PROTECT: FINAL REPORT

CLIMIT PROJECT 233736: PROTECTION OF CAPROCK INTEGRITY FOR LARGE-SCALE CO_2 STORAGE

OBJECTIVES

The primary objective of the PROTECT project is to understand the impact of geomechanics, flow and chemistry on caprock integrity in order to ensure injectivity, maximize storage capacity and protect against CO_2 leakage from large-scale injection operations. Secondary objectives are:

- To determine and constrain the relevant parameters from field and laboratory data;
- To identify mechanisms for poro-elasto-plastic deformation and initiation/propagation of fractures within the caprock due to hydromechanical coupling;
- To investigate the impact of chemical reactions on fracture self-enhancement or self-healing and on overall rock strength;
- To develop coupled models for understanding individual fracture development and the effect of flow, temperature, geomechanics and chemistry;
- To develop upscaled models to simulate large-scale coupled flow-geomechanical-chemical interaction between the storage formation and caprock;
- To establish an integrated framework for designing safe and effective large-scale CO_2 injection strategies.

BACKGROUND

The capacity of saline aquifers on the Norwegian continental shelf (NCS) for storing large quantities of injected CO_2 has been well established. However, the ability to unlock this theoretical capacity in a safe and economically feasible manner is hindered by significant uncertainties. The largest risk factors in carbon capture and storage (CCS) include low injectivity, excess overpressures, and leakage risk. Assessing and managing these risks requires reliable prediction of geomechanical integrity of the caprock when subjected to overpressure in the reservoir. Caprock integrity has been identified as a critical research area in which data, process understanding, and modeling capabilities are still lacking. These deficiencies limit our ability to reliably assure mechanical integrity, especially for gigatonne-scale CO_2 storage. Optimal use of basin-scale storage resources and cost-effective storage operations rely on reducing uncertainty and improving model confidence beyond the current state-of-the-art.

The mechanical integrity of the caprock is connected to a range of processes including thermal, chemical and physical, all which can impact the mechanical behavior of the storage reservoir and surrounding over- and underburden. Understanding coupled complex processes requires a multi-disciplinary effort that combines complementary laboratory and computational investigations stemming from geomechanics, geophysics, geochemistry and mathematical modeling.

PROJECT RESULTS

WP1: DATA COLLECTION AND PROCESS UNDERSTANDING

Fresh samples of the Draupne shale (Ling Depression, North Sea) and the Rurikfjellet shale (Longyearbyen CO_2 Lab, Svalbard) were analyzed in a series of mechanical and geochemical tests. Geomechanical testing has provided data to quantify the shear strength parameters of fractured caprock (Rurikfjellet) using a direct shear box that allows for large displacement. These data give insight in to the impact of flow along the fracture on fracture shear strength, and also quantifies the relationship of shear strength with normal stress. Stress-dependent fracture permeability has also been investigated as a function of the flowing fluid. Results of this study also show that permeability to supercritical CO_2 is higher than to water or oil, indicating that fracture surfaces may undergo alteration that impacts the hydraulic properties of fractured caprock material.

Studies on shale powder pellets (Draupne shale) have not seen evidence of direct impacts of swelling/shrinkage on permeability. Additional research is needed to quantify this effect on natural shale samples. Microfluidic experiments have been performed to investigate how salt crystals precipitated in the fractures can affect the flow inside the fractures in a shale sample. The development of micrometer-sized salt crystals in the fractures suggest that the salt precipitation during injection of CO_2 into the geological formations can be considered as a fracture healing mechanism.

New mathematical approaches have also been developed for geophysical data inversion. Seismic data can be inverted more effectively by combining with other data types such as electromagnetic or gravimetric surveys. The methodology has been tested on the Skade formation synthetic data study with advantageous results. A sensitivity study was performed to determine the possibility of leakage detection using gravimetric monitoring. It was found that densely sampled gravity data can be used to measure density of leaked plumes only if plume position is given by seismic data.

WP2: DETAILED MODELING OF FLOW, REACTION AND DEFORMATION

Specialized mathematical and computational models have been developed to describe the response of fractures to pressure, stress and exposure to reactive CO_2-laden fluids. These codes can reproduce a variety of processes related to fractures. For example, a 2D hydraulic fracturing code has been used successfully to reproduce wellhead pressure during water injection and fracture stimulation in the Adventalen formation on Svalbard. Another important development has achieved a mathematically rigorous approach to fracture flow in porous media, significantly improving the robustness and accuracy of fracture-flow modeling. Participation in an international benchmark study of fracture flow modeling has showed the importance of model comparison to build confidence in new techniques before further application to more challenging problems.

