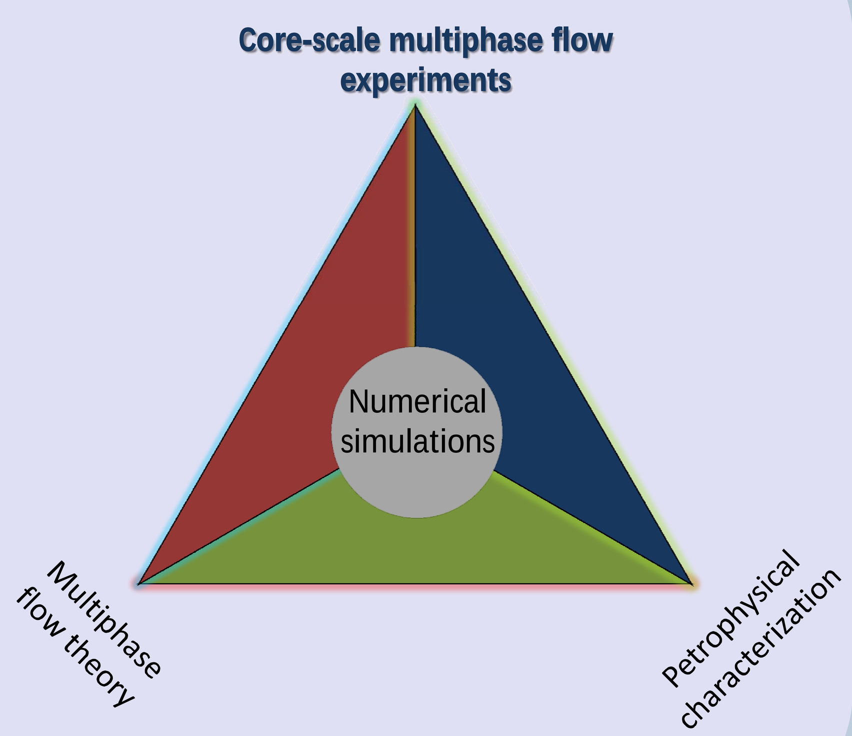
Multi-phase flow experiments of CO_2 and brine in reservoir rocks

Jean-Christophe Perrin and Sally Benson

Department of Energy Resources Engineering, Stanford University

GCEP
Global Climate & Energy Project
STANFORD UNIVERSITY



THE SEQUESTRATION LAB

The goal of the Sequestration Lab is to develop the ability to predict the spatial and temporal distribution of CO_2 saturation and trapping through an improved understanding of the pore and core scale physics over the life cycle of a sequestration project.

INTRODUCTION / BACKGROUND

Relative permeability is a key concept for carbon dioxide storage. Defined in multi-phase flow in porous media as the ratio of effective permeability of a particular fluid at a particular saturation to absolute permeability of that fluid at total saturation, relative permeability controls the majority of the phenomena that are met when two (or more) fluids are flowing through rocks.

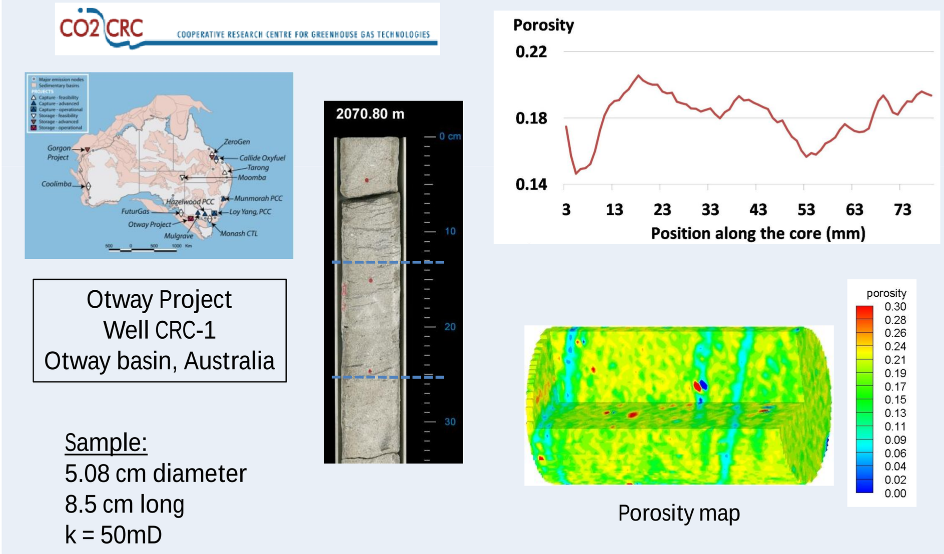
Studying the relative permeability properties of the CO_2-brine system in deep saline aquifers is fundamental to answer important questions that are met *in the field*. For instance:

