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ELEGANCY

Laboratory Studies to Understand the Controls on Flow and Transport for CO_2 Storage

Ronny Pini

Chemical Engineering Department, Imperial College London

Brussel / November 8 2018

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The team

- PIs: Ronny Pini and Sam Krevor
- PDRAs: Swapna Rabha and Sojwal Manoorkar

- Funding:

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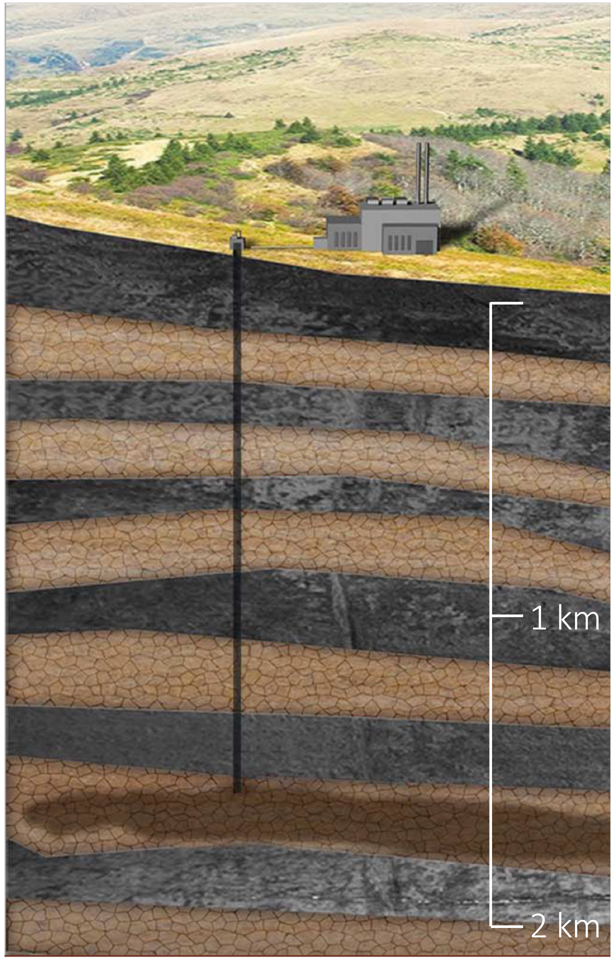
Geologic Carbon Storage (GCS)

- A process designed to store CO_2 in the subsurface safely and to prevent its re-entering the atmosphere
  - Storage in depleted oil and gas fields
  - Storage in deep saline rock formations
  - Storage as part of enhanced oil recovery
  - Storage in coal seams, shales, basalts



[*Image adapted from* Science of Carbon Storage in Deep Saline Formations – Process Coupling across Time and Spatial Scales, Ed. P. Newell and A. G. Ilgen, 2019, Elsevier]

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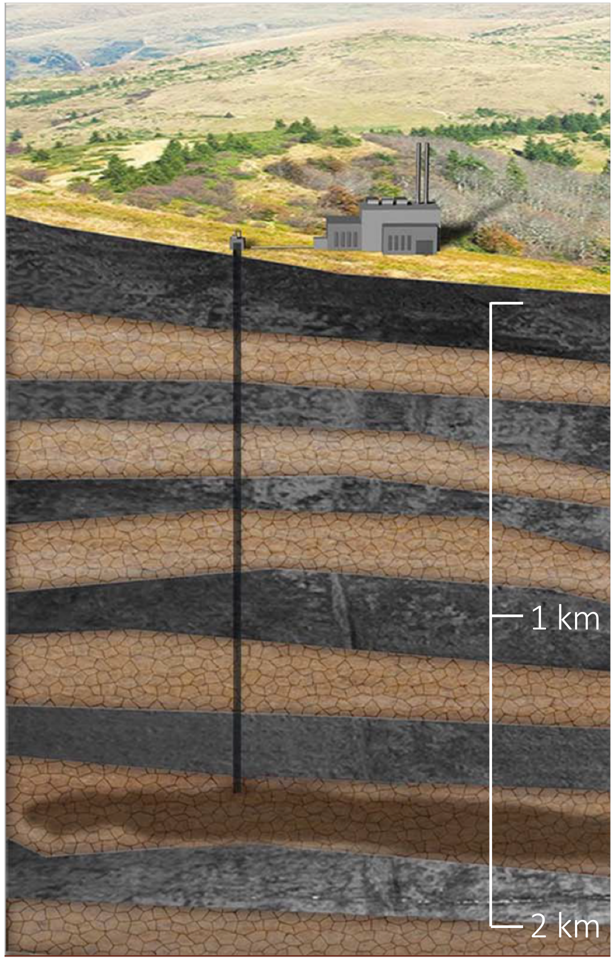
Sealing formation (caprock)

Storage formation



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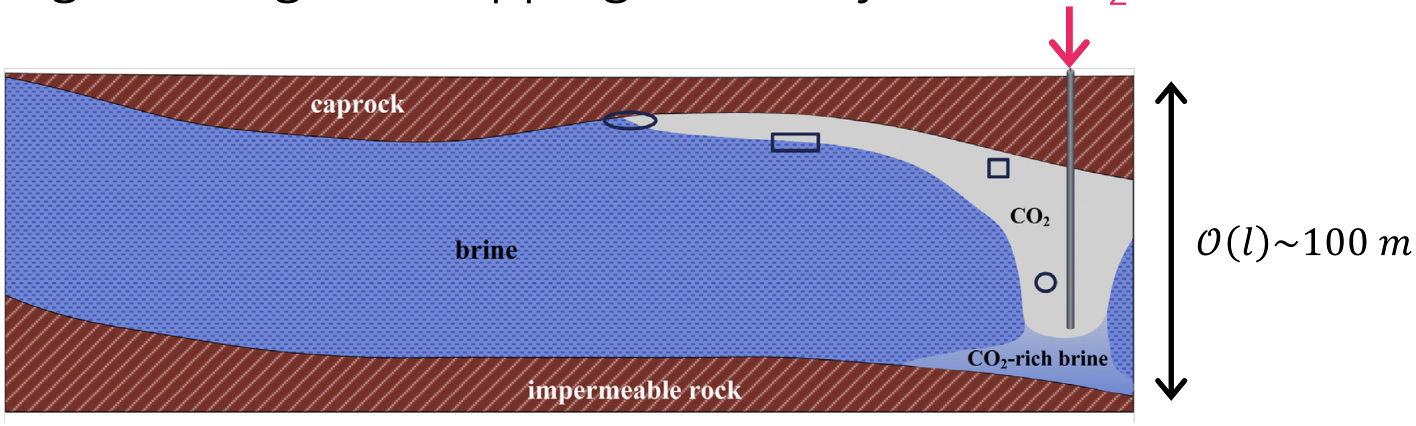
Geologic Carbon Storage (GCS)

- A process designed to store CO_2 in the subsurface safely and to prevent its re-entering the atmosphere
- The injection technology is known in the oil/gas industry, where CO_2 has been used for Enhanced Oil Recovery (e.g., SACROC unit in TX, USA ~ 90 Mt [1])
- GCS knowledge base has continuously improved thanks to several megaton-scale demonstration projects over the past two decades (e.g., Sleipner ~ 17 Mt to date [2])
- Technology is mature at the level of 1–4 Mt/year per project, but needs to ramp up to the Gt/year scale
- GCS currently represents the only viable approach to isolate large volumes of CO_2 from the atmosphere

[1] Han et al **2010** *Am. J. Sci.* 310:282
[2] Mission Innovation Report **2017** https://www.energy.gov/fe/downloads/accelerating-breakthrough-innovation-carboncapture-utilization-and-storage

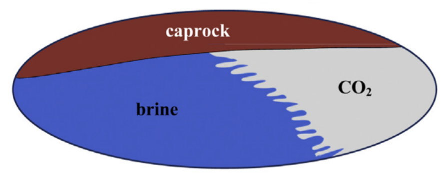
Geologic Carbon Storage (GCS)

Key processes governing the trapping of the injected CO_2

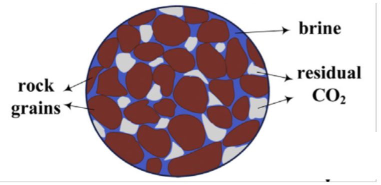


[*Image modified from* Emami-Meybodi et al **2015** *Int J Greenhouse Gas Control* 40: 238]

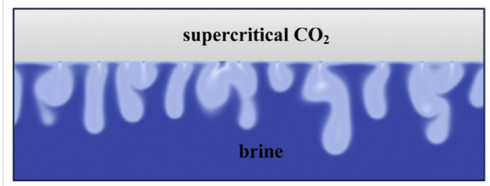
Structural trapping



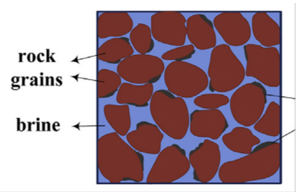
Capillary trapping



Dissolution



Mineralisation



Time since injection

Increasing storage security

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Challenges for GCS

- The subsurface is complex and was not designed by engineers!
- Natural heterogeneity at all scales affects flow and trapping processes
- This challenges our ability to exploit the available pore space efficiently and to reduce uncertainties around storage estimates

