Observations from an in situ experiment to monitor fault sealing integrity

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Accelerating CCS Technologies
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SWISS COMPETENCE CENTER for ENERGY RESEARCH
SUPPLY of ELECTRICITY

In cooperation with the CTI

Energy funding programme
Swiss Competence Centers for Energy Research

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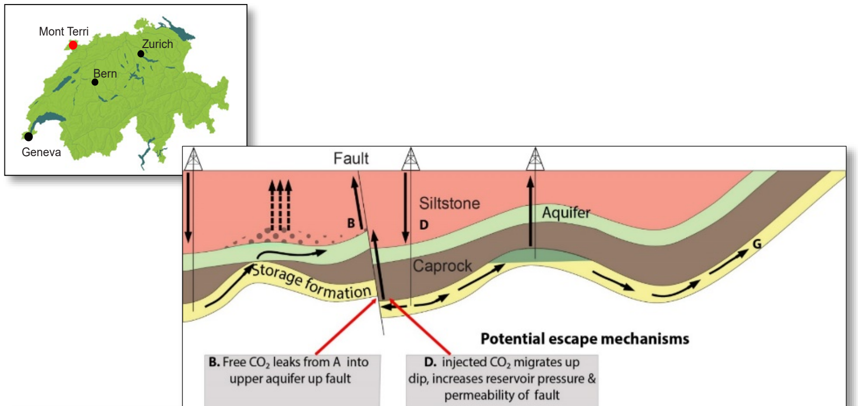
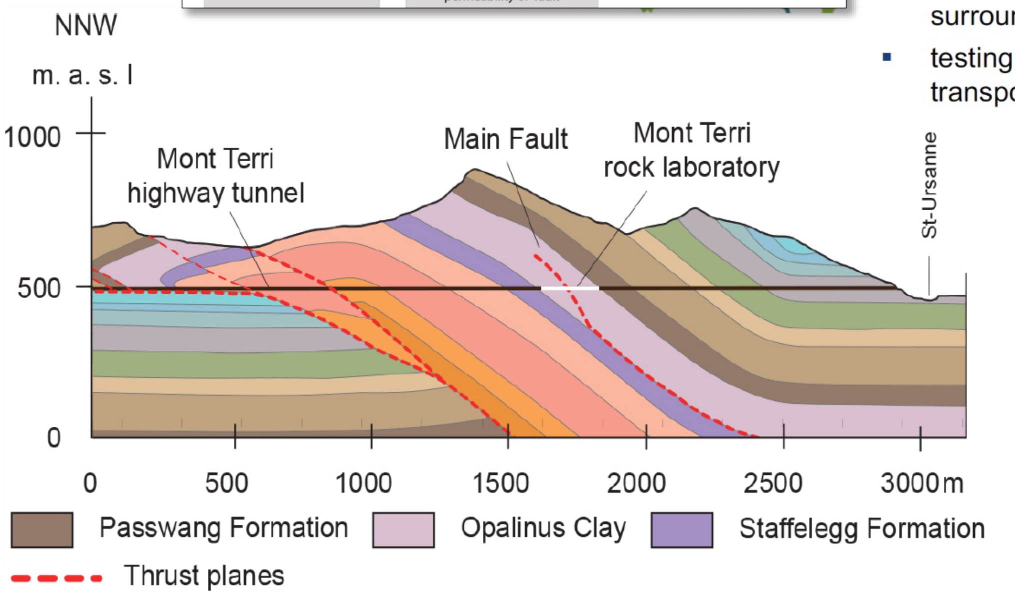
Scientific objectives





After Nussbaum et al. (2017): Tectonic evolution around the Mont Terri rock laboratory, northwestern Swiss Jura: constraints from kinematic forward modelling. Swiss Journal of Geosc., 110, DOI 10.1007/s00015-016-0248-x.

Flow through faults, potential leaks through a cap rock:

Simulating CO_2 (dissolved in formation water) leaking trough a fault in a caprock

Objectives of the CS-D experiment:

- investigating how the exposure to CO_2-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.

More about the CS-D experiment:

Zappone et al. 2018. CO_2 Sequestration: Studying Caprock And Fault Sealing Integrity, The CS-D Experiment In Mont Terri, *First Break* , DOI: https://doi.org/10.3997/2214-4609.201803002

Zappone et al. 2020. Fault sealing and caprock integrity for CO_2 storage: an in-situ injection experiment. *Solid Earth*, accepted.

Wenning et al. 2020. Shale fault zone structure and stress dependant anisotropic permeability and seismic velocity properties (Opalinus clay, Switzerland) *J. Struc. Geol.*, submitted.

(6 more papers are submitted/in preparation)

Layout

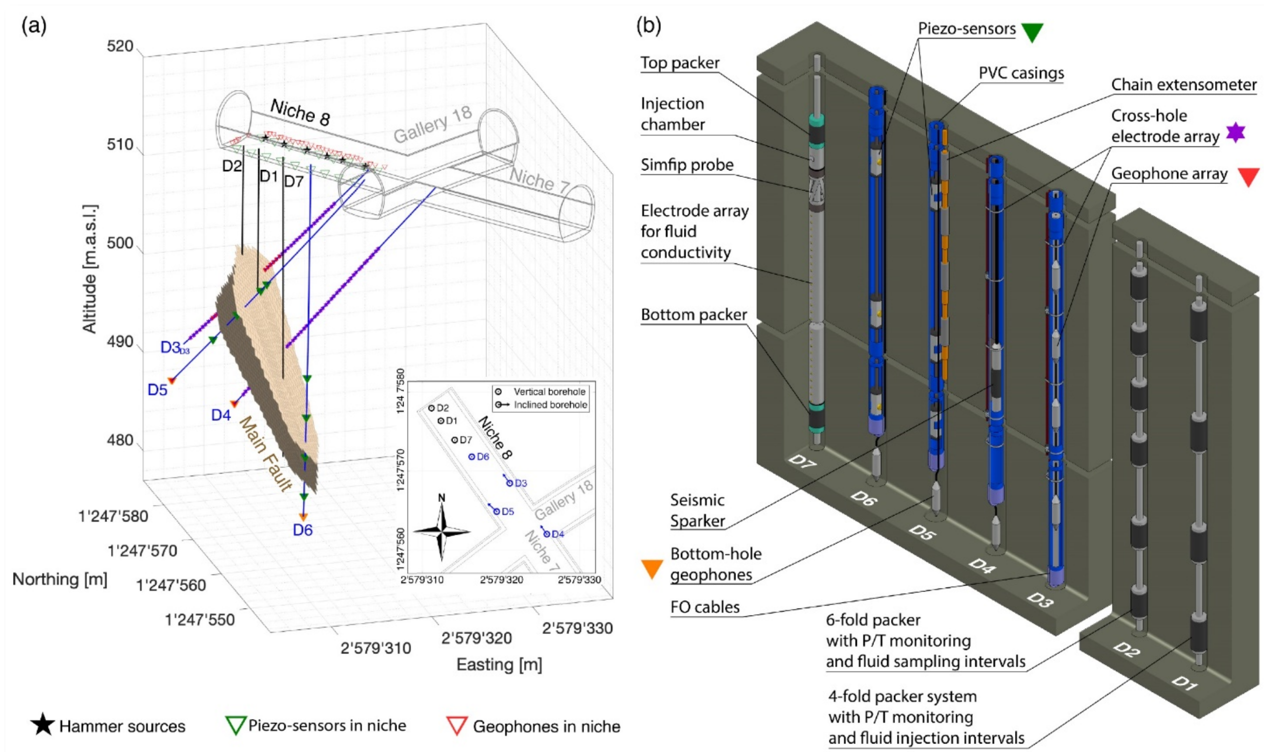
The facility installed for the ELEGANCY experiment at Mont Terri is a semi-permanent in-situ research unit, ideal for studying CO_2 storage/safety related aspects and should be continued to be used in the future.