- What should be the pressure in the injection zone?
- How big the plume is going to be?
- How fast would CO_2 leak up a fault under buoyancy?
- How to maximize sweep efficiency (storage capacity)?

In the laboratory, relative permeability experiments associated with fine rock characterizations are performed in order to address more fundamental issues. For instance:

-What are the trapping mechanisms?
- How do the external factors influence relative permeability (pressure, temperature, injection rates, rock properties/structure)?

CASE 1: heterogeneity effect



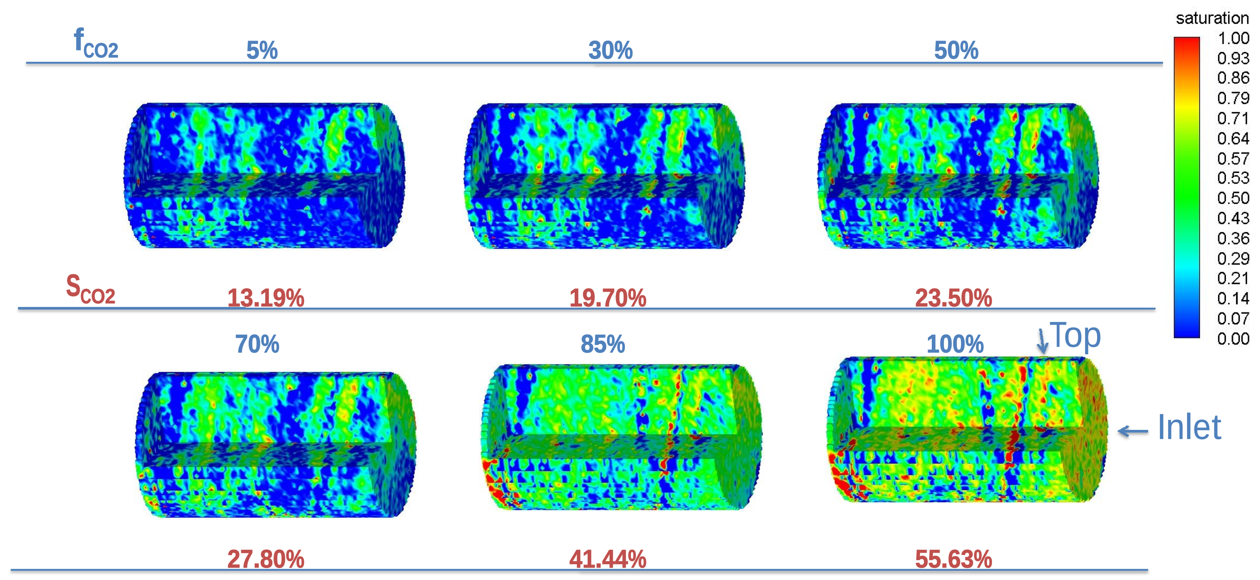
Sample:
5.08 cm diameter
8.5 cm long
k = 50mD