Key requirements for efficient and safe exploitation of the storage complex:

- Understanding CO_2 migration at multiple scales
- Understanding subseismic geologic heterogeneity and its impact on trapping
- Understanding of when and how caprocks fail

ELEGANCY addresses these challenges by combining laboratory- and pilot-scale studies

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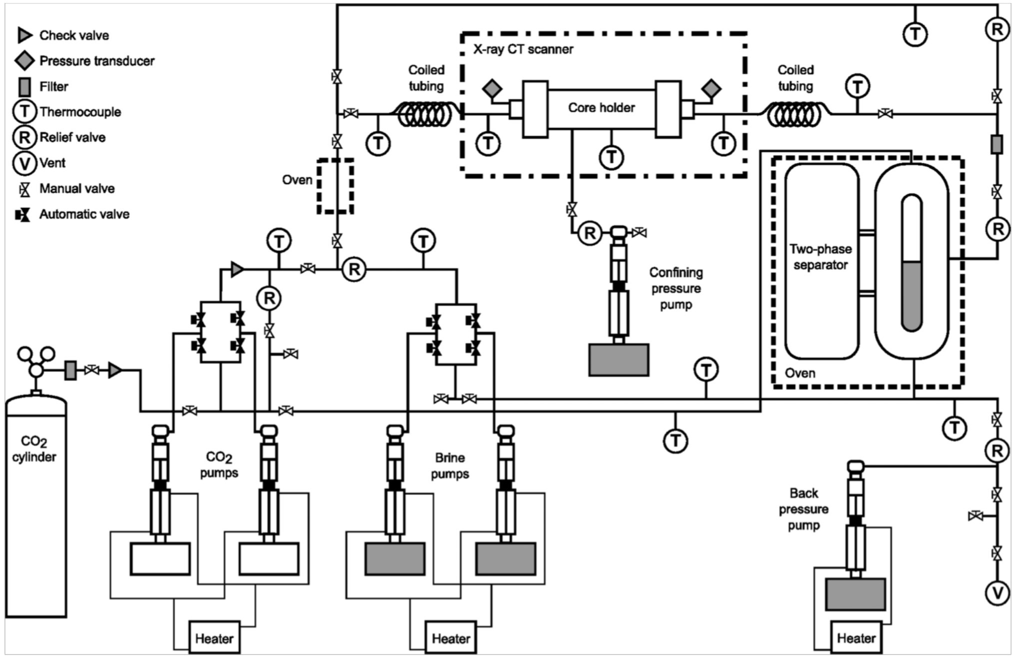
Advanced experimentation in the study of multiphase flows in reservoir rocks

Qatar CCS Multiscale Imaging Laboratory (Imperial College London, 2010)



Reynolds and Krevor **2015** *Water Resources Research* 51(12): 9464–89

- Reservoir condition core-flooding system
- P < 20 MPa, T < 90°C
- Rock cores, $\mathcal{O}(l) \sim cm - m$
- In-situ, operando imaging of flow by X-ray CT and PET, $\mathcal{O}(l) \sim mm$

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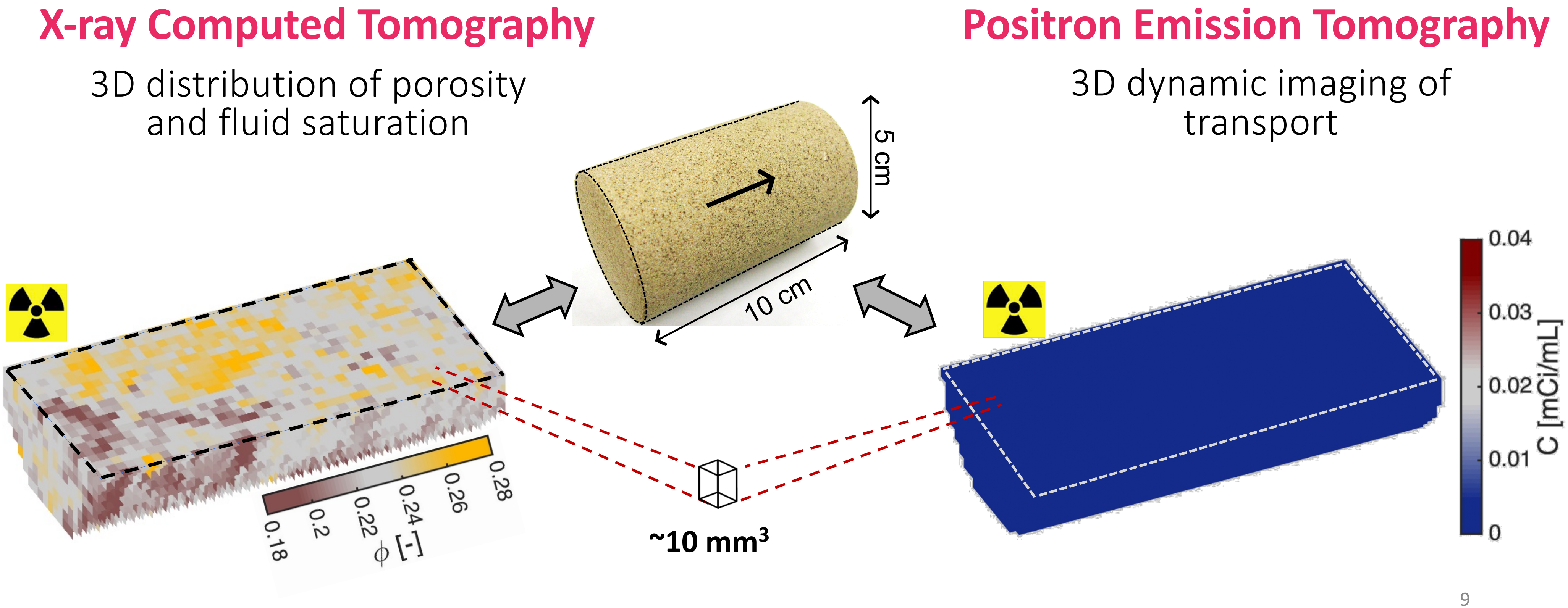
Imaging methods provide a new level of observational detail into properties and processes



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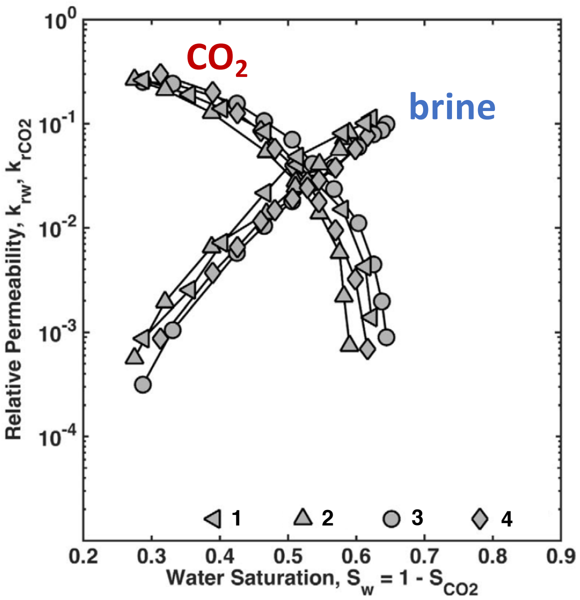
Measurements of the basic properties governing $scCO_2$/brine displacements

Relative permeability



- For $scCO_2$/brine, it is invariant across a wide range of pressure, temperature and brine salinity

P = 11 – 21 MPa; T = 38–42 ° C, salinity = 0 – 5 mol/kg (NaCl)

Niu et al **2015** *Water Resources Research* 51(4):2009–29
Al-Menhali et al **2015** *Water Resources Research* 51(10):7895–14
Reynolds and Krevor **2015** *Water Resources Research* 51(12):9464–89