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**

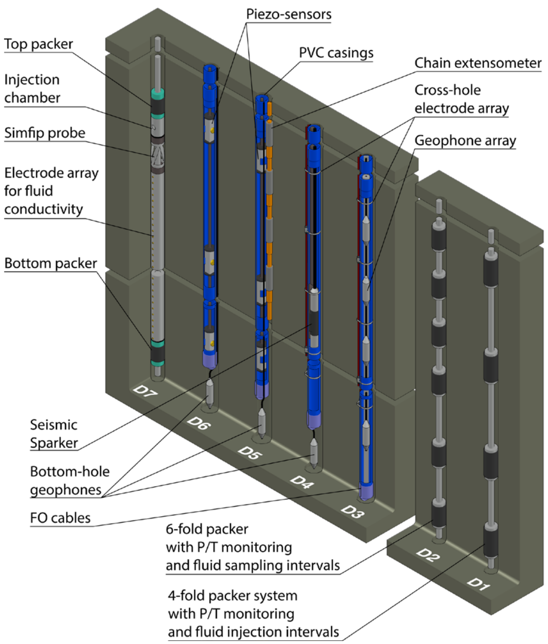


Instrumentation

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



Seismic piezo-sensors

Geophone array

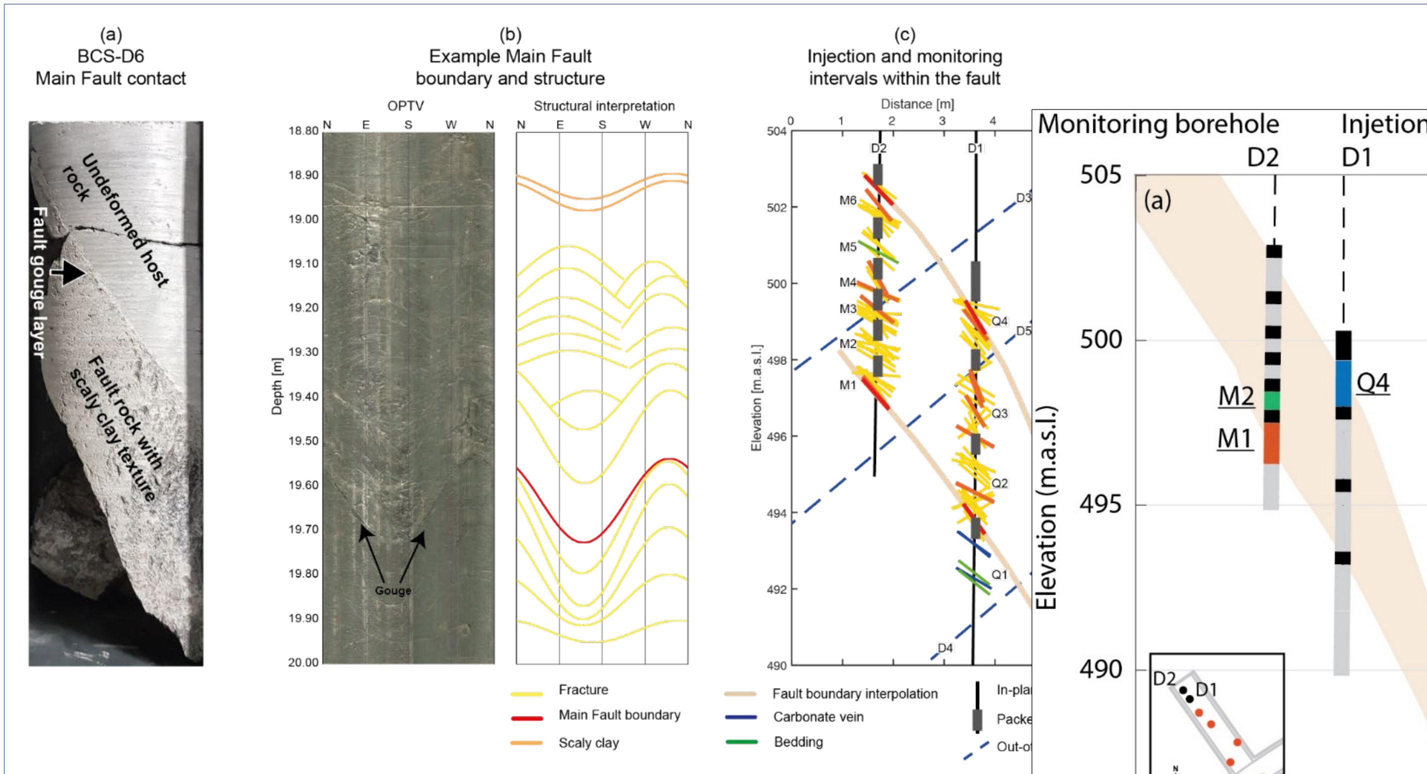
Bottom hole geophone

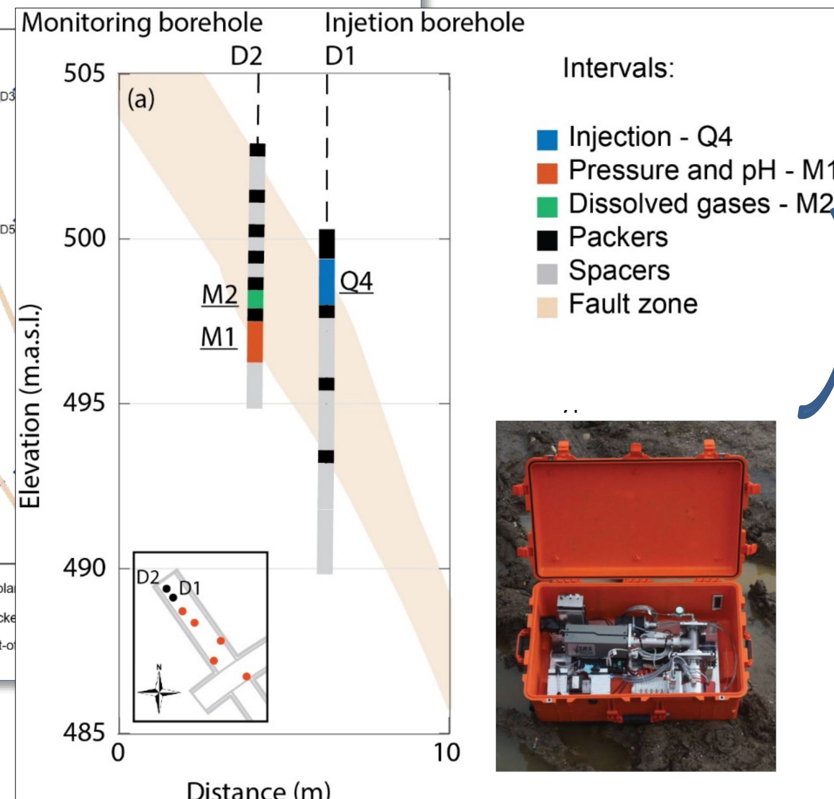
Electrical resistivity sensor

Chain extensometer

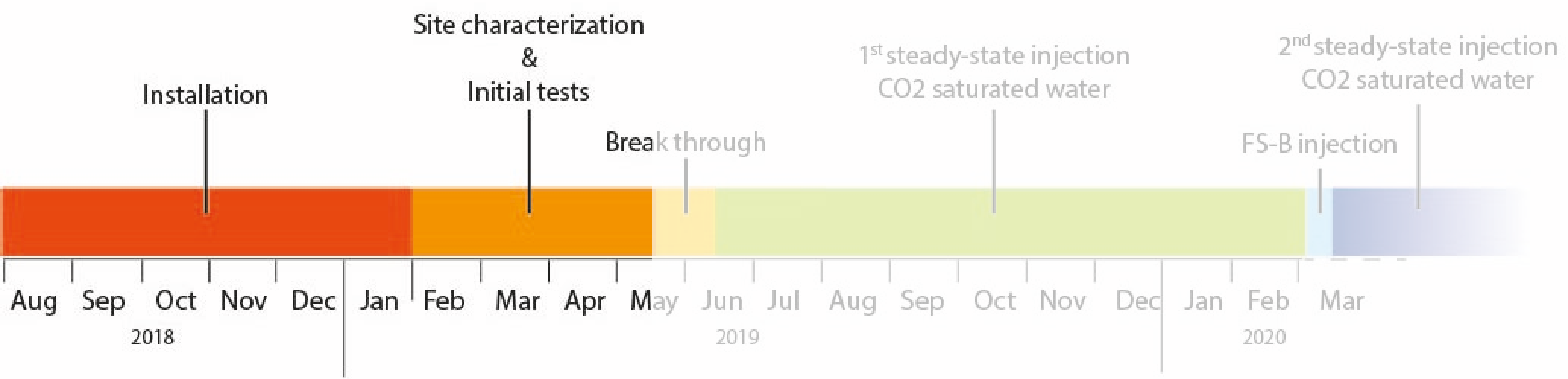
Fiber optic DSS