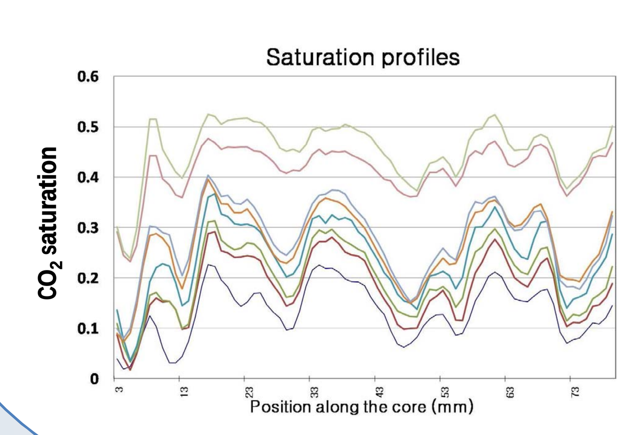
Experimental conditions

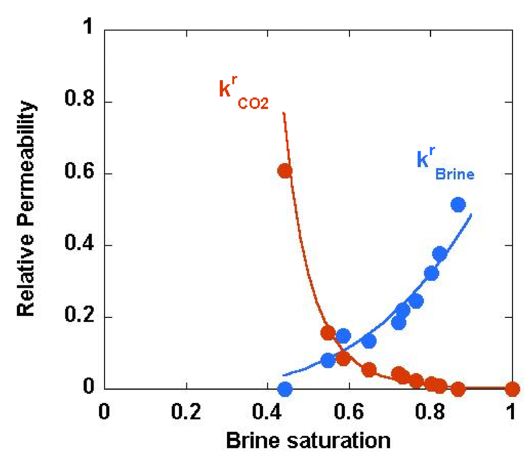
-T = 63°C
-P=1800 psi / 12.4 Mpa
-Brine composition = 6g/L NaCl+ 0.5 g/L $CaCl_2$

Procedure

-drainage at 2 mL/min
-the fractional flow of CO_2 is progressively increased
-steady state is achieved for each step







The rock is very heterogeneous, with a broad distribution of pore size. The structure is clearly visible in the porosity map. There is a strong correlation porosity / CO_2 saturation with a high CO_2 saturation corresponding to a high porosity. There is no visible gravity override.

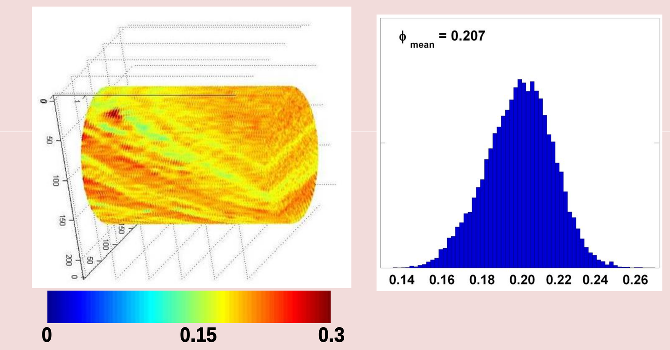
Thermophysical properties of brine and CO_2 at experimental conditions

Temperature	5°C	Room T (21°C)	50°C	63°C
Brine @1700 psi	Liquid μ = 1.50 cP d = 1.004 g/cm³	Liquid μ = 0.97 cP d = 1.002 g/cm³	Liquid μ = 0.54 cP d = 0.990 g/cm³	Liquid μ = 0.45 cP d = 0.986 g/cm³
CO_2 @1700psi	Liquid μ = 0.10 cP d = 0.94 g/cm³	Liquid μ = 0.08 cP d = 0.87 g/cm³	Supercritical μ = 0.042 cP d = 0.56 g/cm³	Supercritical μ = 0.029 cP d = 0.38 g/cm³

