Observations from an in situ experiment to monitor fault sealing integrity

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Scientific objectives

More about the CS-D experiment:

- investigating how the exposure to CO₂-rich brine affects sealing integrity of a caprock, hosting a fault system (permeability changes, induced seismicity).
- observing directly the fluid migration along a fault and its interaction with the surrounding environment.
- testing instrumentation and methods for monitoring and imaging fluid transport.

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(6 more papers are submitted/in preparation)
The facility installed for the ELEGANCY experiment at Mont Terri is a semi-permanent in-situ research unit, ideal for studying CO₂ storage/safety related aspects and should be continued to be used in the future.

With its dense network of monitoring systems, the experiment aims at:

1. collecting multi-parameter data from independent but strongly integrated monitoring techniques;

2. establish a dataset at high spatial resolution that yield insight into the interrelationship of hydraulic, geomechanical, and geochemical processes within a fault in a caprock.

In situ is complemented by lab tests at Imperial College and EPFL.
Instrumentation

Geophysical borehole monitoring

- 27 Borehole Geophones each with 3-components
- 30 Geophones on the surface (1-component)
- 8 Piezosensors in the boreholes
- 16 Piezosensors on the surface
- Chain extensometers: 12 measuring sections for axial deformation and temperatures
- DSS FO in all boreholes

Geophones: 0.1-2 kHz; piezo: 1-100 kHz
Fault characterization and instrumentation in D1,2
Phase 1:
Fault transmissivity and Fault Opening Pressure

Prolonged step test:
Aim: understand the system response to pressurization

- P increased by steps of 300 kPa,
- Step 28-30 hours
- $P_{\text{max}}$ 4.8 Mpa (FOP)

Analysis of pressure decay (3 days):
- transmissivity in the order of $10^{-13} \text{ m}^2/\text{s}$
- $\sim 10^{-21} \text{ m}^2$ permeability

The value is close to previous estimates (Marschall et al. 2005)

Estimated transmissivity at FOP: $9 \cdot 10^{-12} \text{ m}^2/\text{s}$
Active/passive seismic monitoring

• The fault at Mont Terri could be nicely detected by seismic tomographic data.

• Seismic velocities are sensible to pore pressure variation in the system with c.a. ~1 % variation (P waves)

• No notable induced microseismic event was recorded.
Active Seismic monitoring

- P-wave sparker shots repeated after each injection step-up
- Change in P-wave velocity ($dV_p$), relative to $V_p$ from baseline tomogram
- Figure a: $dV_p$ at injection pressure of 2.4 MPa (first step)
- Figure b: $dV_p$ at injection pressure of 4.5 MPa (last step)
- Reduction of $V_p$ by around 1% in the vicinity of the injection interval
Phase 1:
Deformation and slip during break through
(Y. Guglielmi, D. Rebscher)

- Different types of optical fiber based sensors:
  - Bragg for local strain (SIMFIP)
  - Brillouin for distributed temperature and strain (DTS and DSS)
  - Rayleigh for distributed acoustic (DAS)

- 5 bi-axial tiltmeters set at the gallery floor

Findings:
- Reverse shear to the NW during excavation
- About 150 microns shear after excavation

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Some observations from Phase 1

- Fault Transmissivity: \( \sim 10^{-13} \text{ m}^2/\text{s} \); Permeability: \( \sim 10^{-21} \text{ m}^2 \)
- Fault opening pressure c.a. 4.8 MPa
- Seismic velocities are sensible to pore pressure variation in the system with c.a. \( \sim 1 \% \) variation (P waves)
- No seismicity was detected during injection activities
- Fault response to fault excavation (collaboration with LBNL & BGR)
Phase 2:
Injection of CO₂-enriched water

**Phase 2:** injection at 4.5 MPa, syn. water+Kr+CO₂ (mixed at about 2.2 MPa)

- Constant pressure of 4.5 MPa
- Injection fluid: Pearson water+Kr+CO₂ (mixed at about 2.4-2.7 MPa)
- Flow rate steady-state value of about 0.035 ml/min (Fig. 2a).