For geochemical impacts, an existing pore-scale simulator was coupled to PHREEQC to include dissolution and precipitation reactions relevant for CO_2 storage. The model has been used to investigate the alteration of a single fracture surrounded by a heterogeneous rock surface composed of reactive and nonreactive minerals. The results demonstrate the need for well-characterized mineralogy when estimating permeability of reacted fractures. For saturation-dependent deformation, a new finite-volume numerical model was developed. The model has been implemented in Matlab and used to study desiccation processes in clayey soils. Preliminary numerical results agree with experimental results, showing that tensile stresses develop as the soil dries that can lead to cracking.

WP3: LARGE-SCALE COUPLED MODELING AND UPSCALING

To consider large-scale injection systems of up to tens to hundreds of megatons per year, new large-scale computational models have been developed specifically to address the response of the caprock under massive injection into deep storage reservoirs. These large-scale systems are well beyond the scale of individual fractures, and therefore simpler techniques must be used in order to be computationally efficient. The project has compared different approaches and demonstrated that analytical estimates of seabed uplift are reasonably accurate and saves time. A benchmark study of large-scale simulator has been carried out to determine the effectiveness of different (yet necessary) simplifications on model predictions. This study shows that more accurate representation of CO_2 in the storage reservoir is as, or more, important than accurate geomechanical representation of the over- and under-burden. This allows for simplification of the mechanical system, which is advantageous when many simulations are needed to evaluate uncertainty and sensitivity to input data. Seepage of brine into the over and underburden affects pressure build-up in the storage site. This impact can also be simplified using analytical techniques coupled to numerical reservoir simulation, which is accurate and cost-efficient.

WP4: INTEGRATION AND APPLICATION

New technological developments in this study were integrated into regional-scale studies to help understand practical capacity of NCS aquifers. The Utsira formation was used as a relevant case study was designed to demonstrate this workflow and understanding the impact of large-scale pressurization. Using all available data for the Utsira assembled within this study, the VESA simulator was used to estimate the maximum allowable injection rate that can be sustained over a 50-year storage project (total 5 Gt CO_2 injected at 100 Mt/y for 50 years) without water production and closed boundaries. Sensitivity to rock properties and boundary conditions at the very large scale was performed based on input from other aspects of the study. Different simulation methods lead to the same conclusion that the Utsira can potentially withstand injection rates 100 times the current Sleipner injection rate, with lower capacity estimates for a lower compressibility in the Utsira sand before reaching the estimated fracture pressure limit of the caprock.

WP5: BEST PRACTICES GUIDELINES AND REPORTING

The project concluded with an international workshop on seal integrity that summarized recent findings and identified a set of priorities to help guide future research in protection of caprock integrity for large-scale CO_2 storage. The main recommendations for future research should focus on: mechanical properties of fractures representative of faulted caprock, larger-scale geochemical impacts on fracture leakage, impact of CO_2 exposure on mechanical stability, effective parameters for faults and fracture networks, impact of fracture/fault leakage at the field scale, improved integration of monitoring data for detecting CO_2 leakage, the impact of uncertainty on predicting caprock failure. The recommendations are published in a report available on the project webpage: http://protect.w.uib.no

KEY R&D TASKS AND PARTNER ROLES

In this study, we combined these approaches to advance new knowledge in three key areas: (1) characterizing fractured rocks, including the impact of chemical and physical processes on fracture activation, propagation and/or healing; (2) identifying computational methods best suited to study fractures at the small-scale and monitor for leakage; and (3) integrating understanding from detailed data and models into large-scale hydromechanical simulations of CO_2 injection. All research partners have played a key role in the project.

NGI has carried out the mechanical testing on fractured shale samples, primarily focused on direct shear box testing. In addition, NGI has contributed with development of large-scale geomechanical simulator and a geophysical monitoring study.

UiO led a PhD project on geochemical impacts on fractured shale hydraulic properties. An associated PhD contributed with geophysical characterization of fractured media, while a master student thesis addressed geomechanical characterization of Svalbard shale.