CASE 2: flow rate effect

Berea Sandstone

Sample:
5.08 cm diameter
15.24 cm long
k = 450mD

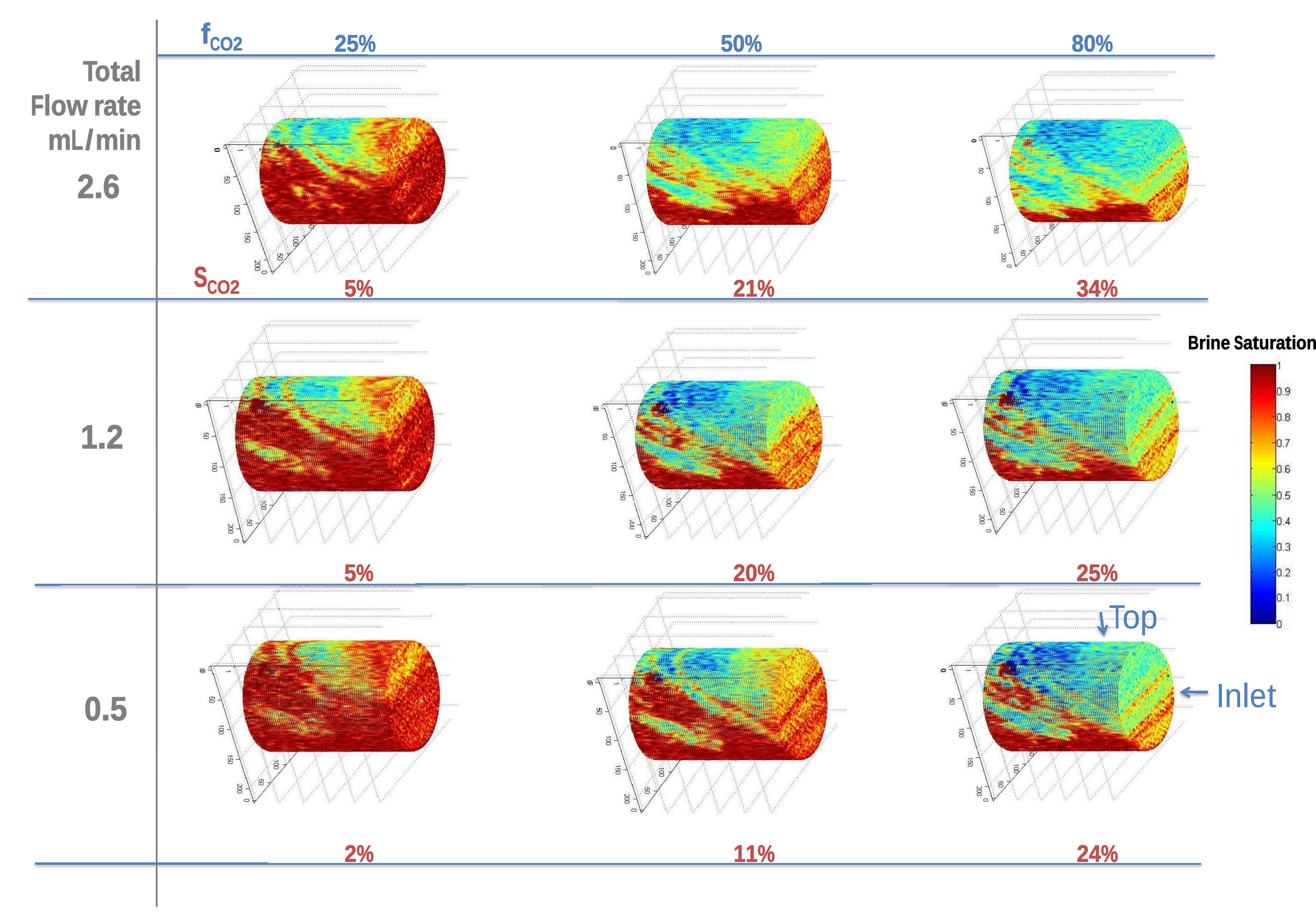


Experimental conditions

-T = 50°C
-P=1300 psi / 9 Mpa
-Brine composition = 10g/L NaCl

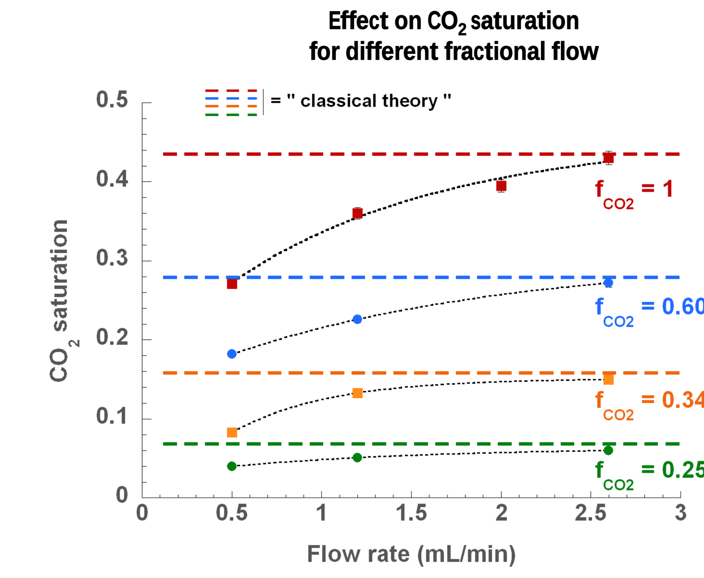
Procedure

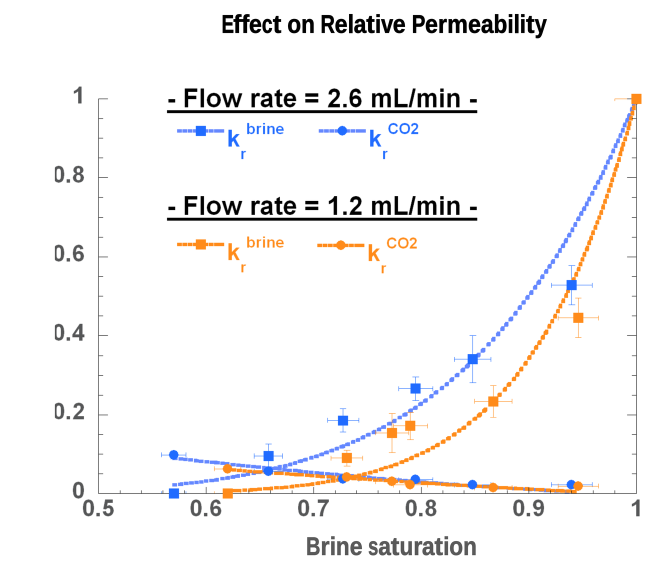
-drainage at 2.6, 1.2 and 0.5 mL/min
-the fractional flow of CO_2 is progressively increased
