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Quantifying The Risk Of CO2 Leakage Along Fractures Using An Integrated Experimental, Multiscale Modelling And Monitoring Approach

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Summary

Existing CO2 storage sites have illustrated that intact low-permeability mudrocks are effective barriers to avoid upward migration of CO2 from the storage complex. However, widespread deployment of Carbon Capture and Storage (CCS) as a means of climate change mitigation requires gigaton-scale CCS, rather than the few current megaton projects, to be deployed near large point sources of CO2. In the future, geological storage sites with faulted caprocks cannot always be avoided. We therefore need to rigorously assess geological leakage risks for CCS and specifically improve our understanding of multi-phase fluid migration in faulted and fractured caprocks. The DETECT research program will provide new insights by integrating experimental characterization with multiscale modelling of the combined hydrochemical, hydromechanical and clay swelling and shrinking effects in faulted and fractured mudstones. The purpose of the models is to establish determine realistic flow rates across fractured and faulted mudstone caprocks, to identify existing monitoring tools capable of detecting such fluid migration. Based on these quantitative leakage scenarios, risk and mitigation bow-tie analyses are developed with which suitable and cost-effective monitoring tools can be identified.

Introduction

Long-term geological CO_2 storage requires a storage site with a caprock that acts as an impermeable seal over geological time scales. Existing CO_2 storage sites were selected based on the availability of an ideal caprock, typically a fine-grained mudstone, carbonate or evaporate formation, with low matrix permeability and high geochemical reactivity. Caprocks with faults and fault damage zones are generally avoided, to minimize the uncertainty on caprock leakage potential. It is known from hydrocarbon production that faults can act as flow pathways, and that faults that were initially sealing, may become permeable after reactivation due to local pore pressure changes (Morris *et al*., 2011; Rutqvist *et al*., 2007). The most notable examples of fault reactivation are associated with injection, for example wastewater injection (Improta *et al*., 2015). The In Salah CO_2 injection project in Algeria also showed signs of leakage through fracture corridors in the primary caprock, which were reactivated during injection of CO_2 (Rinaldi *et al*., 2016).

Widespread deployment of Carbon Capture and Storage as a means of climate change mitigation requires gigaton-scale CCS, rather than the few current megaton projects, to be deployed near large point sources of CO_2. In the future, geological storage sites with faulted caprocks cannot always be avoided. We therefore need to rigorously assess geological leakage risks for CCS and specifically improve our understanding of multi-phase fluid migration in faulted and fractured caprocks.

The DETECT research program, co-funded by the European Union and national governments as part the ACT initiative, intends to determine realistic flow rates across fractured and faulted mudstone caprocks, and aims to identify existing monitoring tools capable of detecting such fluid migration. Numerical models, integrated with experimental data, provide a range of realistic flow rates for different storage site scenarios. Based on these quantitative scenarios, risk and mitigation bow-tie analyses are developed with which suitable and cost-effective monitoring tools can be identified.

Approach

An increasing amount of laboratory and modelling studies on the flow properties of mudstones in general, and more specifically fractures and faults in mudstones, is available in the literature (e.g. Kampman *et al*., 2014; Makhnenko *et al*., 2017). However, most studies focus on a subset of chemical or mechanical processes in the caprock that affect flow, whereas the potential leakage rates depend on the interplay between fluid pressure and stress regime, and mechanical and chemical interactions in fractures and faults. These combined effects can result in an increase or decrease in fracture permeability and network connectivity over different temporal and spatial scales. The highly coupled nature of these processes makes experimental parameterization and predictive modelling highly challenging, especially at the large temporal and spatial scales relevant to CO_2 storage.

DETECT studies the combined impact of these different processes on fluid flow in fractured and faulted caprocks. Specifically, experimental data is acquired on:

- The impact of calcite precipitation and dissolution on the walls of geological fractures on fracture CO_2 permeability;
- The relation between swelling or shrinking of clays within fractures and flow of CO_2;
- Changes in fracture permeability in shear fractures as a result of changes in shear displacement and confining stresses.

