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CO2 Sequestration: Studying Caprock And Fault Sealing Integrity, The CS-D Experiment In Mont Terri

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Summary

A key challenge for CO2 geological storage is the integrity of the caprock. This challenge is addressed by executing a decameter-scale experiment at the Mont Terri Underground Rock Laboratory in Switzerland, under the umbrella of ELEGANCY (Enabling a Low-Carbon Economy via Hydrogen and CCS). ELEGANCY is an European project aiming at advance sustainable geo-energy processes through studies on risk mitigation, characterization and public perception, whose achievements will benefit the fields of carbon dixode sequestration. The experiment will investigating the mechanisms and the physical parameters governing the migration of CO2-rich brine through a faults. In particular, the test seeks to understand the conditions for slip activation (seismic vs. aseismic slip) and the stability of clay faults, as well as the coupling between fault slip, pore pressure, fluid migration and possible induced "micro" seismicity. To this end, we will inject CO2-rich brine into the fault core for a period of about eight months, while monitoring its geo-mechanical response. Additional tracer and transmissivity tests will be conducted at regular time intervals to determine the fluid path evolution of the injected fluid and to infer the potential evolution of CO2 from the brine. Numerical simulation work assist the different phases of the field experiment.

Introduction

Faults represent one of the possible leakage pathways for CO_2 to migrate out of the storage reservoir through the caprock. It is widely recognized that this pathway plays a key role for the safe, long-term containment of a CO_2 storage site as well as for the phenomenon of induced seismicity. Thus, the presence of damaged zones within faults will greatly affect the site characterization process in terms of the safety assessment, and consequently the monitoring, verification, and risk management plan (prevention, mitigation, remediation measures). The mechanisms and the physical parameters governing leakage through a damaged zone within faults and the neighbouring rocks present many open questions. Although numerical modelling of CO_2 migration along faults is quickly spreading (e.g. Rinaldi et al., 2015) and empirical evidence from the oil industry and the management of radioactive waste provide much supporting data, CO_2-specific information, especially coupling geomechanical and geochemical interactions, is still lacking. Hence, the geomechanical testing of faults subjected to CO_2 injection is of particular interest.
The Mont Terri rock laboratory, located in north-western Switzerland, 300 m underground in the safety gallery of a motorway tunnel, comprises 700 m of galleries and niches in clay formation, named Opalinus Clay, and offers a unique opportunity for a pilot-scale research on the injection of CO_2 into a fault. The CS-D experiment (August 2018 - July 2020) at the Mont Terri Lab, aims to investigate caprock integrity by determining CO_2-rich brine mobility in a fault zone. We monitor for geochemical and geomechanical changes induced by fluid injection for prolonged time (approximately eight months), with the aim to better understand mechanisms of CO_2 leakage, and develop strategies to detect/monitor/predict it. Moreover, we focus on understanding the relative contribution of aseismic vs seismic slip associated with the fluid leakage in the fault zone.
The experiment offers a unique opportunity to develop improved, and advenced monitoring technologies. In particular, a multi-component monitoring network of stress propagation within the fault will be integrated with the three-dimensional displacement probe (SIMFIP, Guglielmi et al., 2014), and will be employed in parallel with other monitoring systems (e.g. micro-seismicity and active seismic monitoring, cross-hole electrical resistivity monitoring, deformation, geochemical fluid sampling). The monitoring program will be continued after the end of injection (July 2019) in order to allow for studying not only the short-term poro-visco-elastic response, but also the geochemical and mineralogical changes within the damaged zone. This experiment will help improving the methods for monitoring and imaging fluid flow. Numerical simulation assists the different phases of the experiment and is calibrated by experimental (in-situ and laboratory) results.

Concept

The experiment is designed to investigate the mechanisms and the physical parameters governing the migration of CO_2-rich brine through the fault, and the impact of long time exposure to CO_2 on the rocks permeability. To this end, we will inject CO_2-rich brine into the core of the main fault hosted in Opalinus clay at the Mont Terri Lab, with well head pressure just below the stimulation pressure, and monitoring the geo-chemical and geo-mechanical response of the fault. The injection is planned to last several months, and includes:

- repeated short (a few days) pulse tests, where brine/water is injected at two different location within the fault zone, in order to define the fault opening pressure(FOP);
- steady state injections of few months, at pressure below the FOP, where we will use CO_2 enriched fluid and tracers such as Helium and Bromic salt.

This will allow inferring about the fluid path evolution and different trapping mechanisms of the CO_2-rich brine. Injection activities will be closely monitored by detailed passive acoustic emission sensors, and seismic and resistivity characterization will be carried out during active injection.
After the injection phase, a detailed petrophysical and geo-mechanical characterization will be performed on rock samples collected from sampling drills that will reach the volume exposed to CO_2-rich brine. This will allow observation of mineralogical and chemical changes due to the rock-fluid interaction and will provide the data for the validation of numerical models. Finally, post-mortem modelling, i.e. comparing the measured data with model predictions, will allow improving the predictive capabilities of the models employed/developed.