Fault characterization and instrumentation in D1,2





Phase 1:



Site characterization
&
Initial tests
Installation
Break through
1st steady-state injection
CO2 saturated water
2nd steady-state injection
CO2 saturated water
FS-B injection
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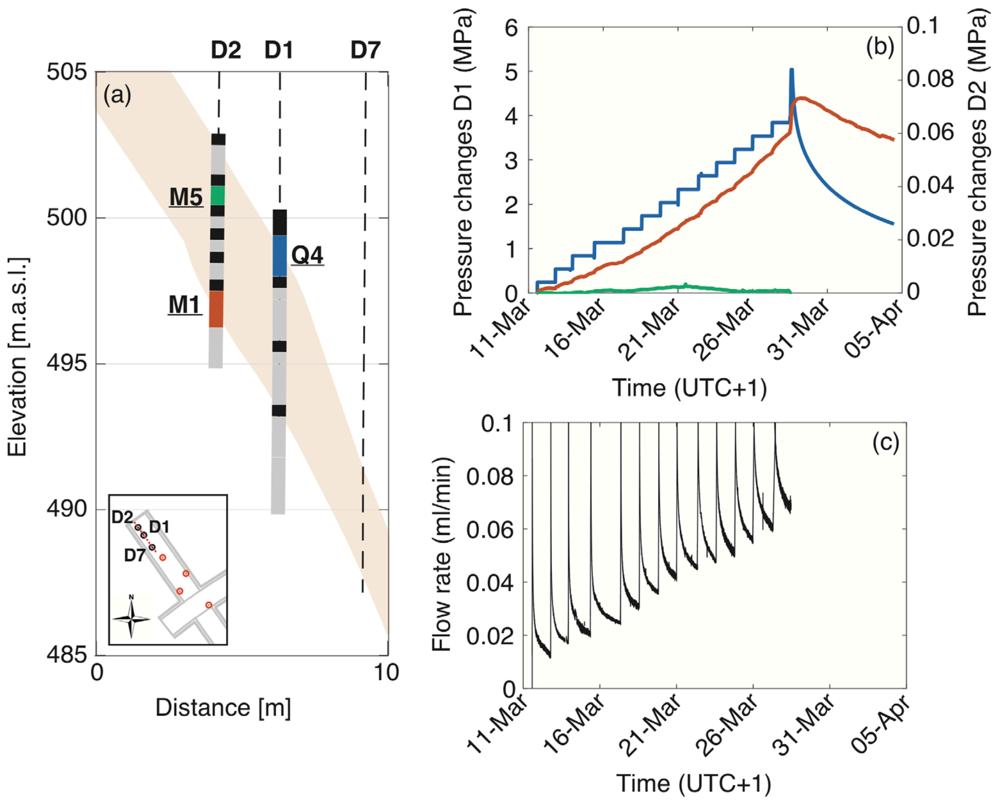
2019
2020

Fault transmissity 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_{max} 4.8 Mpa (FOP)

