic monitoring, which has provided invaluable insights into CO_2 plume dynamics and subsurface behavior. Previous studies have primarily relied on homogeneous reservoir models and discipline-specific workflows, while effective given past technological constraints, often lacked the necessary integration to fully capture reservoir heterogeneity and complex plume migration mechanisms.

This research introduces an integrated workflow that combines advancements in petrophysics, geophysics, geology, geomechanics, geochemistry, and reservoir engineering for optimum and safe CO_2 storage. The objective is to assess how spatial variations in reservoir quality, geochemical interactions, and geomechanical responses influence CO_2 migration and long-term containment. By leveraging 4D seismic data and advanced numerical modeling techniques, this study aims to enhance the accuracy of subsurface models, improve predictive capabilities, and optimize CCS methodologies for long-term storage security and reliability.

Methodology

Sleipner benchmark model is provided by Equinor and available online (CO2datashare, 2019). Available well logs and core data are used to calculate petrophysical and 1D mechanical earth model properties. Seismic pre-injection data is interpreted and used as a basis for the structural model. Unlike previous studies, which focus on modeling the aquifer with homogenous properties and without coupling with geomechanics (Singh et al. 2010), in this study Top-down 3D modeling is conducted to model from seabed to the aquifer. Heterogeneous 3D static properties and 3D geomechanics modeling are conducted, and the geomechanics parameters are calculated from the seabed (Figure 1). A fully coupled fluid flow and geomechanics simulation is performed to inject CO_2 based on historical or existing design.

Four main CO_2 storage mechanisms are modelled, which are structural and stratigraphical trapping where the migration of free or CO_2 mobile in response to its buoyancy and/or pressure gradients within the reservoir is prevented by the caprock. Secondly, residual saturation trapping as a function of capillary forces and adsorption onto the surfaces of mineral grains within the rock matrix immobilize a proportion of the injected CO_2 along its migration path. Then, dissolution or solubility trapping where injected CO_2 dissolves and becomes trapped within the formation water. Lastly, geochemical trapping in which the dissolved CO_2 reacts with the minerals making up the rock matrix of the reservoir.

An integrated workflow is then constructed by incorporating uncertainty in geology, geomechanics, and reservoir rock and fluid properties. Then, the simulated CO_2 storage and CO_2 plume distribution are validated based on 4D seismic post injection data via assisted history matching from the integrated uncertainty workflow. Once the model is validated, the forecasting is performed to continue the base case CO_2 injection operation and create new CO_2 injection scenarios while observing rock properties changes, stress and roof deformation during the injection period.

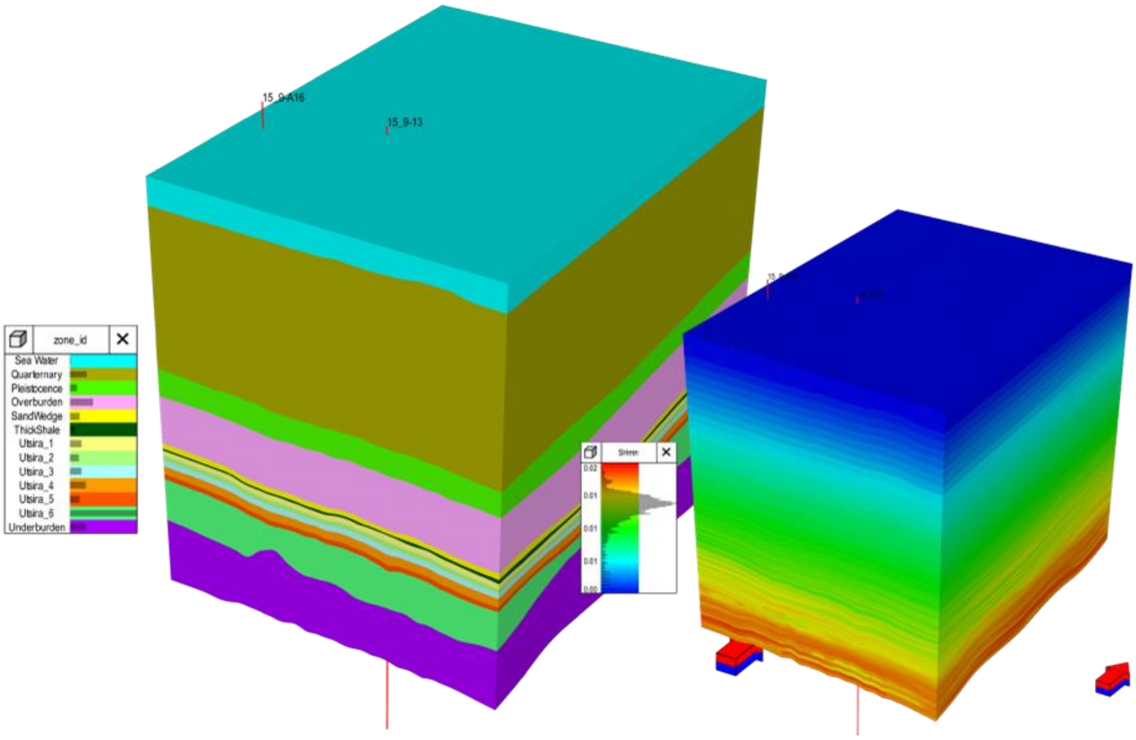

Figure 1 *New 3D model from seabed to underburden (left) and stress (right) of the Utsira Formation.*

Conclusions

The results of this innovative workflow allow the studies to incorporate uncertainties from geology, geomechanics, fluid and dynamic rock properties to address the subsurface uncertainties in saline aquifer CO_2 sequestration. Top-down 3D model from seabed provides a comprehensive formation integrity evaluation in which deformation at seabed can be directly estimated and CO_2 leakage to surface can be observed. Simulation study indicates that structural and solubility trapping are the predominant mechanisms governing CO_2 storage in the Utsira Formation, however understanding water-rock-CO_2 interactions is essential for assessing security, reservoir integrity, and potential geochemical reactions over time.

Acknowledgements

The authors would like to thank Rock Flow Dynamics for supporting this study. Thanks to CO_2 DataShare (https://co2datashare.org/) for providing the online platform of the CO_2 Storage database.

References

CO2datashare. (2019). https://co2datashare.org/dataset/sleipner-2019-benchmark-model

Singh, V. P., Cavanagh, A., Hansen, H., Nazarian, B., Iding, M., & Ringrose, P. S. (2010, January 1). Reservoir Modeling of CO2 Plume Behavior Calibrated Against Monitoring Data From Sleipner, Norway. Society of Petroleum Engineers. doi:10.2118/134891-MS.