The fundamental flow behaviour as a function of chemical and mechanical changes is captured and integrated in fine-scale numerical models. Fine scale in this context refers to models of several discrete fractures, that capture the observed hydromechanical and hydrochemical behaviour as well as the mechanical interplay between intersecting and adjacent fractures. The numerical complexity of these models limits the number of fractures that can be simulated explicitly. Instead, effective flow properties as a function of limited chemical and mechanical parameters are derived from these models and applied to larger models that capture the explicit, deterministic geometry of fault zones in caprocks. The fault zone consists of a fault core and a damage zone, represented by a high-density network of discrete fractures. The model geometries are based on mapped analogue fracture networks acquired from outcrops. At this model scale, we derive effective fault zone permeabilities as a function of the geometry of the fault zone and its chemical and mechanical properties, derived from the finer-scale models.

In a final upscaling step, the effective fault zone permeability is assigned to a reservoir flow model of the entire CO_2 storage site, which is loosely coupled to chemical and mechanical solvers to capture the effective fault zone permeability as a function of CO_2 injection, considering effective chemical and mechanical changes. Using effective properties allows for computationally efficient reservoir-scale models that can be used to explore a wide range of storage site configurations and leakage scenarios, with fundamental hydrochemical and hydromechanical behaviour calibrated to fine-scale models and experimental data.

Deliverables

The flow rate predictions from these models will be compared to the monitoring performance of state-of-the-art technologies, to identify which monitoring technologies are effective for detecting realistic CO_2 leakage rates from a storage site with non-sealing faults in the caprock. Furthermore, the improved understanding of the potential flow rates will feed into an integrated life cycle risk assessment using the established bowtie method to provide an overall picture of the natural paths via which CO_2 leaks could occur from subsurface storage reservoirs. The bowtie model will be expanded to include quantitative risk assessment, with the goal of calculating the probability/likelihood of site-specific leakage risks.

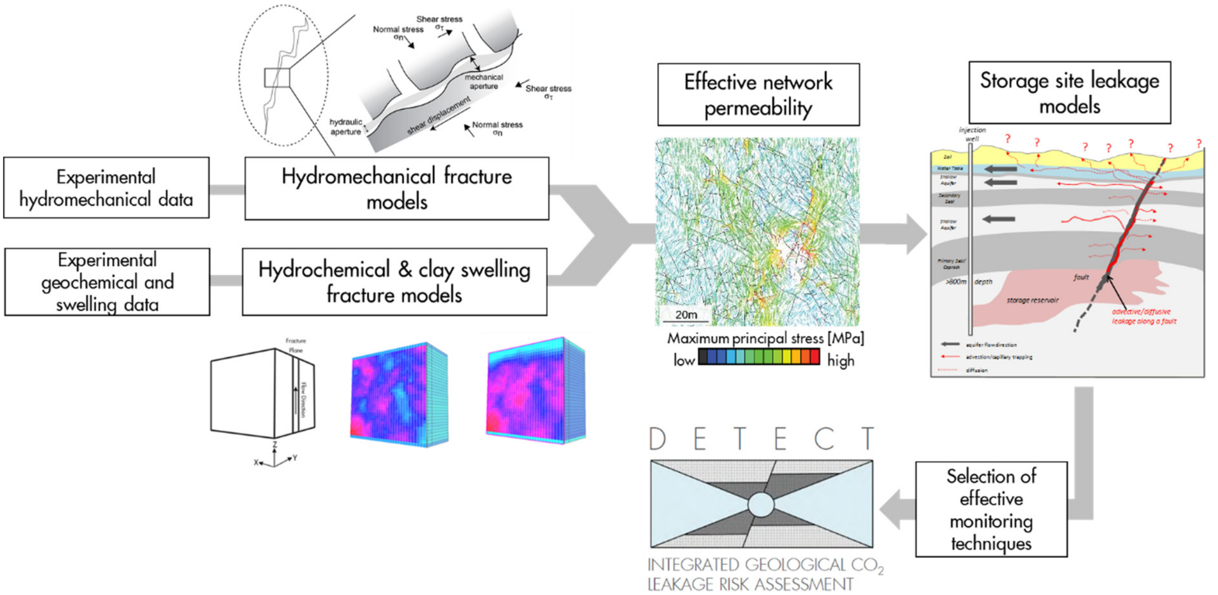

Figure 1 *Integration of multi-physics experiments, including hydrochemical, hydromechanical and clay swelling/shrinkage behaviour in caprock fracture networks, with multi-scale modelling to assess which leakage detection and monitoring tools are most effective for deployment in CO_2 storage sites. Images adapted from (Bisdom et al., 2017; Kampman et al., 2016).*

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