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

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

Estimated transmissivity at FOP: 9 ▪ 10^{-12} m^2/s

Active/passive seismic monitoring

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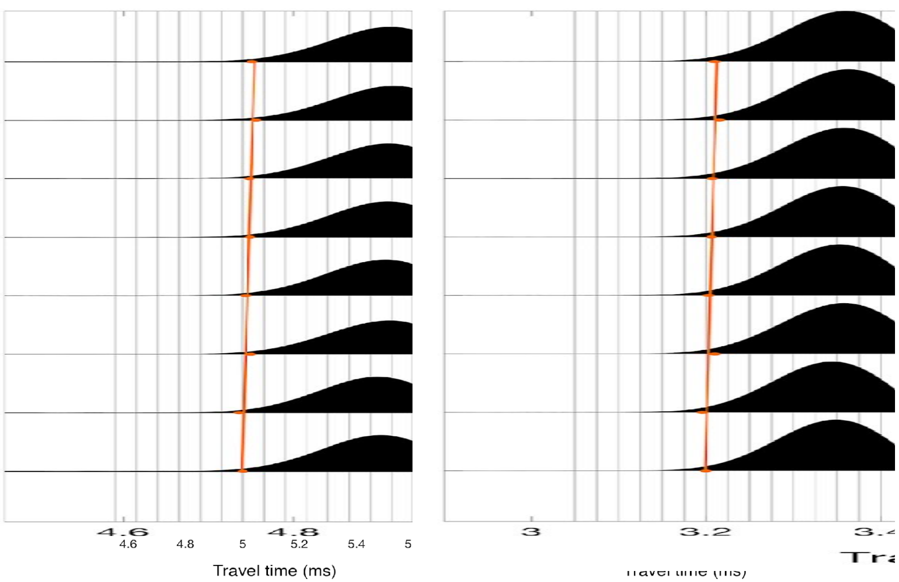
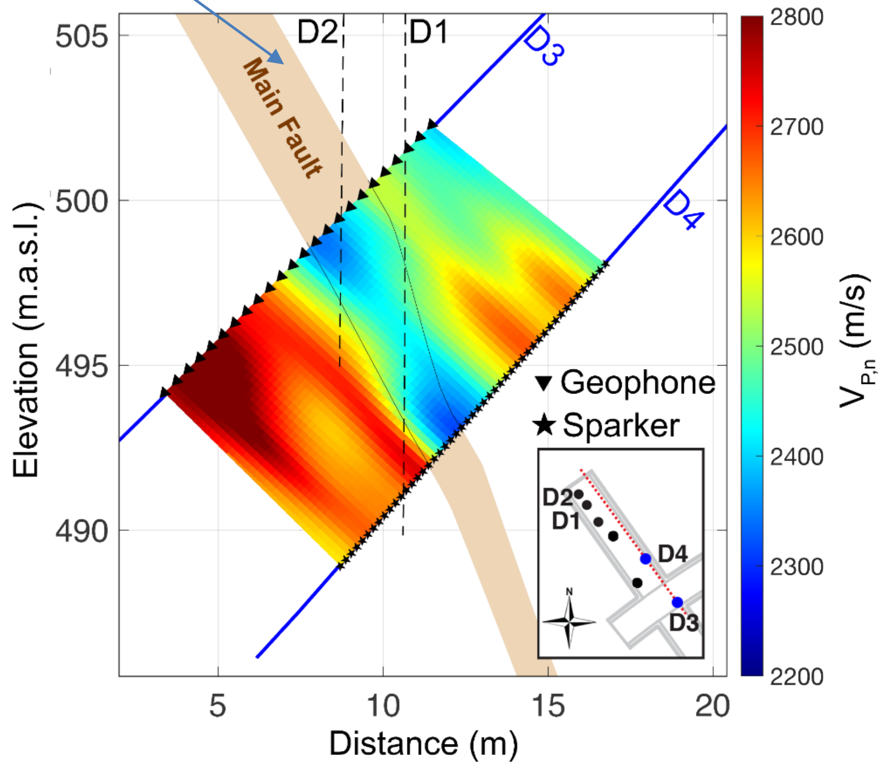
- The fault at Mont Terri could be nicely detected by seismic tomographic data.
- Seismic velocities are sensible to pore pressure variation in the system with c.a. ~1 % variation (P waves)



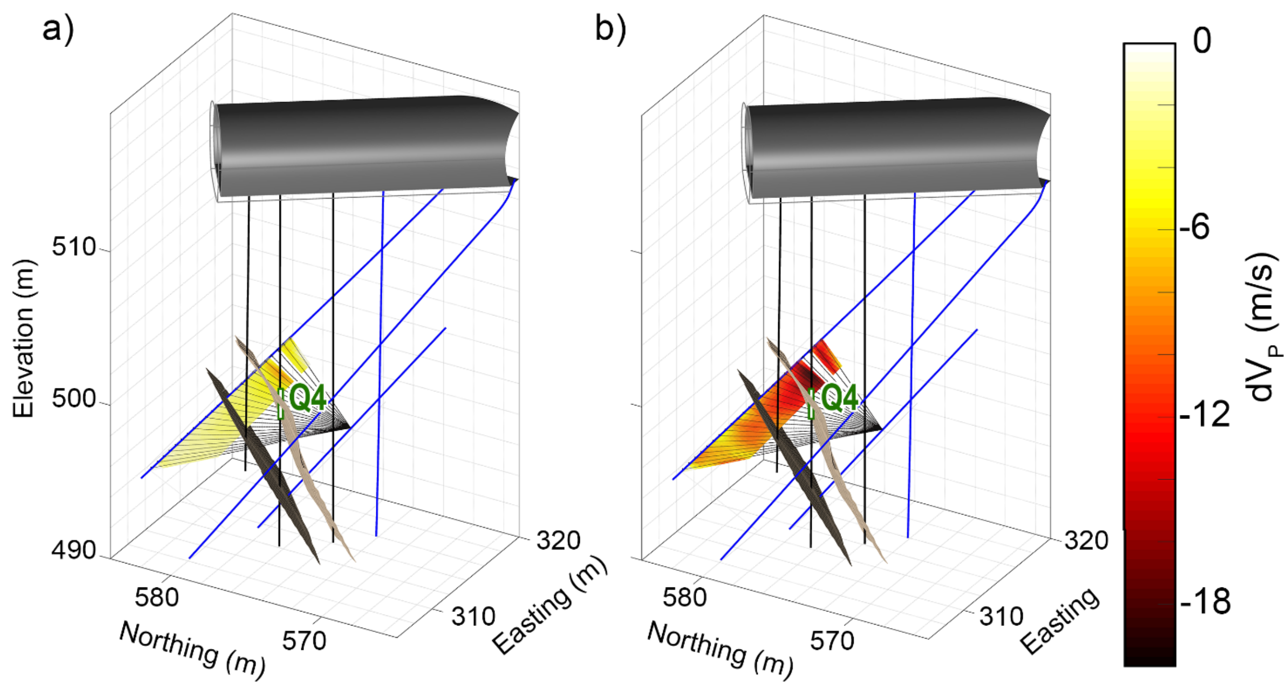


- No notable induced microseismic event was recorded.