-steady state is achieved for each step



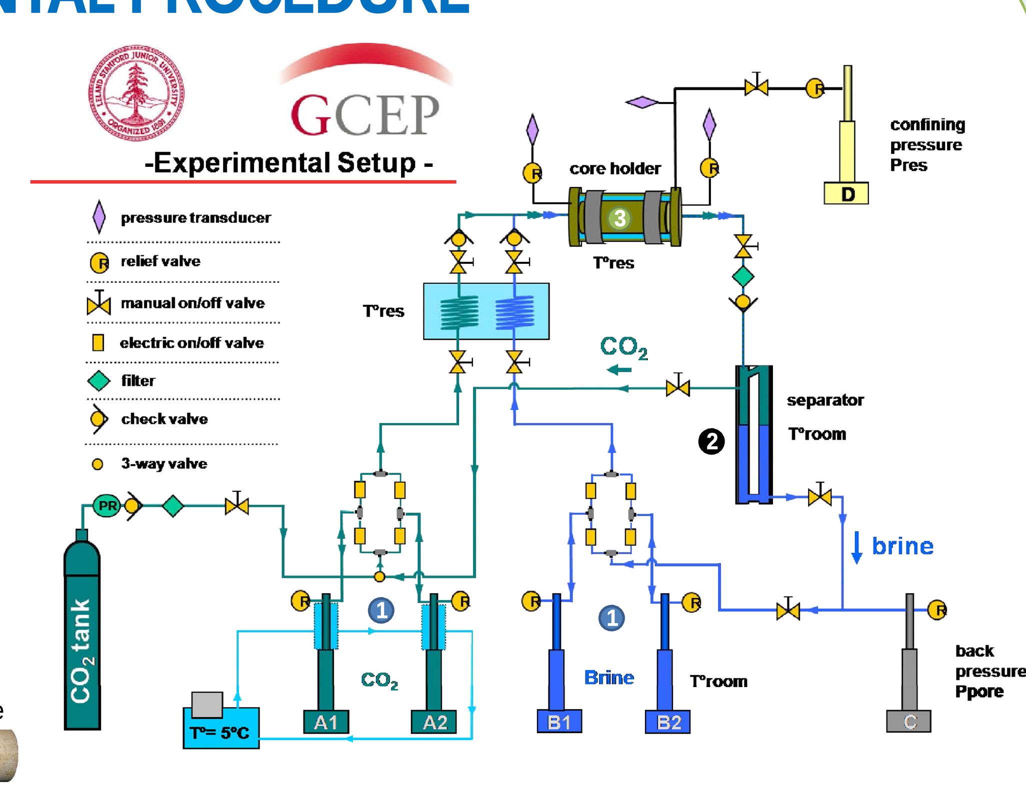
The rock is very heterogeneous with a structure composed of successive layers that are not parallel to the main axis of the cylinder.
Contrarily to the commonly accepted theory, the CO_2 saturation is a function of the total flow rate. As a consequence, the relative permeability varies with flow rate.