Total injected volume = 25.37 l
Injection of CO$_2$-enriched water

**Phase 2**: injection at 4.5 MPa, syn. water+Kr+CO$_2$ (mixed at about 2.2 MPa)

Pressure at monitor first increased then decreased after plateau
Could it be fault/fracture self-sealing?
Swelling?
Modeling the injection

**Modeling:** iTOUGH2; inverse modeling by accounting for the pressure recorded during one week long injection test

The behaviour at the monitoring point is captured when assuming the fracture not directly connected to the near well region, and allowing for closure (lower permeability) during shut-in (c). The trend in (e) better agrees with a model where the porosity decreases in the vicinity through time of the injection interval (green line in Fig. 4e, with a fix 0.5% decrease at each step) compared to a model with no porosity changes (orange line).
Injection of CO$_2$-enriched water

**Phase 2:** injection at 4.5 MPa, syn. water+Kr+CO$_2$ (mixed at about 2.2 MPa)

- Dilution with in-situ water pushed toward monitoring interval
- Break-through
- Re-equilibration

$pH$ synt. water in D2=7.8
$pH$ injected water (syn+CO$_2$)=5.5
A) The limited fluid injected do not travel far from the injection point, some \textbf{in-situ water is pushed} from the rock to the monitoring interval. Because the pH of the in-situ water is lower than the synthetic, we observe a dilution of this latter with pH dropping to a value of 6.95. (exact pH of the in-situ unknown=impossible to estimate the amount of mixing)

B) \textbf{in-situ water is pushed} from the rock toward the monitoring interval, allowing for further dilution of the synthetic water and a further decrease of the pH. At this stage the pressure is still increasing at the monitoring point, and pCO2/pN is constant. CO2 has not travel far from the injection point, and it has then not reached the monitoring borehole.

C) Breakthrough in October 2019. CO2-rich water at the injection point has a pH of 5.5, hence we would have expected a stronger decrease in pH. We interpret these observation as the CO2-rich water arriving at the monitoring, but with a pCO2 much below the one at injection: e.g. 1%-2% if compared to pressure difference) would be observed. Consequently, the increasing pH could be related to the injected synthetic water with a minor amount of CO2. The mass spectrometer measurement confirms the increasing CO2 content in time. In this phase the pressure at the monitoring reaches its peak, and start decreasing after such breakthrough has occurred.

d) In the current phase, both the CO2 content and the pH are still slightly increasing, confirming that the breakthrough has actually occurred but not all the fluid has been replaced. Given enough time would lead to a stable amount of CO2 and a pH below 7.8.
Some observations from Phase 2

• The spectrometer detects CO$_2$ at the monitoring borehole after December 2019.
• pH and EC are hard to interpret
  (The current increase in pH could indicate fluid-rock interaction).

Moreover....new “perturbations” to the system are coming....
CS-D/FS-B collaboration

Active Rupture patch

Passive Rupture patch

~24 Months Monitoring

MPa

4.0-
3.5

CO₂ brine

H₂O

CO₂ brine

H₂O

H₂O+Sealant

Injection Water patch

Post-Injection Water patch

Injection CO₂ patch

Post-Injection CO₂ patch

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Conclusions

• The leakage is confined along tiny fractures.

• Seismic velocity changes during pressurization, fault could be nicely imaged, however, results of a time-lapse tomography could not identify the connective fracture through which the CO$_2$ moved.

• Potential porosity decrease in the near injection region. Self healing?

• The time scale of CS-D was probably too short to have measurable effects

• The risk of induced seismicity in the caprock is confirmed very low.
Outreach

- Media event in January 2019, c.a. 20 journalists, c.a. 40 articles in local and national newspapers
- Interviews with Reuters, Radio France,
- A report broadcasted on the national TV
- Many schools, and other visitors

We can help social acceptance!
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