Active seismic monitoring

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



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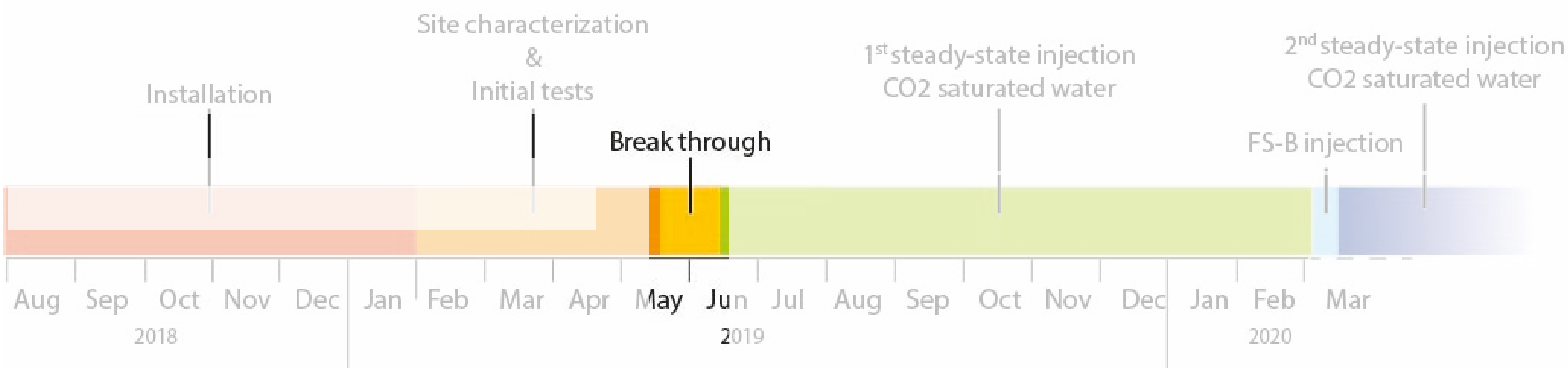

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Deformation and slip during break through

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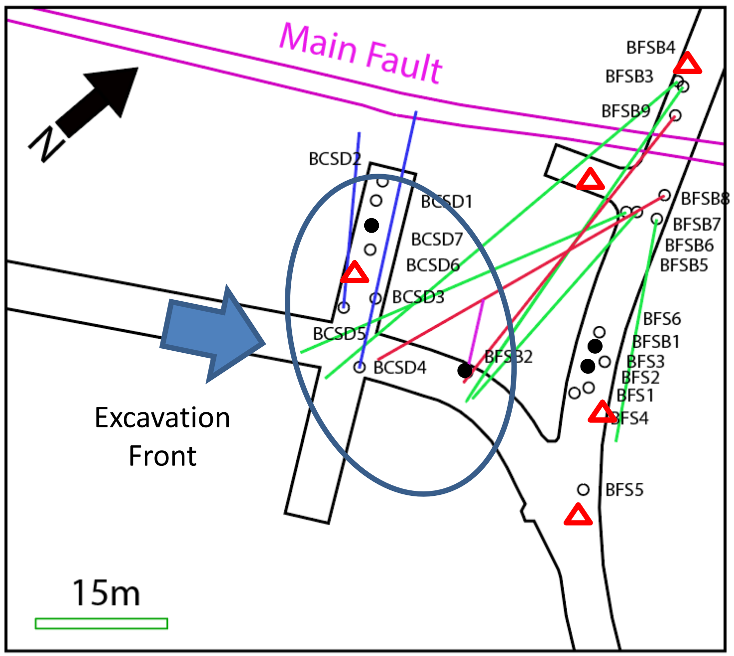
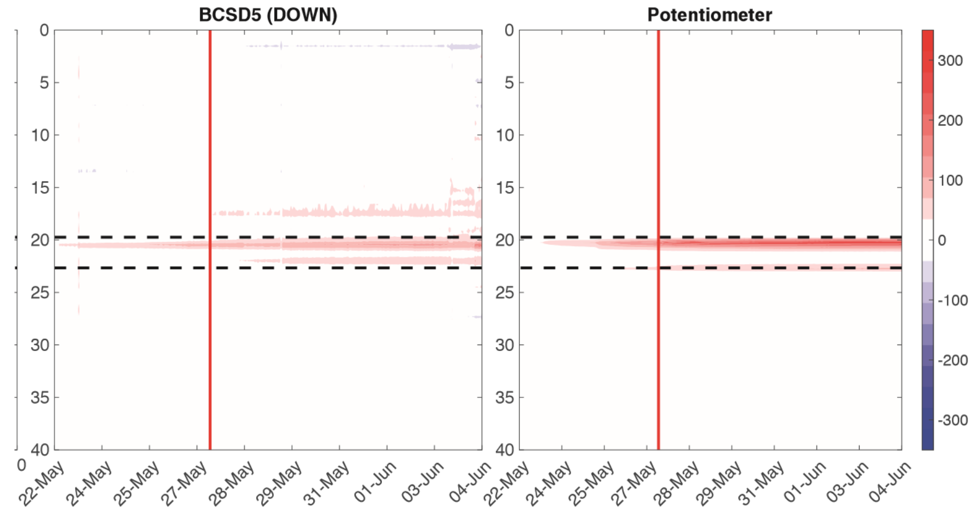
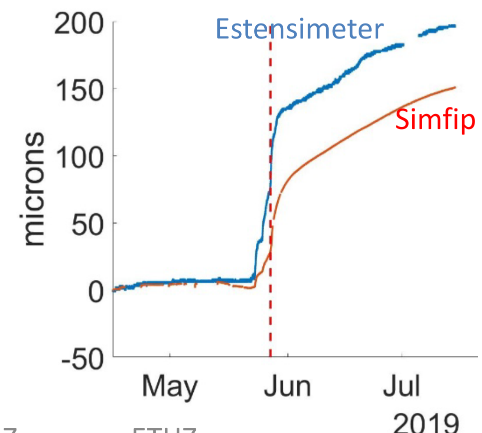
(Y. Guglielmi, D. Rebscher)

- 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

Normal opening
After excavation

Some observations from Phase 1

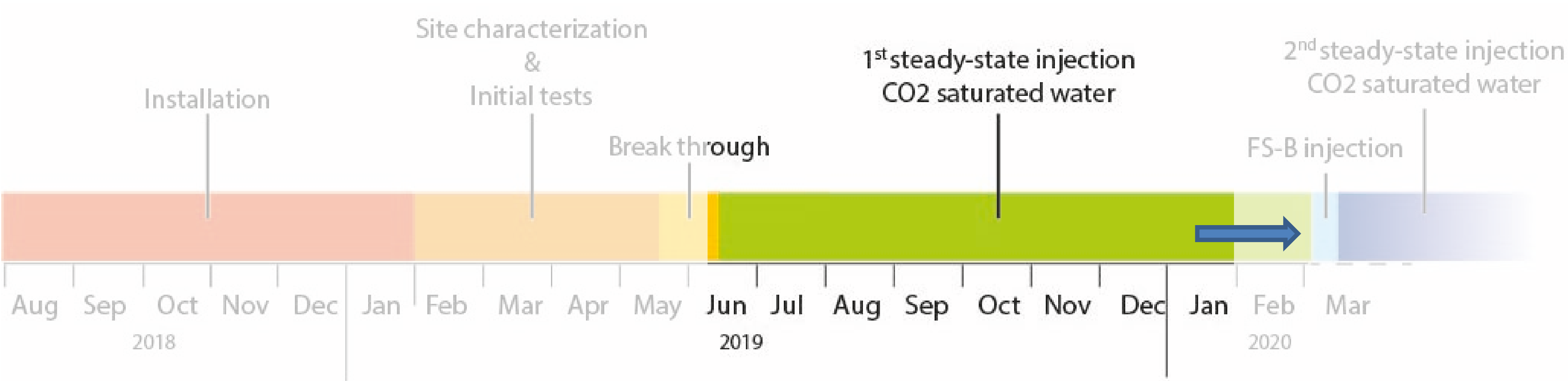
- Fault Transmissivity: ~10^{-13} m^2/s ; Permeability: ~10^{-21} m^2
- Fault opening pressure c.a. 4.8 MPa