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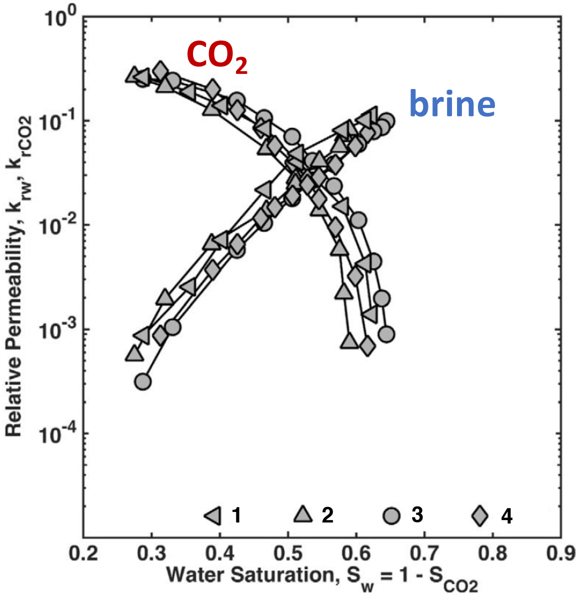
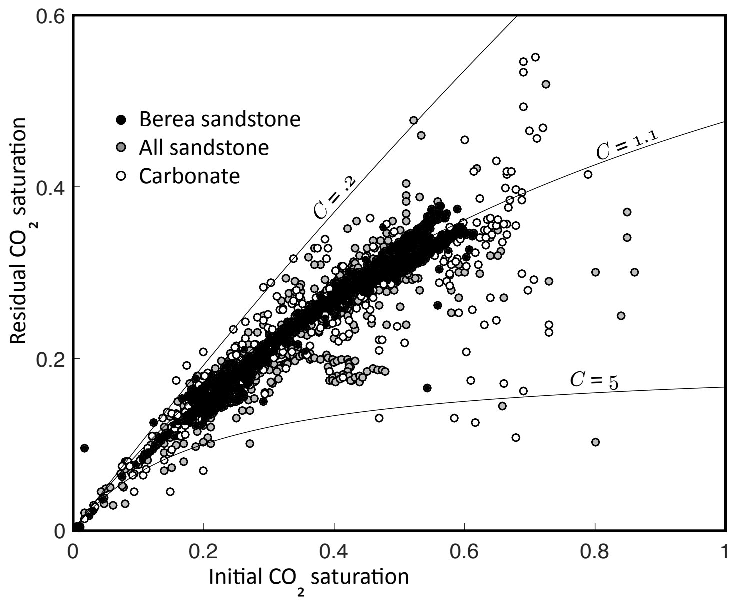


Capillary trapping



- Residual CO_2 saturation constitutes between 10–40% of the swept pore volume

- Stable up to 100 pore volumes injected

Niu et al **2015** *Water Resources Research* 51(4):2009–29
Al-Menhali et al **2015** *Water Resources Research* 51(10):7895–14
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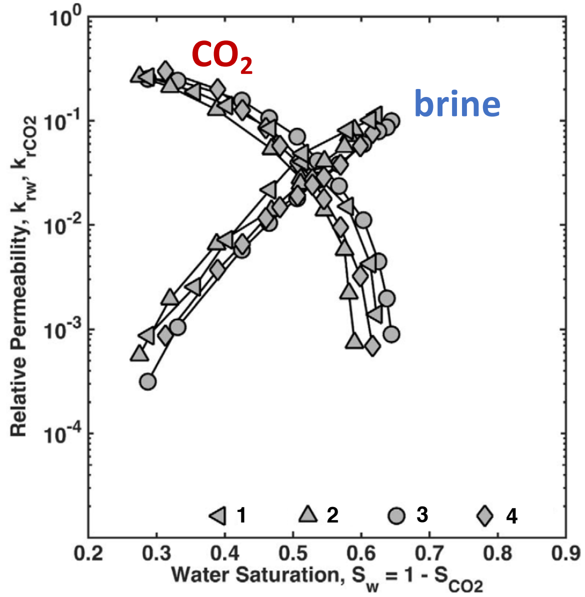
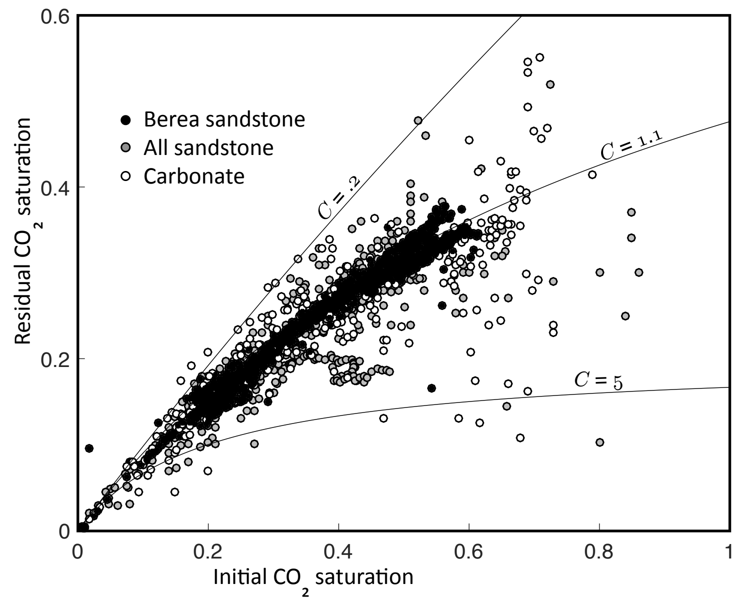
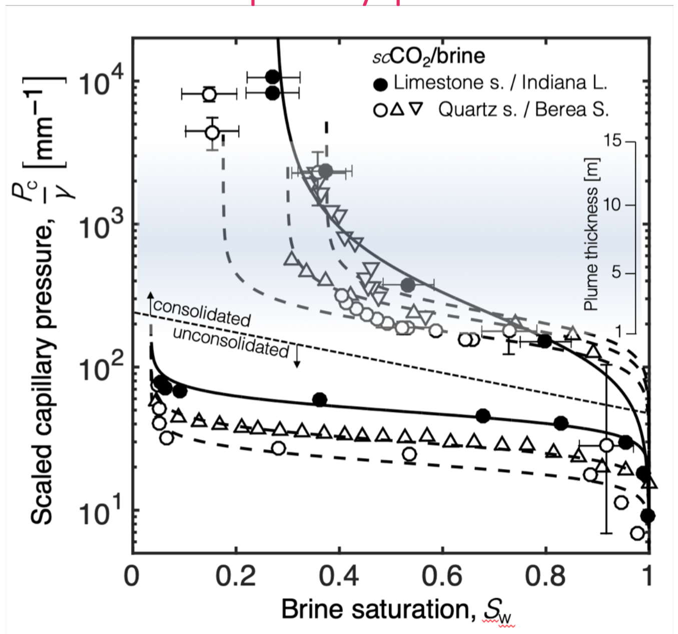


Capillary trapping



Capillary pressure



Niu et al **2015** *Water Resources Research* 51(4):2009–29
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Pini and Krevor **2019** *in* Science of Carbon Storage in Saline Aquifers. Ed. Newell and Ilgen, Elsevier

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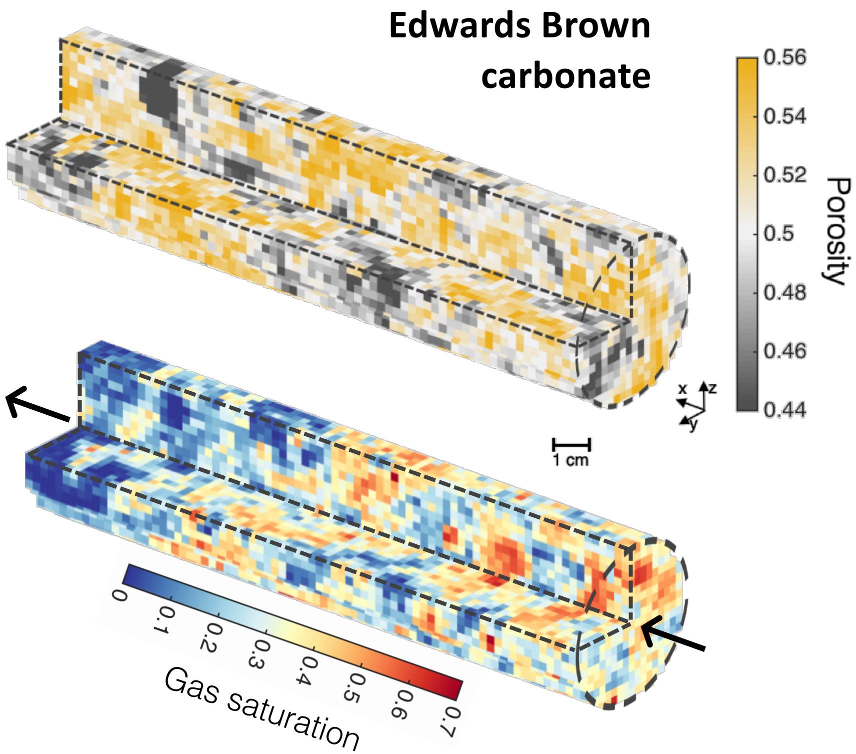
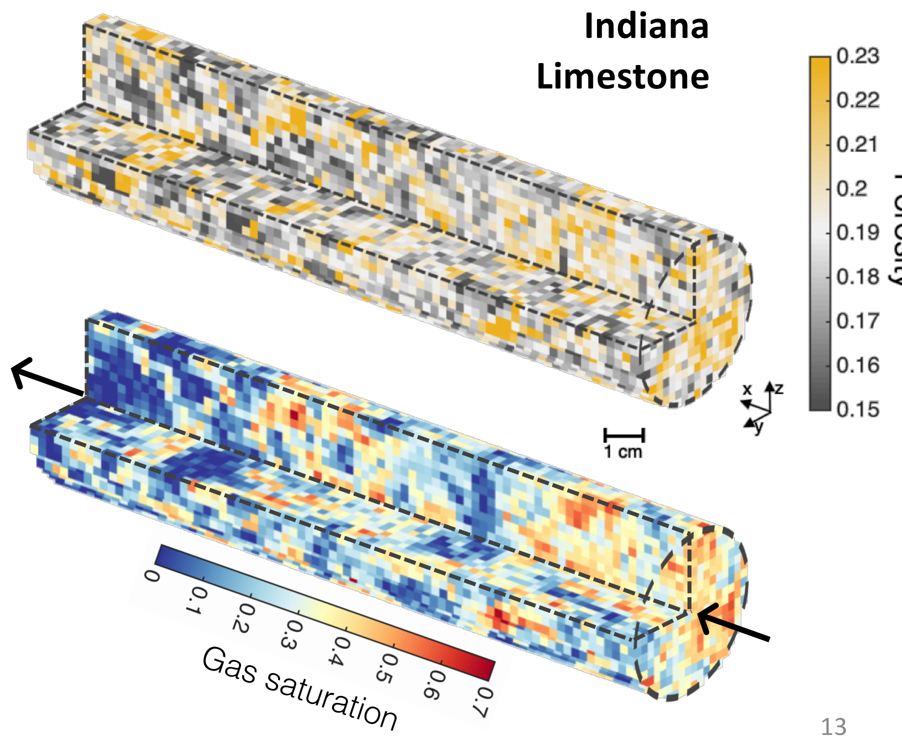
The low-viscosity contrast of $scCO_2$/brine makes the displacements dominated by capillarity