UiB led the other PhD project in developing a new unified approach for discretization of flow in fracture porous media. A master student at UiB also contributed with development of a computational model for saturation-dependent mechanics.

IFE led activities on both the experimental and modeling side, investigating the impact of supercritical CO_2 on shale samples and developing simulation tools for hydrofracturing as well as large-scale coupled flow and geomechanics.

Uni Research contributed with project management and development of the vertical equilibrium simulator for large-scale flow and deformation. Uni provided co-supervision for the PhD and master student at UiB, led the geomechanical simulation benchmark and dynamic capacity estimation studies.

IMPLEMENTATION AND USE OF RESOURCES

The project was carried out according to plan. Deliverables were achieved in each of the planned tasks, with minor adjustments required as the science demanded. In total, the project produced: 25 peer-reviewed articles, 10 conference papers and extended abstracts, >24 presentations at conferences, 4 technical reports, 2 PhD theses, and 2 Master theses. Technological infrastructure developed in the project includes: shear box test methodology and 7 advanced simulation codes.

Project resources were used for project meetings and a final international workshop. The use of resources ensured good integration through semi-annual project meetings, which complemented collaboration within the SUCCESS center. Frequent visits and teleconferences between individual researchers occurred as a consequence of more intense collaborative activity. The workshop on seal integrity at Geilo was a successful 2-day gathering of researchers and industry representatives from inside and outside of the project. The participants discussed the state of research in seal integrity, particularly focused on faults and fractured shales, and a report was produced that outlined the status and recommended future research priorities for seal integrity research.

ANTICIPATED SIGNIFICANCE/BENEFITS OF THE RESULTS

The PROTECT project has significantly advanced the ability to assess the capacity of the large-scale storage sites with reliable simulation tools and improved data. Robust capacity estimation of large offshore stores is of vital importance for cost-effective planning and development of central storage sites. Understanding the potential for leakage and the processes that control the impact of leakage are also important for effective detection and remediation. For industry, project results can be used to optimize CO_2 storage projects, e.g. through pressure management, to achieve the maximum capacity possible while minimizing risks associated with CO_2 injection and long-term pressurization. For society, more reliable tools and data are valued for ensuring the safety of large-scale CCS and enabling better oversight of multi-project operations on the NCS.

The project has also trained two PhD students and two masters students, building national competence in CCS. Students have been co-advised by an interdisciplinary team, have been involved in collaborative, joint projects, and participated in extended visits at partner and international collaborating institutions.

DISSEMINATION AND UTILIZATION OF RESULTS

A project website has been established that describes all results obtained in the project, with links to associated articles, reports and presentations. The website will be maintained as long as possible. Publicly available documents can be downloaded, while copyrighted material can be accessed with appropriate credentials. Open access is available for most published results. In addition, the project leader was interviewed by an online magazine (Energi og Klima). The project was featured in the SUCCESS center annual report in 2016 and CLIMIT annual report for 2017. Results will be utilized in the following ways (not-exhaustive):

- Mechanical and geochemical data can be used to benchmark computational models and also be further analyzed using complex modeling that focuses on fundamental processes at the microscale.
- The unified framework for flow in fractured porous media developed at UiB has been implemented into the PorePy open-source software. Future projects will use the PorePy software to study leakage rates in faulted CO_2 storage reservoirs such as the Smeaheia site and for geothermal applications.
- Large-scale geomechanical models can be used to study the pressure-constrained capacity of other basin-scale systems besides the Utsira. Uplift at the seabed can be a predicted over large scales and utilized to design and execute monitoring networks, i.e. seafloor uplift, gravimetry, seismic.
- Vertical equilibrium simulation can be coupled with inverse modeling methods to estimate basin-scale parameters and with optimization methods to design strategies for optimal use of regional stores.

ANTICIPATED RESULTS POST-COMPLETION

The PhD student at UiO is nearing completion. The expected defense date is at the end of 2018. The PhD project will result in a total of three papers. One has been published, while one is currently in press: Fazeli H, et al., Three-dimensional pore-scale modeling of fracture evolution in heterogeneous carbonate caprock subjected to CO_2-enriched brine, *ES&T*, 2018. A third article will be completed for the thesis.

An article based on the results at UiB is currently in press: Nordbotten, J. et al., A unified approach to discretization of flow in fractured porous media, *Computational Geosciences*.

The model comparison study for large-scale geomechanical simulation by Gasda and co-authors will be submitted for publication in 2018.