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

- No seismicity was detected during injection activities

- Fault response to fault excavation (collaboration with LBNL & BGR)

Phase 2:



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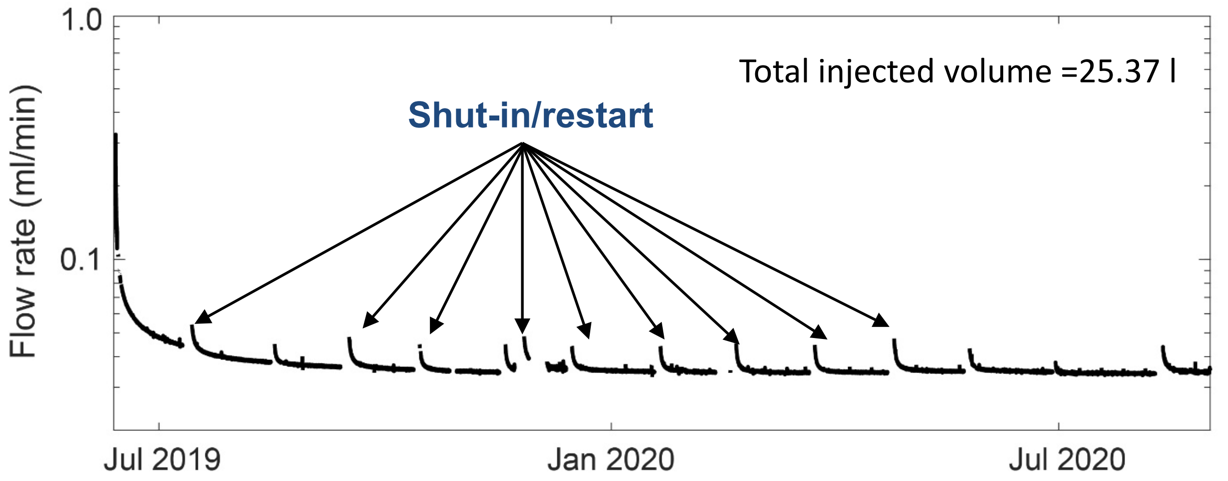
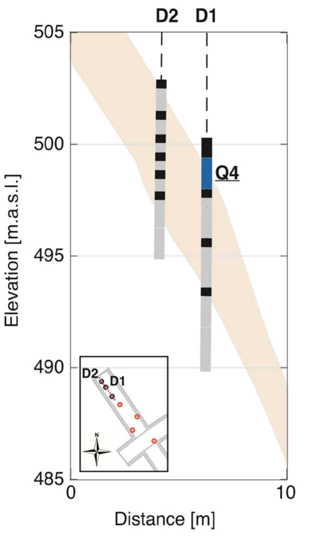
Injection of CO_2-enriched water

Phase 2: injection at 4.5 MPa, syn. water+Kr+CO_2 (mixed at about 2.2 MPa)

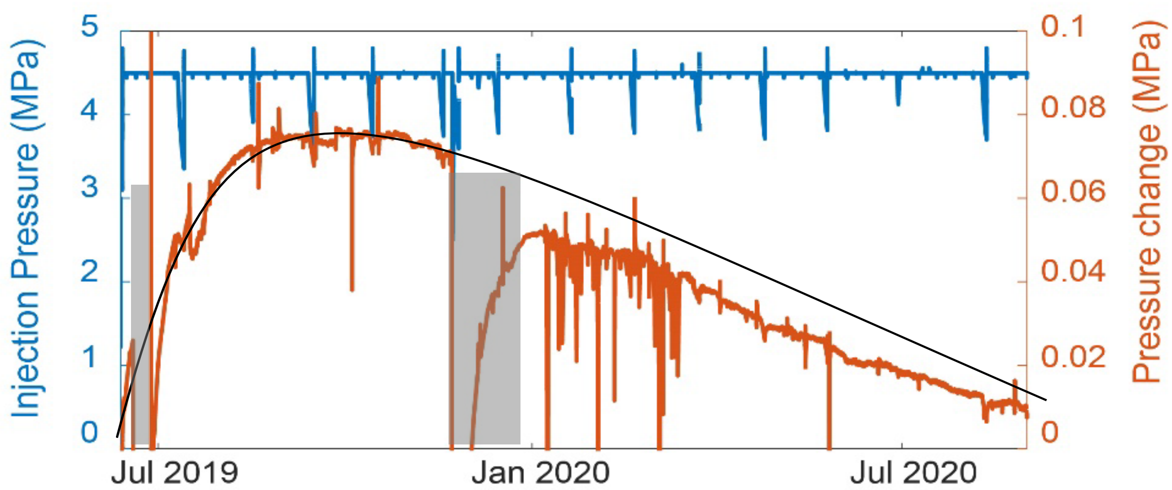
- Constant pressure of 4.5 MPa
- Injection fluid: Pearson water+Kr+CO_2 (mixed at about 2.4-2.7 MPa)
- Flow rate steady-state value of about 0.035 ml/min (Fig. 2a).

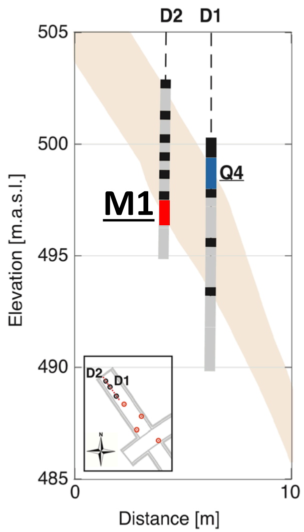




Injection of CO_2-enriched water

Phase 2: injection at 4.5 MPa, syn. water+Kr+CO_2 (mixed at about 2.2 MPa)