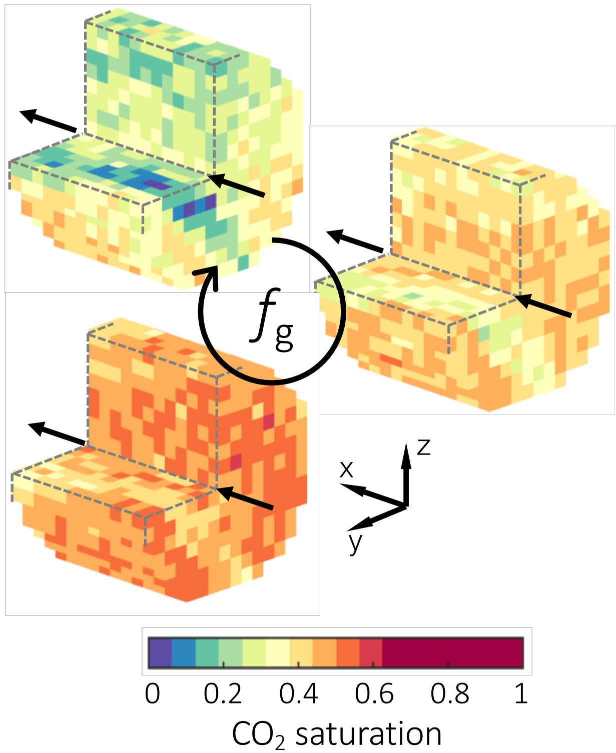
Fluid invasion largely controlled by the presence of subcore-scale heterogeneities

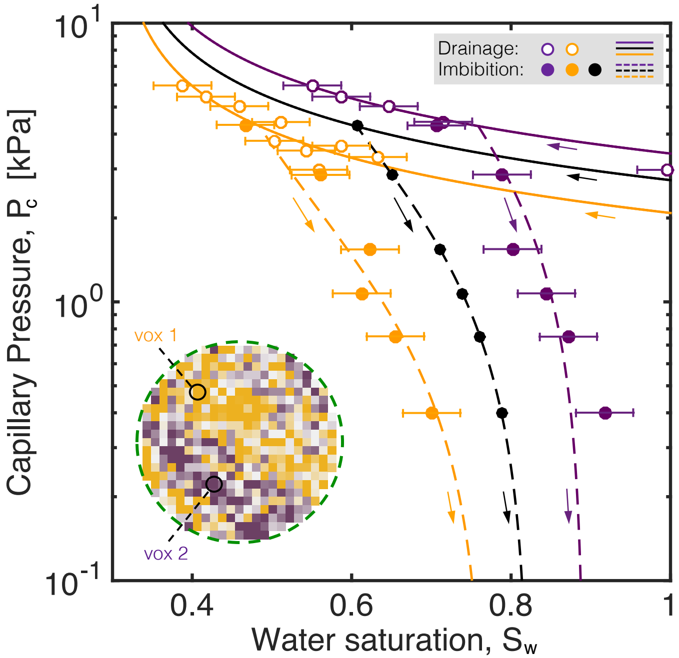




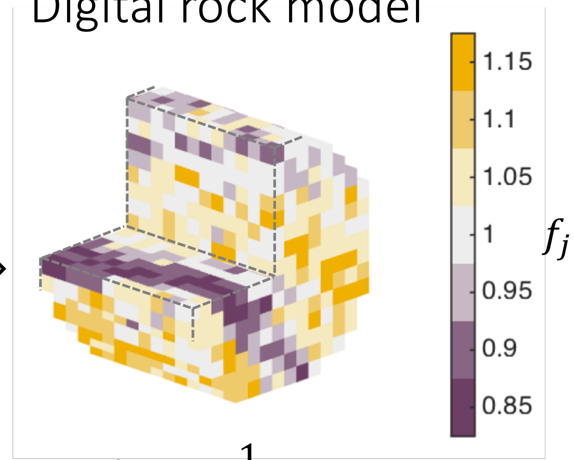
Subcore-scale capillary heterogeneity can be quantified experimentally

Local measurements of capillary pressure curves and parameterisation in a digital rock model





Digital rock model



$$p_c^j(S) = \frac{1}{f_j} p_c(S)$$

Pini et al **2012** *Adv Water Res* 28, 48–59
Pini and Benson **2013** *Geophys Res Lett* 40: 3903-8
Pini and Benson **2017** *Adv Water Res* 108: 277-92

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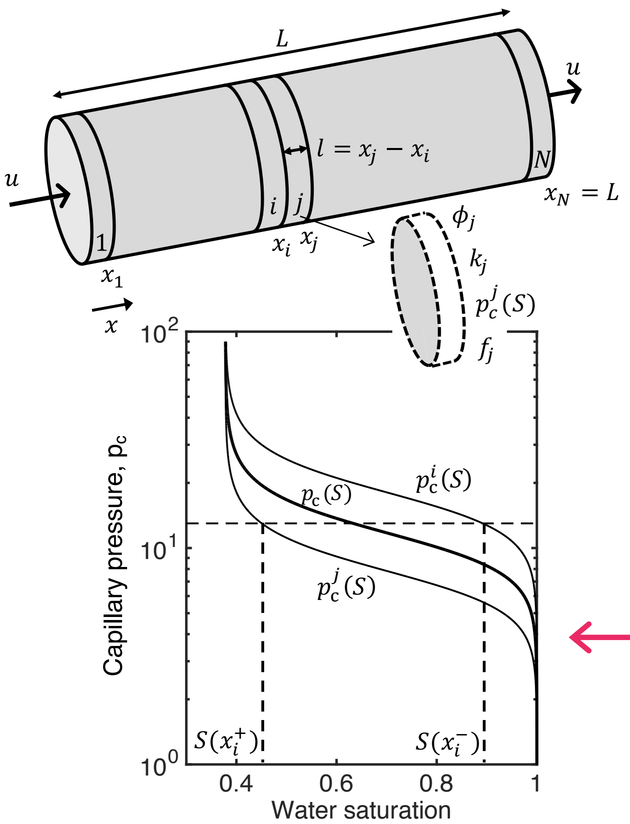
Digital rock models that account for subcore-scale heterogeneities