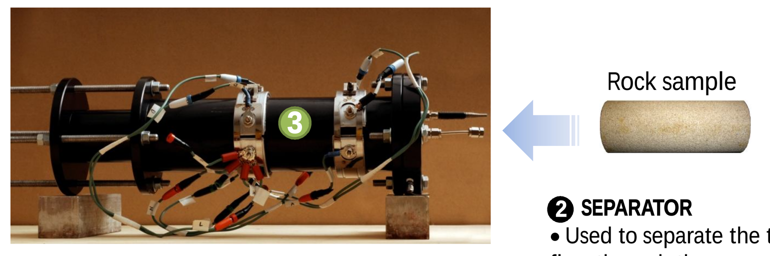
The higher the flow rate, the higher the CO_2 saturation and the lower the relative permeability at a given saturation.





EXPERIMENTAL PROCEDURE





1 PUMPS INJECT HIGH-PRESSURE CO_2 AND BRINE
- A system of dual-pumps (A & B) using electric valves injects fluids continuously and refills automatically.
- Max Pressure: 3750 psi.
- Flow rate: 1µL/min - 200mL/min
- Pump D applies confining pressure around the core to mimic reservoir conditions.
- Pump C creates back-pressure after separator. Also serves as a buffer container between separator and injection pumps.

2 SEPARATOR
- Used to separate the two fluids after they flow through the core.

3 AN ALUMINUM COREHOLDER CONTAINS THE CORE
- Aluminum 1/2 inch thick
- Rated to 3000 psi, 100°C
- For use with core up to 8 in. long (2 in. diameter)
- Fluids are distributed at the inlet and outlet ends by concentric grooves machined into the aluminum.
- Heaters keep fluid inside the core-holder at reservoir temperature.

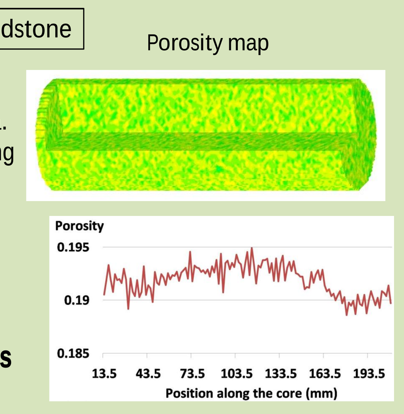
4 A MEDICAL CT SCANNER PRODUCES IMAGES OF THE CORE'S INTERIOR DISTRIBUTION OF CO_2 AND BRINE
- Saturation profiles are derived from these images.
- Images are taken in real time during injection experiments.

5 A DATA LOGGER RECORDS:
- Temperature and confining pressure inside the coreholder.
- Flow rate, pressure, delivered volume at each pump.
- Pressure drop across the core.