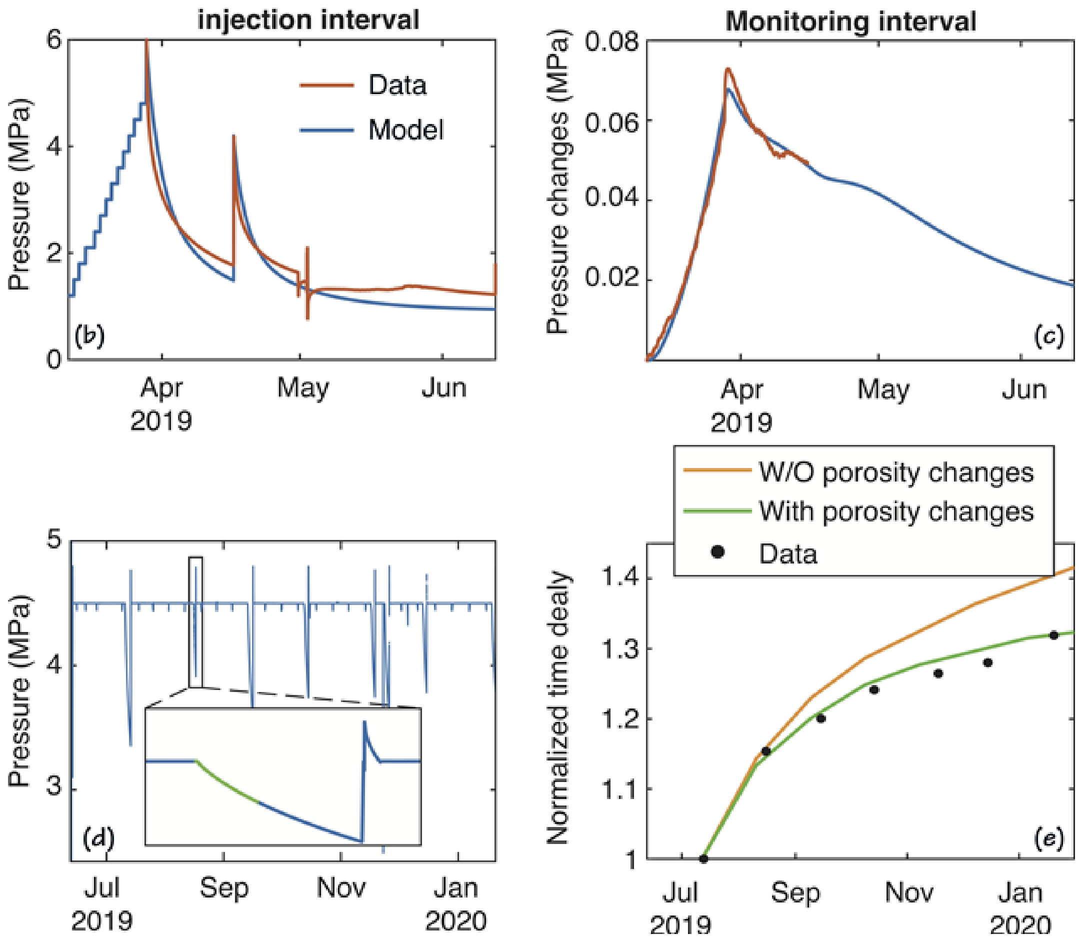


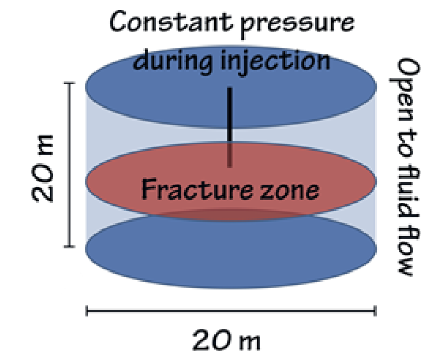


Pressure at monitor first increased then decreased after plateau
Could it be fault/fracture self-sealing?
Swelling?

Modeling the injection

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

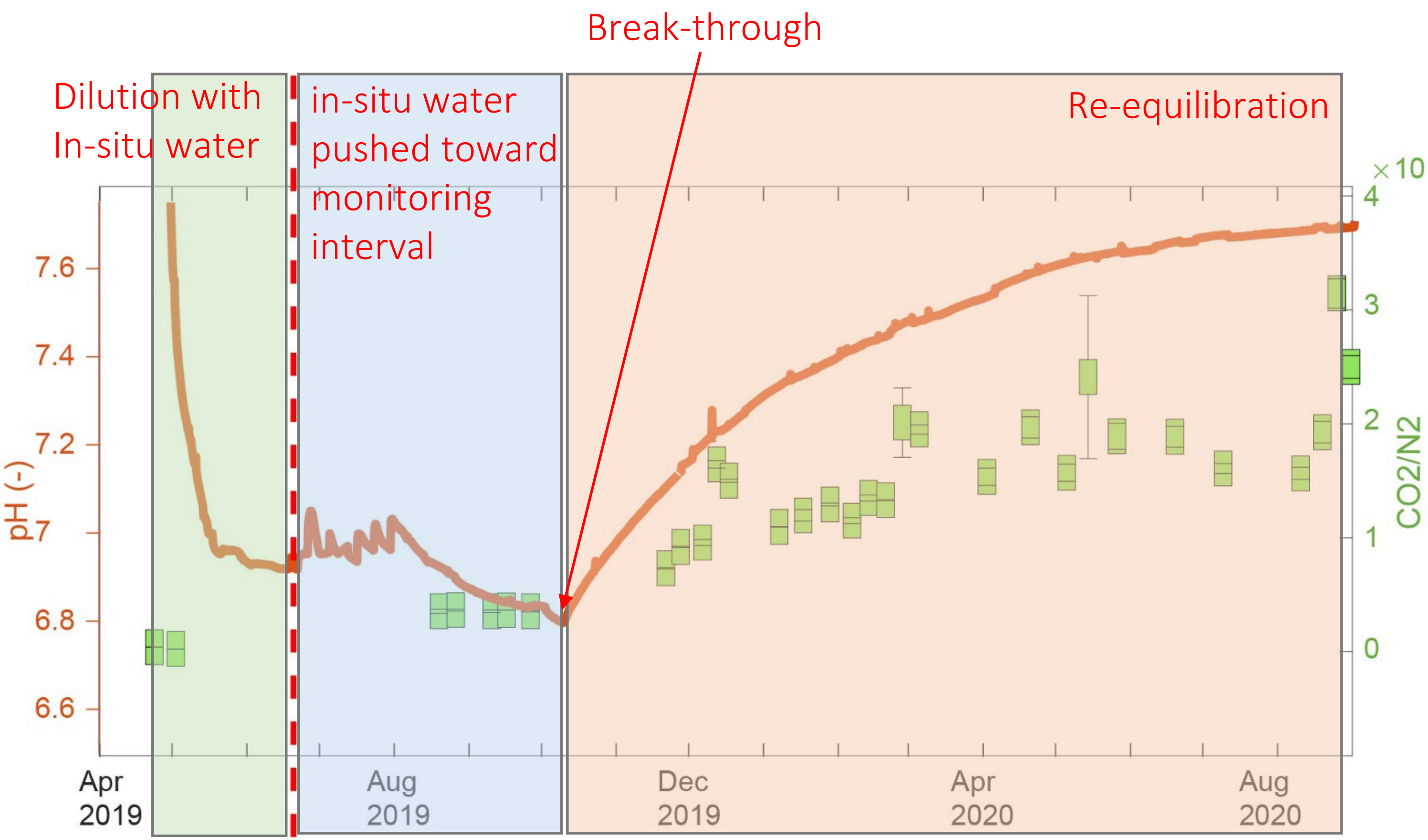


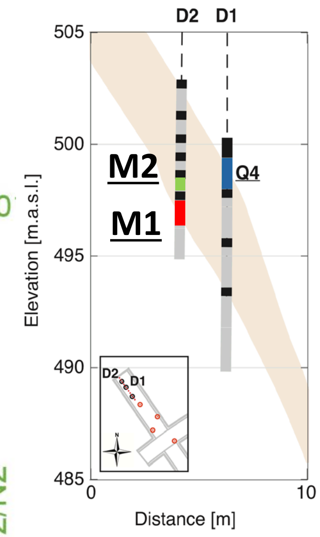


The behaviour at the monitoring point is captured when assuming the fracture not directly connected to the near well region, and allowing for closure (lower permeability) during shut-in (c).
The trend in (e) better agrees with a model where the porosity decreases in the vicinity through time of the injection 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