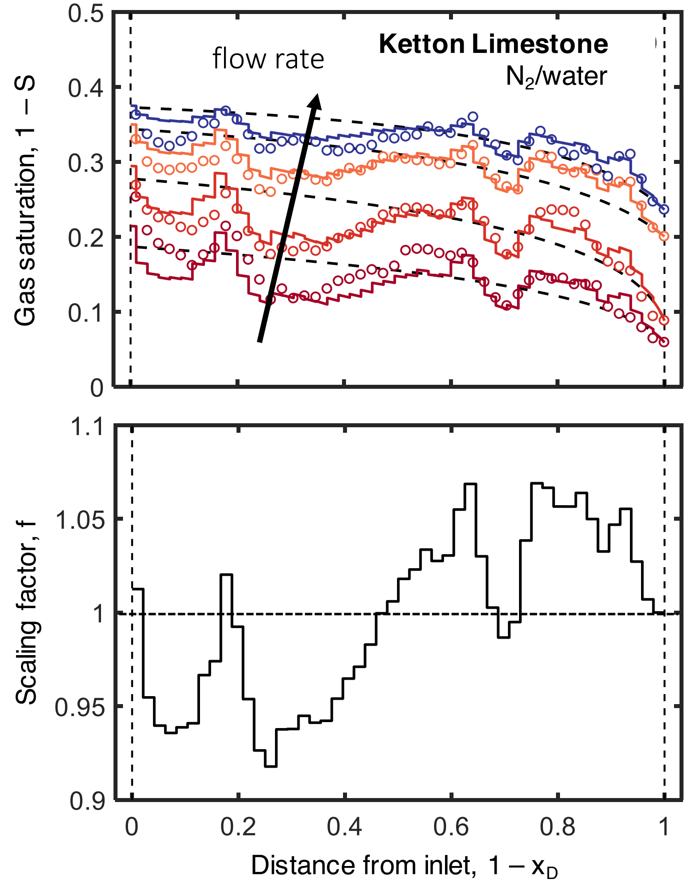
Steady-state multiphase of flow under local capillary equilibrium

$$p_c(S(x)) = p_{nw}(x) - p_w(x)$$

$$u_k = -\frac{k_m k_{rk}(S(x))}{\mu_k}\frac{dp_k(x)}{dx}$$

$$p_c^j(S) = \frac{1}{f_j} p_c(S)$$

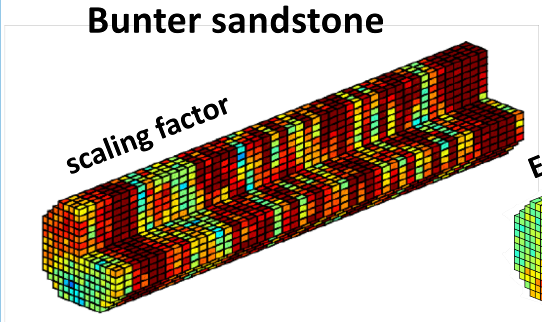
$$k = \mathrm{nw, w}$$

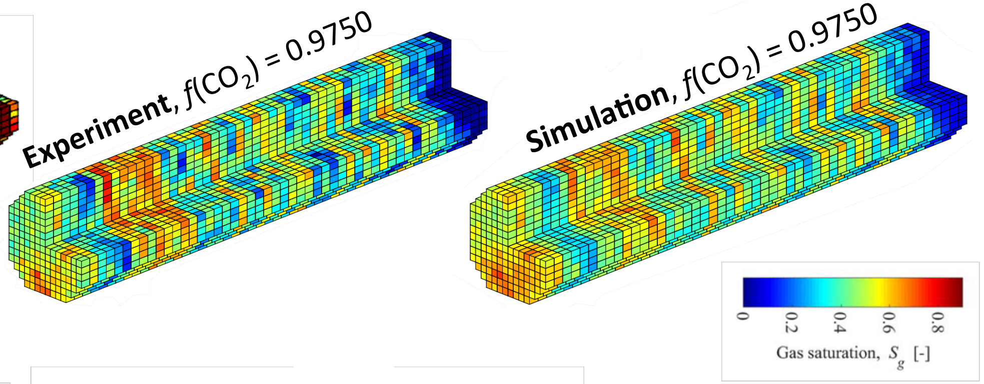


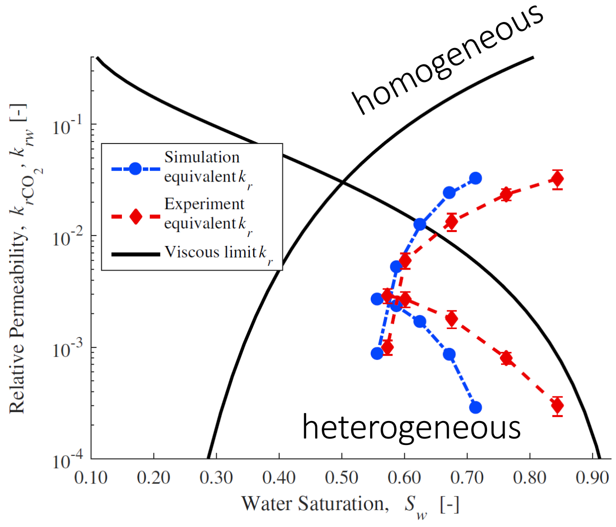
Hosseinzadeh Hejazi et al. **2018** *submitted*

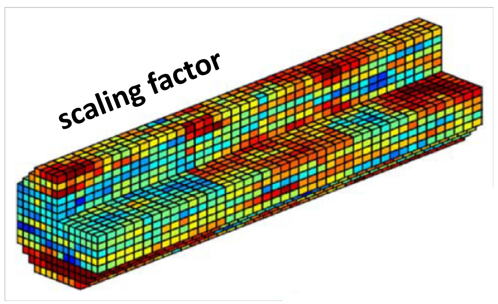
Beyond conventional core analysis

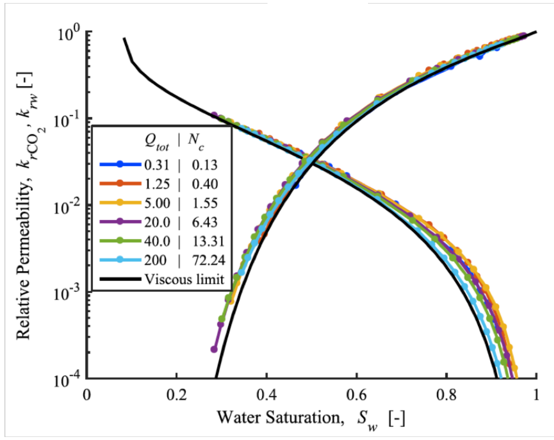
The calibrated numerical model is used to derive properties representative of subsurface flow regimes…









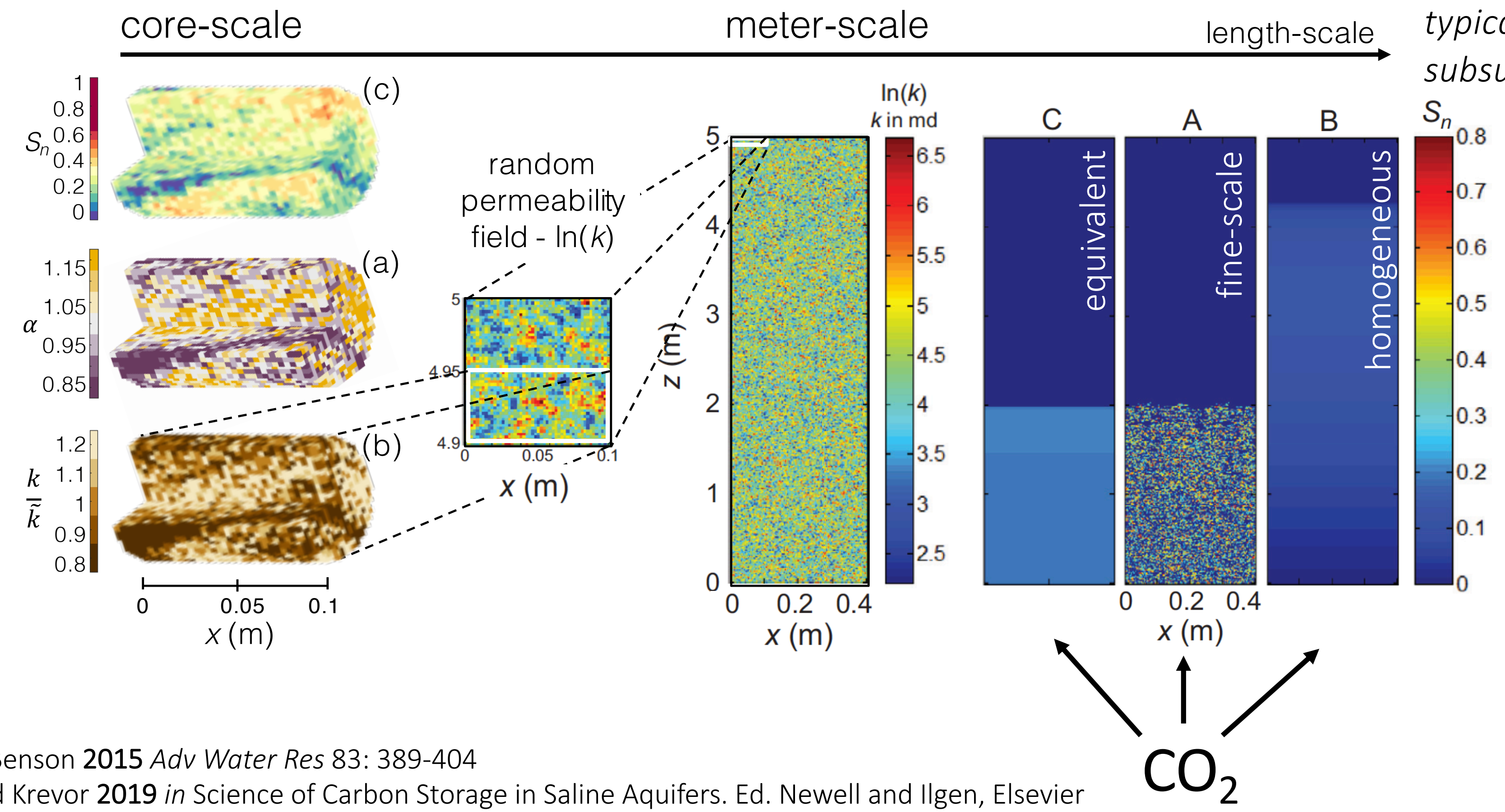


….and to build statistical realisations of synthetic cases with re-orientated heterogeneities