CASE 3: Gravity effect

Berea Sandstone

Sample:
5.08 cm dia.
20.2 cm long
k = 150 mD

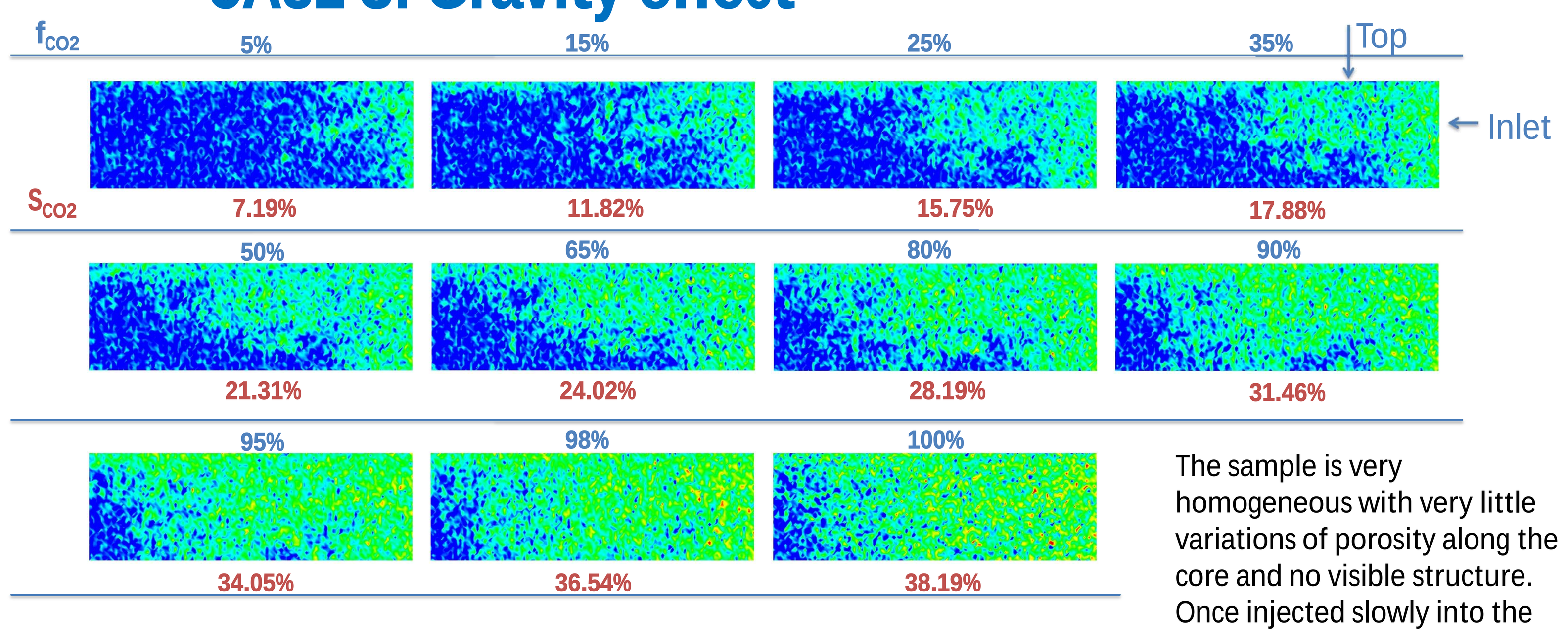


Conditions

-T = 63°C
-P=1800 psi / 12.4 Mpa
-Brine composition = 6g/L NaCl+0.5g/L $CaCl_2$

Procedure

-drainage at 1mL/min
-the fractional flow of CO_2 is progressively increased
-steady state is achieved for each step



The sample is very homogeneous with very little variations of porosity along the core and no visible structure. Once injected slowly into the core, CO_2 is rising up under the influence of gravity.

CONCLUSIONS

Studying relative permeability properties of CO_2 and brine in reservoir rocks is of major importance for carbon sequestration.
In the lab, we see that:
-When the core is structured, the heterogeneities are controlling the spatial distribution of CO_2 at steady state. The less porous layers are hardly invaded.
-When the sample is homogeneous and the injection flow rate is low enough, gravity effects become important and the CO_2 invades preferentially the top part of the core.
-CO_2 saturation and relative permeability are seen to be flow rate dependant. At higher flow rate, CO_2 saturation is higher and relative permeability lower.
- Numerical simulations are underway to validate these observations (see Chia-Wei Kuo's poster) as well as sub-core scale analysis (see Michael Krause's poster).