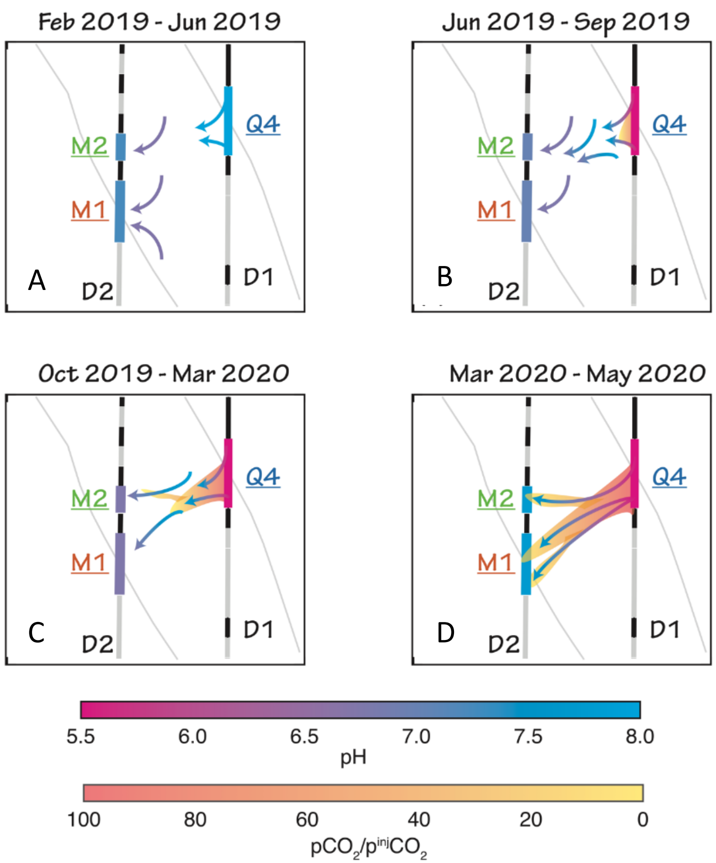
Phase 2: injection at 4.5 MPa, syn. water+Kr+CO_2 (mixed at about 2.2 MPa)





pH synt. water in D2=7.8
pH injected water (syn+CO2)=5.5

Conceptual model



A) The limited fluid injected do not travel far from the injection point, some **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) **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. CO_2 has not travel far from the injection point, and it has then not reached the monitoring borehole

C) **Breakthrough** in October 2019. CO_2-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 CO_2-rich water arriving at the monitoring, but with a pCO_2 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 CO_2. The mass spectrometer measurement confirms the increasing CO_2 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 CO_2 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 CO_2 and a pH below 7.8.

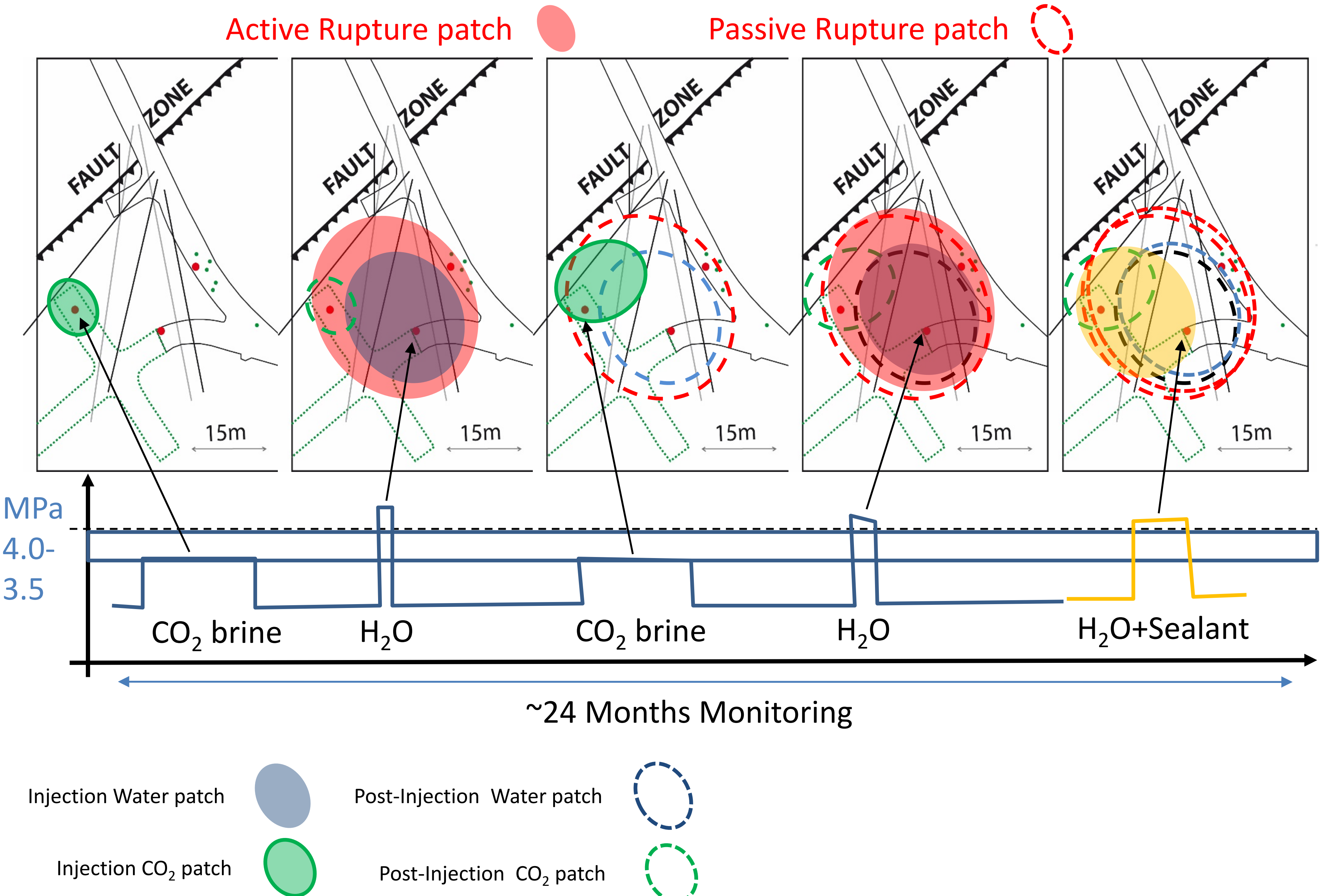
Some observations from Phase 2

- 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



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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Acknowledgements

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