Jackson et al. **2018** *Water Resources Research* 54: 3139–61

Tackling heterogeneity across scales

Buoyant CO_2 flow through an uniformly heterogeneous aquifer



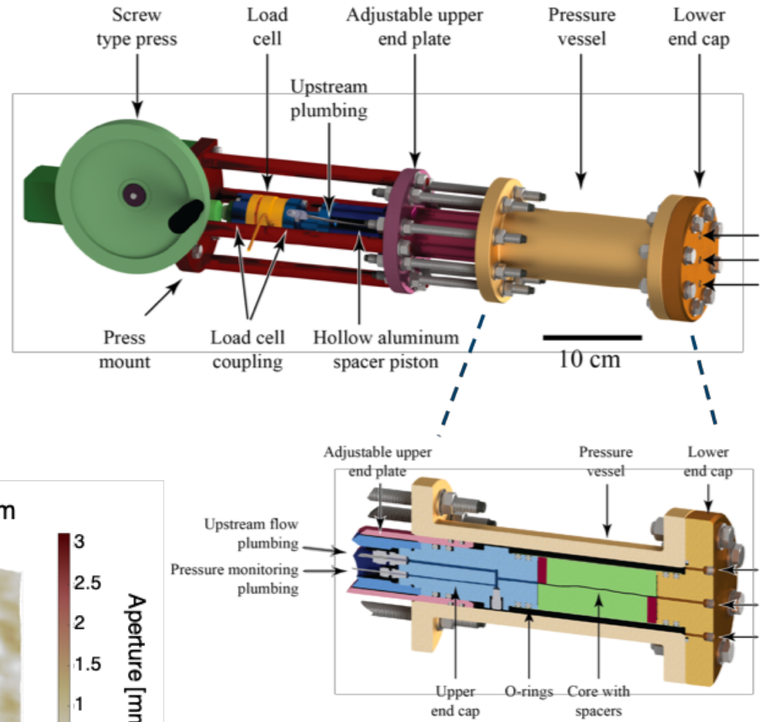
typical resolution limit of subsurface seismic imaging!

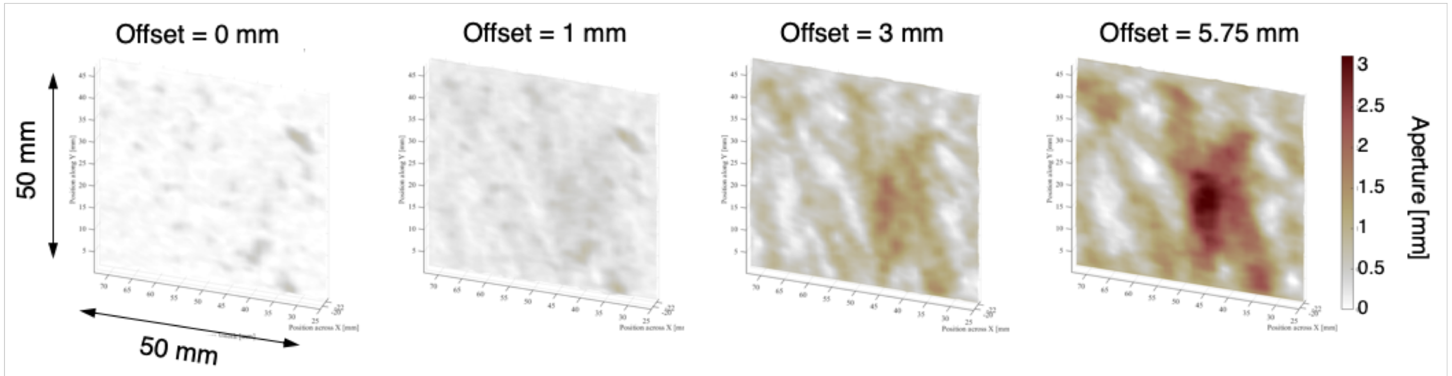
Li and Benson **2015** *Adv Water Res* 83: 389-404
Pini and Krevor **2019** *in* Science of Carbon Storage in Saline Aquifers. Ed. Newell and Ilgen, Elsevier

When and how does a caprock fail?

Flow pathways in fractured rocks depend largely on the stress conditions

- Support the design of Mont Terri field experiment
- Quantify fracture geometry during shearing
- Build a digital model of the fracture
- Observe and predict transport of tracers



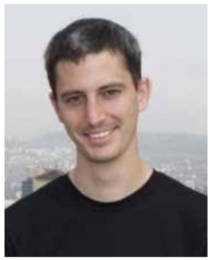


Decametre-scale experiment at the Mont Terri Underground Rock Laboratory (CH):

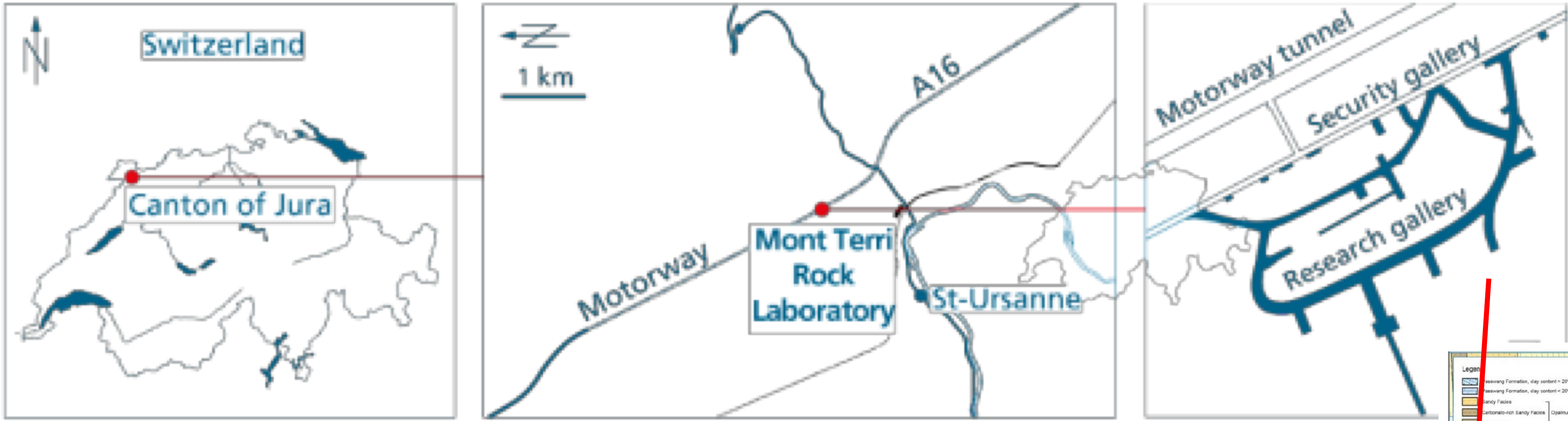
Injection of CO_2-rich brine in a fault zone

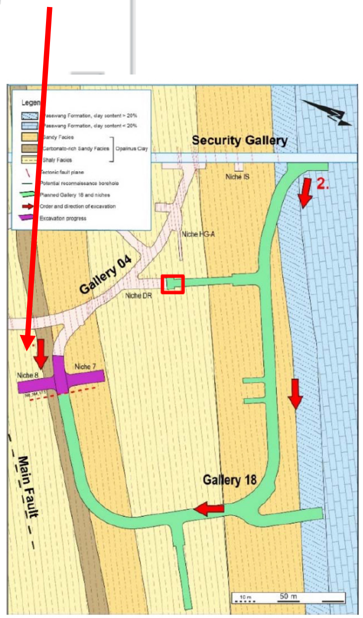
Projectmanager: Alba Zappone

Team: Melchior Grab, Claudio Madonna, **Anne Obermann**, Antonio Rinaldi, Quinn Wenning



Mont Terri Underground Laboratory (CH)





New niche build for this project.