Experimental design

A new niche has been drilled and equipped in the Mont Terri Underground laboratory to host the CS-D experiment (Fig. 1a). A set of vertical and inclined boreholes are drilled and equipped in order to perform a long-term injection of CO_2 saturated fluid and to monitor the movement of the brine in the fault by geophysical methods and by sampling of fluids (Fig. 1b).
The injection will be performed in a vertical borehole (BCS-D1) equipped with a four-fold packer system, allowing for multiple injection/monitoring intervals, both in the fault zone and in the host rock. A secondary injection borehole (BCS-D7), is equipped with SIMFIP for monitoring evolution of fault displacement, and it can be switched to injection mode for testing different point of the fault. The borehole BCS-D2 is dedicated to fluid flow monitoring and it is equipped with a circulation pump for collecting fluid sample (Fig. 2b). For geophysical monitoring, four boreholes BCS-D3, D4, D5, and D6 are drilled, logged and cored, and will provide fundamental information on the geometry of the fault. BCS-D3 D4 and D5 will be inclined by 25° to 45° (normal to the bedding plane) in order to enable the tomographic planes being parallel to the symmetry axis of the anisotropy of the electrical and elastic rock properties. These geophysical boreholes will be instrumented with permanently installed (electrodes and geophones) and mobile (piezo streamers and seismic sparker sources) equipment for active and passive geophysical monitoring (Fig. 2b).
The electrical resistivity will be monitored between boreholes D3 and D4 using a similar electrode array as for example employed at the Ketzin pilot site in Germany (e.g. Schmidt-Hattenberger et al. 2016), consisting of ring-shaped stainless-steel electrodes. They will be grouted behind the PVC-borehole casing with a bentonite-cement mixture, in order to ensure a good electrical coupling with the surrounding geology. Each electrode array consists of 50 electrodes, separated by 0.5 m. For the active seismic monitoring, borehole D3 will contain a cemented 3- component geophone array inside the casing. This geophone array is similar to the one used in the GM-A experiment in Mont-Terri (e.g. Manukyan et al., 2012) and consists of 24 geophones, with sensitivities up to the kHz

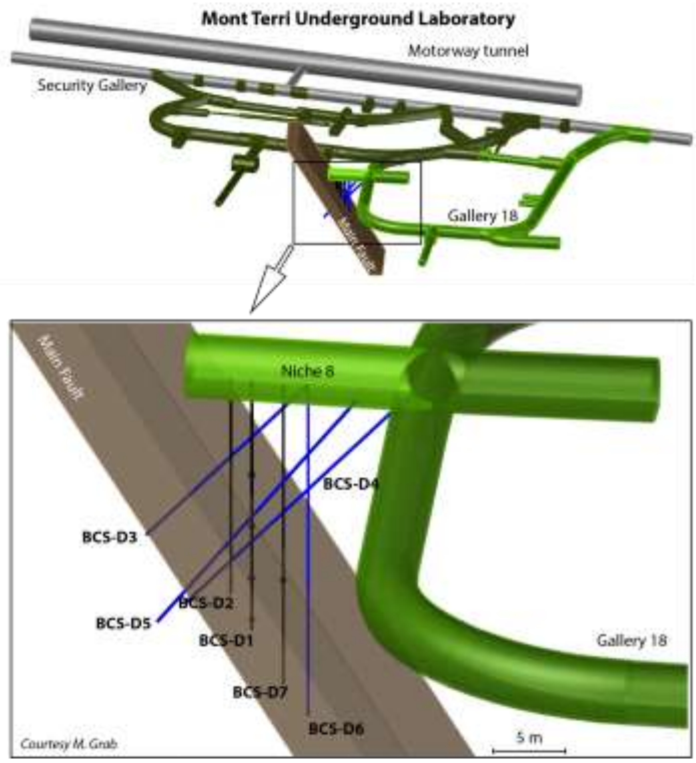

Figure 1 *(top) The Mont Terri Underground laboratory with the new tunnels (light green) and the fault zone (brown). Niche 8, hosting the CS-D experiment, is in yellow-green. (bottom) Position of the boreholes for injection (BCS-D1), SIMFIP (BCS-D7), fluid monitoring (BCS-D3), and geophysical monitoring (BCS-D3-6).*

range and an interspacing of 0.5 m. Inside the casing of borehole D4, a P- and S-wave sparker source will be deployed, which will be pneumatically pressed to the casing. Optionally, these sparker sources can also be operated from the boreholes D5 or D6 at times these boreholes are not used for passive seismic monitoring. In addition, small spots of the gallery wall are kept free of shotcrete, such that the seismic array can be complemented with geophones placed inside the gallery, and one 3-component geophone is permanently cemented at the bottom of each of the source-boreholes D4, D5, and D6. Monitoring microseismicity during metre-scale injection requires high-sensitivity sensors. For this purpose, we will use the 32 channel GmuG acquisition system at a sampling rate of 1 MHz (Amman et al., 2018). This system uses piezo-sensors that are highly sensitive in the frequency range of 1–100 kHz, with the highest sensitivity at 70 kHz. For network layout, we use a borehole sensor array with 8 piezo-sensors that can be split in two or three smaller arrays to be placed in different boreholes. These sensors are pressed pneumatically against the borehole wall. At the remaining 24 channels, we will use 20 piezo-sensors and 4 accelerometers that will be placed beside a piezo-sensor for calibration purposes, as mentioned above. These sensors will be clamped to the tunnel walls.