Partners with CS-D

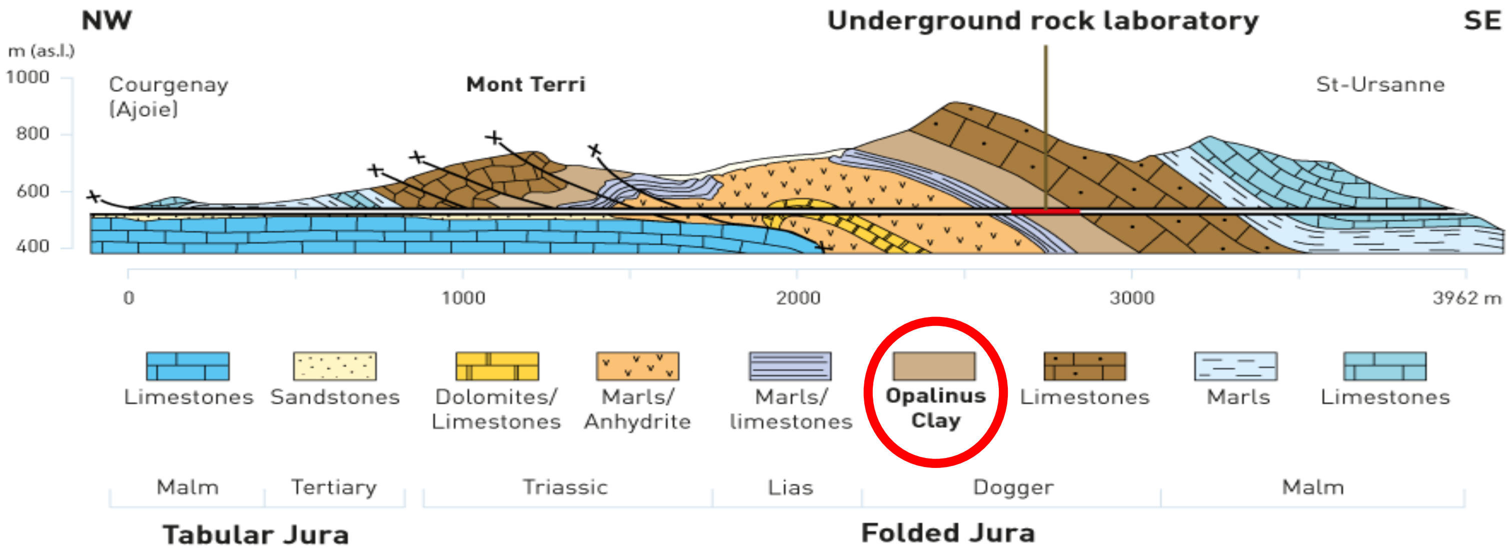
swisstopo

U.S. DEPARTMENT OF ENERGY

Chevron

TOTAL

Mont Terri Underground Laboratory (CH)



Opalinus Clay: Typical low permeability rock that acts as a cap rock in reservoirs.

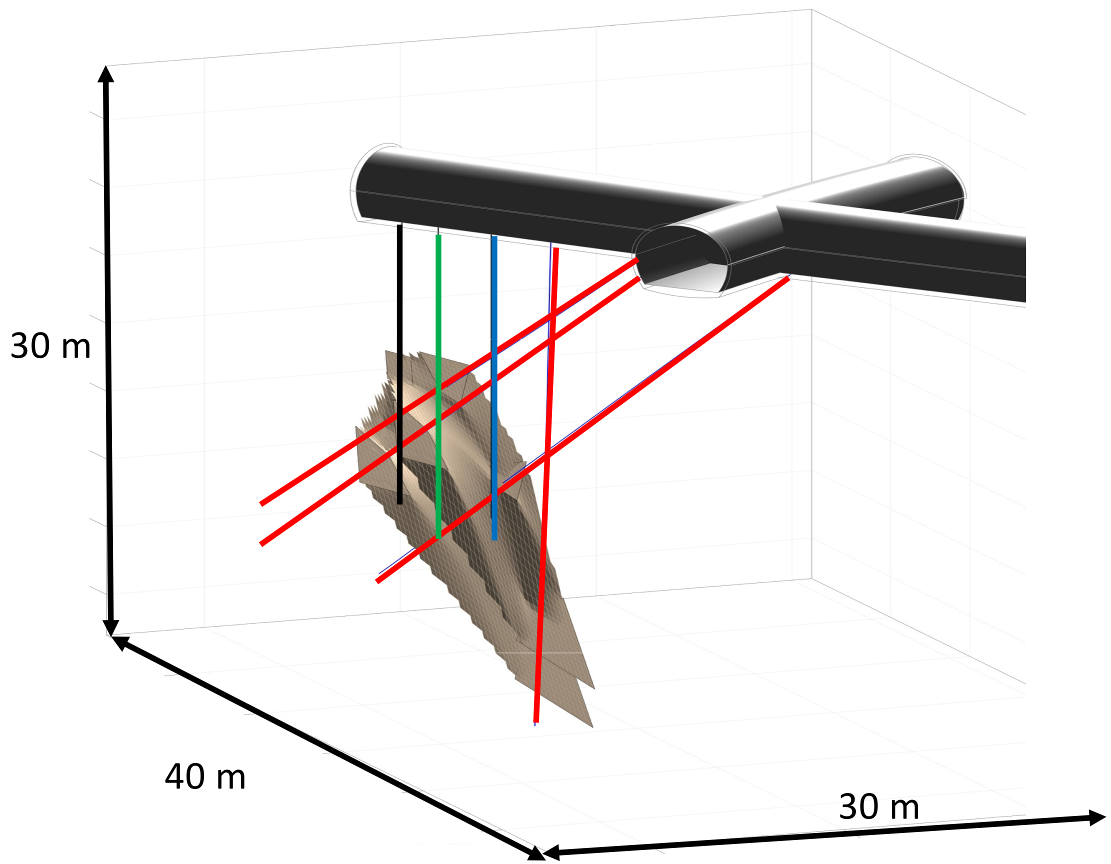
Ideal rock to capture CO2?
What happens in the presence of faults? Sealing integrity affected?

Scientific objectives

- Understanding how the exposure to CO_2-rich brine affects **sealing integrity** of a caprock (hosting a fault system): permeability changes? Induced seismicity?
- **Direct observation** of fluid migration of along a fault and its interaction with the surrounding environment
- **Quantification of fluid interactions** with the host rock
- Development and testing of improved and integrated **monitoring technologies** in a relevant environment (clay-rich seal rock)
- Validate Thermo-Hydro-Mechanical-Chemical **(THCM) simulations**

What is the extent of the migration of CO_2-rich brine?

Experiment Design



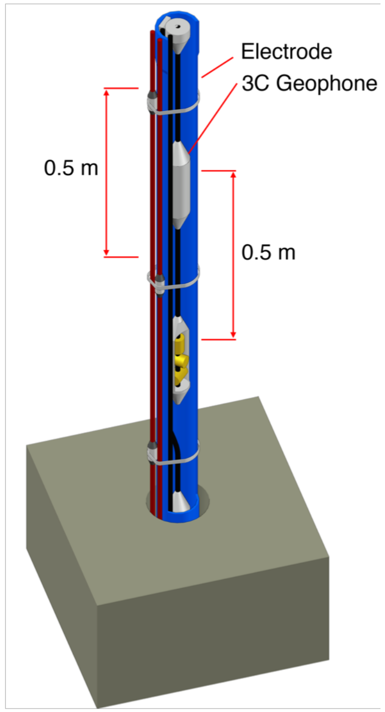
4 Boreholes for geophysical monitoring

- Active seismic tomography
- Electrical resistivity tomography (ERT)
- Passive seismic monitoring for the case of induced seismicity

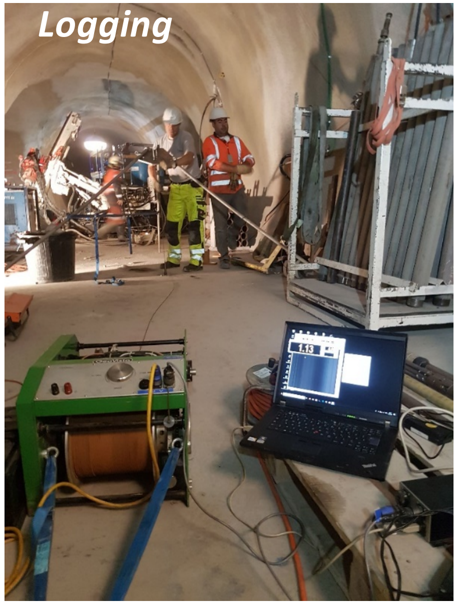
Injection Borehole

Fluid Monitoring Borehole

SIMFIP – strain measurement



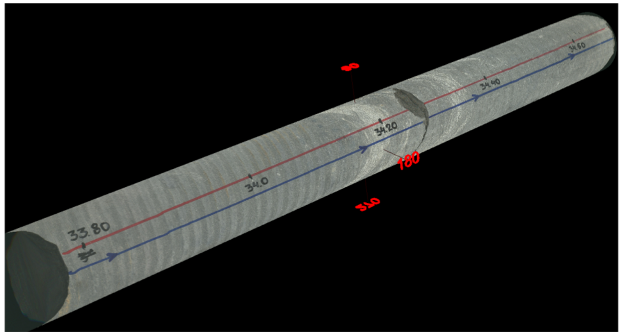
Experiment Execution (completed)



Core Logging and Fault mapping

CoreScan[3]

Roll scan for structure mapping



Top of Main Fault Zone

Un-deformed Opalinus clay

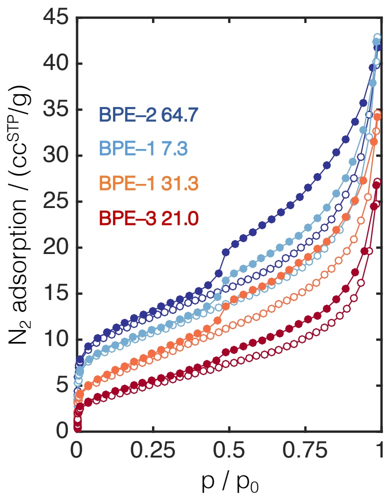
Top of Fault

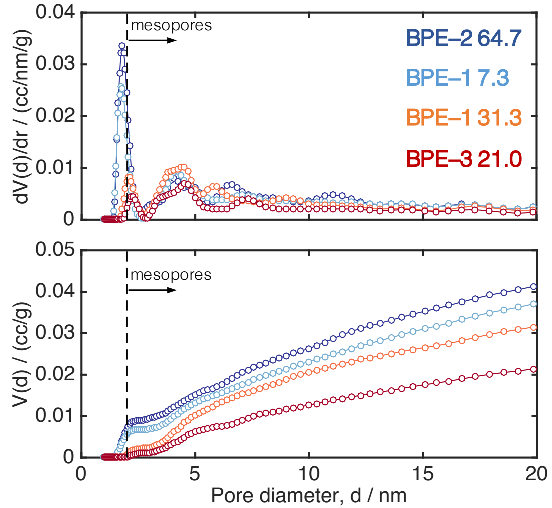
Highly deformed fault zone

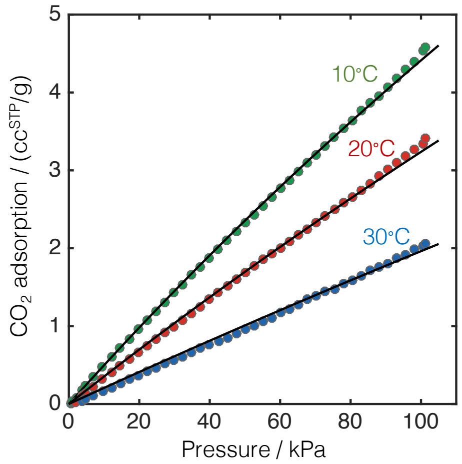
SE

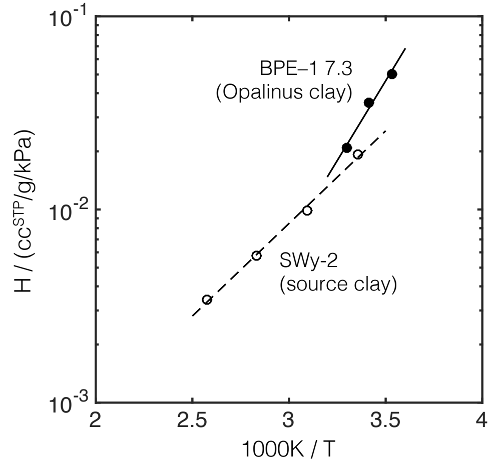
Increasing depth

Pore and gas sorption properties of Opalinus Clay









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Ronny Pini, Alireza Hejazi, Swapna Rabha, Sam Krevor, Sojwal Manoorkar

Pini et al., Pore and gas sorption properties of Opalinus Clay, technical report

“CO_2 adsorption experiments have been carried out on the sample from the homogeneous shaly facies. The data suggest that the **uptake is significant** and similar to observations on source-clays.”

Geomechanical Analysis

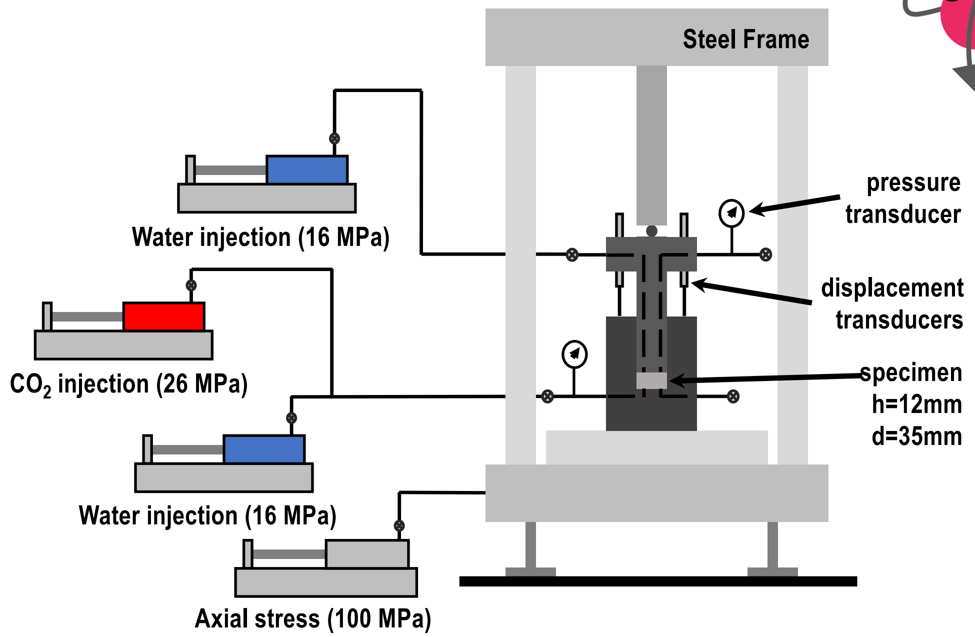
1) Basic characterization of the material (density, porosity, water content) for comparison before-after testing

2) Long-term CO_2 injection tests

   - CO_2-rich brine injection
   - stress conditions
   - saturated sample

Evaluation of the chemical effects on

- Mechanical properties (stiffness and compressibility)
- Transport properties (permeability)
- Volumetric response during CO_2-rich brine injection



Alberto Minardi, Alessio Ferrari, Lyesse Laloui

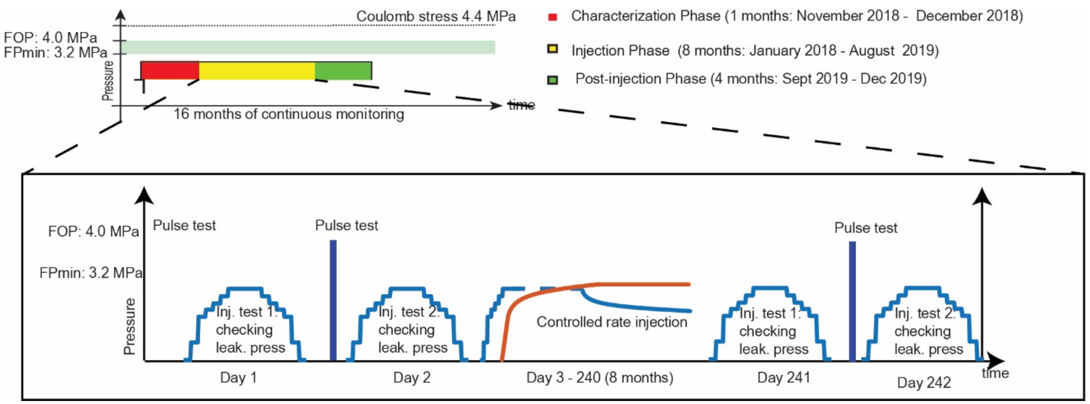
Concept of the longterm CO_2 injection

Baseline measurements

- Resistivity
- Vs, Vp

Nov 2018,
12^{th} -16th

Longterm injection of CO2-rich brine



Nov. 2018 - April/June 2019
(6-8 months)

Time-lapse measurements

- Resistivity
- Vs, Vp
- Microseismicity
- Strain
- Fluids

Hourly, daily,
weekly, bi-weekly

Expected observations

Will we be able to track the CO_2/pressure perturbation with our monitoring systems?

How is the CO_2 plume evolving ?

Will CO_2 arrive in time (1 year)?
Or are we only seeing pressure perturbation?

Will the CO_2 remain limited to the fault (core and damage zone)?

Where is the permeable zone? Will there be channels or a diffusive behaviour?

The **infrastructure** we are building is **permanent**.
The tests can be continued …