Preliminary modelling

For the Opalinus clay, hydraulic diffusivity can vary from 10^{-8} m^2/s (for joints) to 10^{-11} m^2/s (for rock matrix), implying that the zone by pure diffusion grows significantly slowly. Given this scenario and considering that the Opalinus clay is substantially a tight rock (intrinsic permeability is in the order of 10^{-20} m^2), the injection process is expected to involve a competitive mechanism between the reopening of the fault slip lines and the dissipation of the overpressure in the natural fracture network. We investigate the possible distribution of pressure and brine in the Mont Terri fault with the continuum hydro-mechanical code TOUGH-FLAC (Rutqvist, 2011).
We employed an injection strategy similar to the previous FS-experiment (Guglielmi et al 2017), limiting the pressure to be below the reactivation threshold observed previously. We stretched the time to account for a long-term injection (8 months). We fixed the pressure at the injection point in a 20×20×20 m domain with a fault plane dipping 65˚. The fault plane is simulated with a finite width (1 m) and we model it as a fracture zone accounting for possible elastic opening (Rinaldi & Rutqvist 2018). We perform some sensitivity analysis to assess

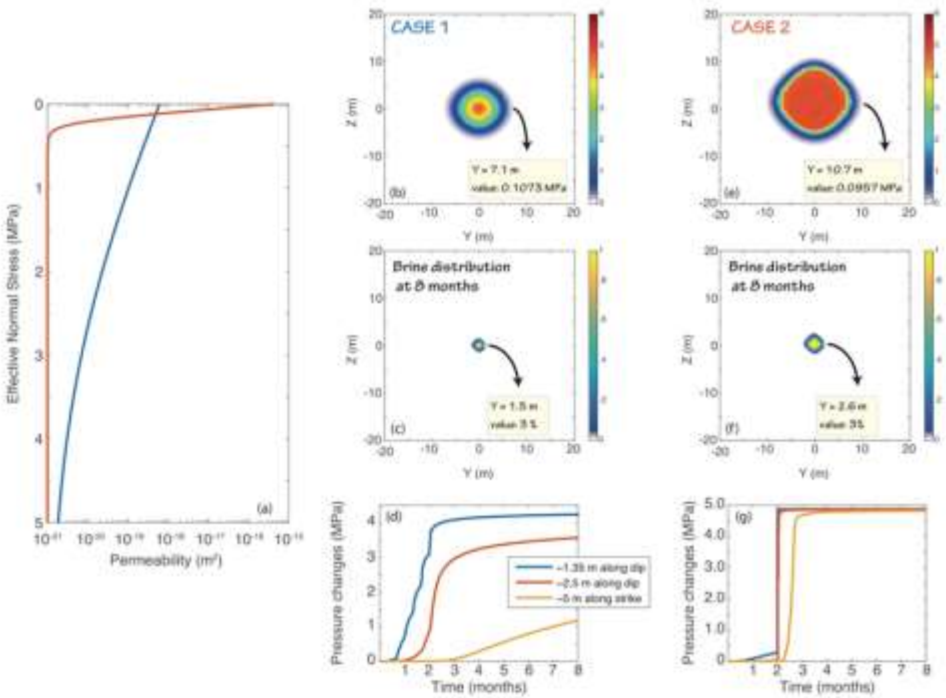

Figure 2 *(a) Assumed permeability function for the two cases. (b-d) Analysis for Case 1 (elastic behavior); (e-g) analysis for Case 2 (opening).*

the maximum reach of the pressure front and the injected brine. At this stage, the brine is pure and not yet saturate with CO_2. We analysed two possible cases: (i) assuming a constant increase of permeability with decreasing normal effective stress (elastic behaviour) and (ii) assuming that the fracture jack opens after reaching small value in effective normal stress (opening). For both cases (Fig. 2) is clear that both pressure and brine should reach a distance at which the monitoring should be possible (i.e. around 2 m). Quite interestingly, in case of opening (case 2), no pressure changes should be recorded in the first months, and after jacking the pressure should reach a similar value in the entire opened region.

Conclusions

In this extended abstract, we describe the experimental setting and conceptual aims for the CS-D experiment and the preliminary modelling that assisted us in design the experiment. The installation is currently ongoing and the first logging and coring is taking place. We plan to start the injection by November 2018 and continue for about 8 months. We plan a pulse test by the beginning of the injection, with repetition of the tests in April 2018 and early summer 2019.
Given the preliminary results of the numerical modelling, we expect that to the pressure plume to be well visible, with the brine propagating few meters away from the injection point. The planned geophysical monitoring will allow measuring the propagation of the plume if modelling prediction are correct, and will allow to estimate if induced seismicity is an indicator for CO_2 leakage. Finally, the current setting will allow for high-pressure injection (at same or nearby injection borehole), allowing for the study of sealing capacity before and after a fault reactivation, determining the best observables to monitor and evaluating possible mitigation strategies (e.g. injection of sealant).

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