Department of Physics and Technology

CO_2 Foam for EOR and CO_2 Storage in CCUS

From Laboratory to Field-scale

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UNIVERSITY OF BERGEN

Reservoir Physics Group Research

- Carbon capture, **utilization and storage** (CCUS)
- Hydrogen storage and production
- Gas hydrates

Fluid flow in porous media
Laboratory to field-scale

Climate change mitigation and energy security

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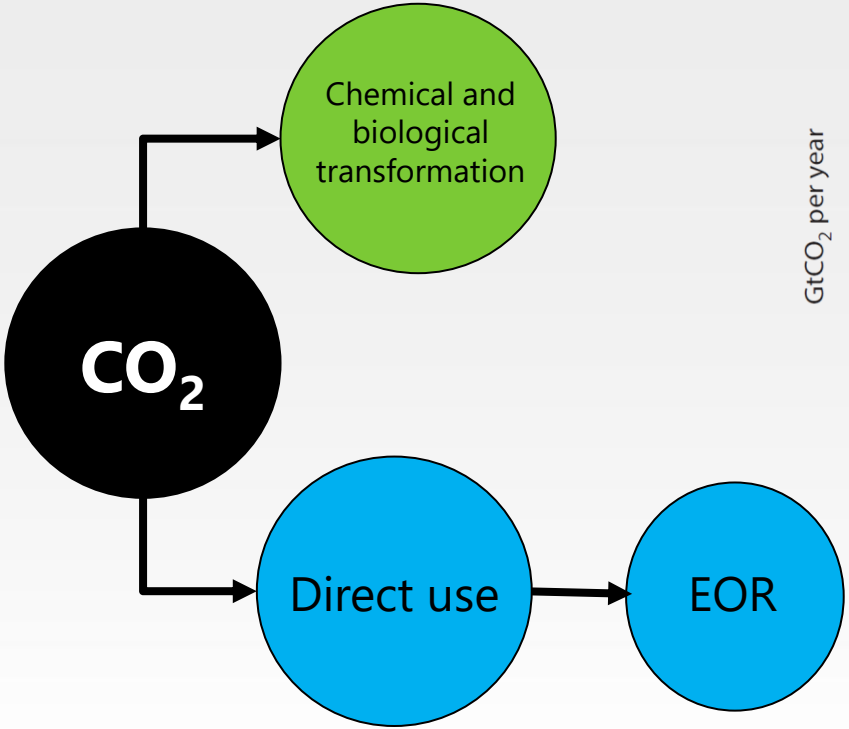
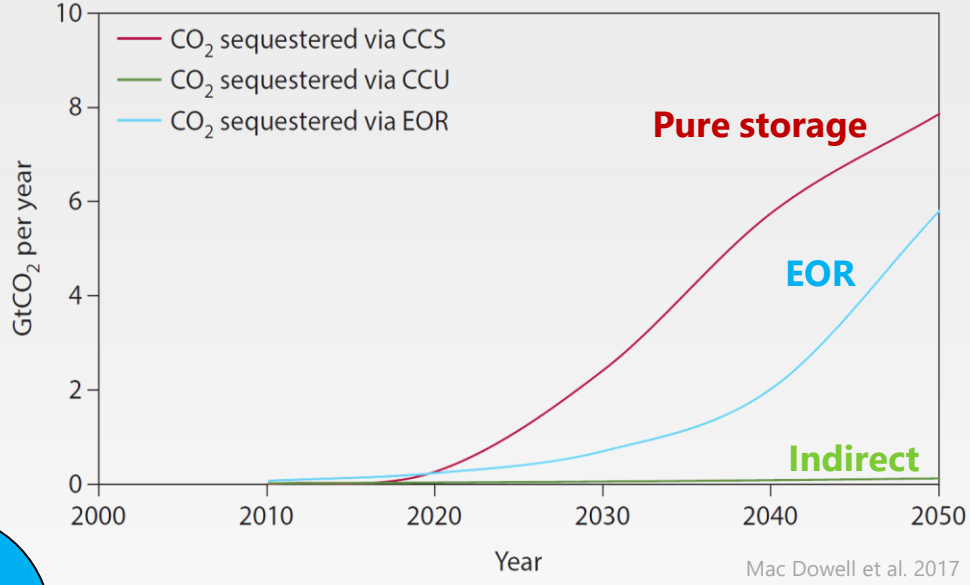
CCUS, CO_2 EOR and storage, CO_2 foam, reservoir simulation, energy transition

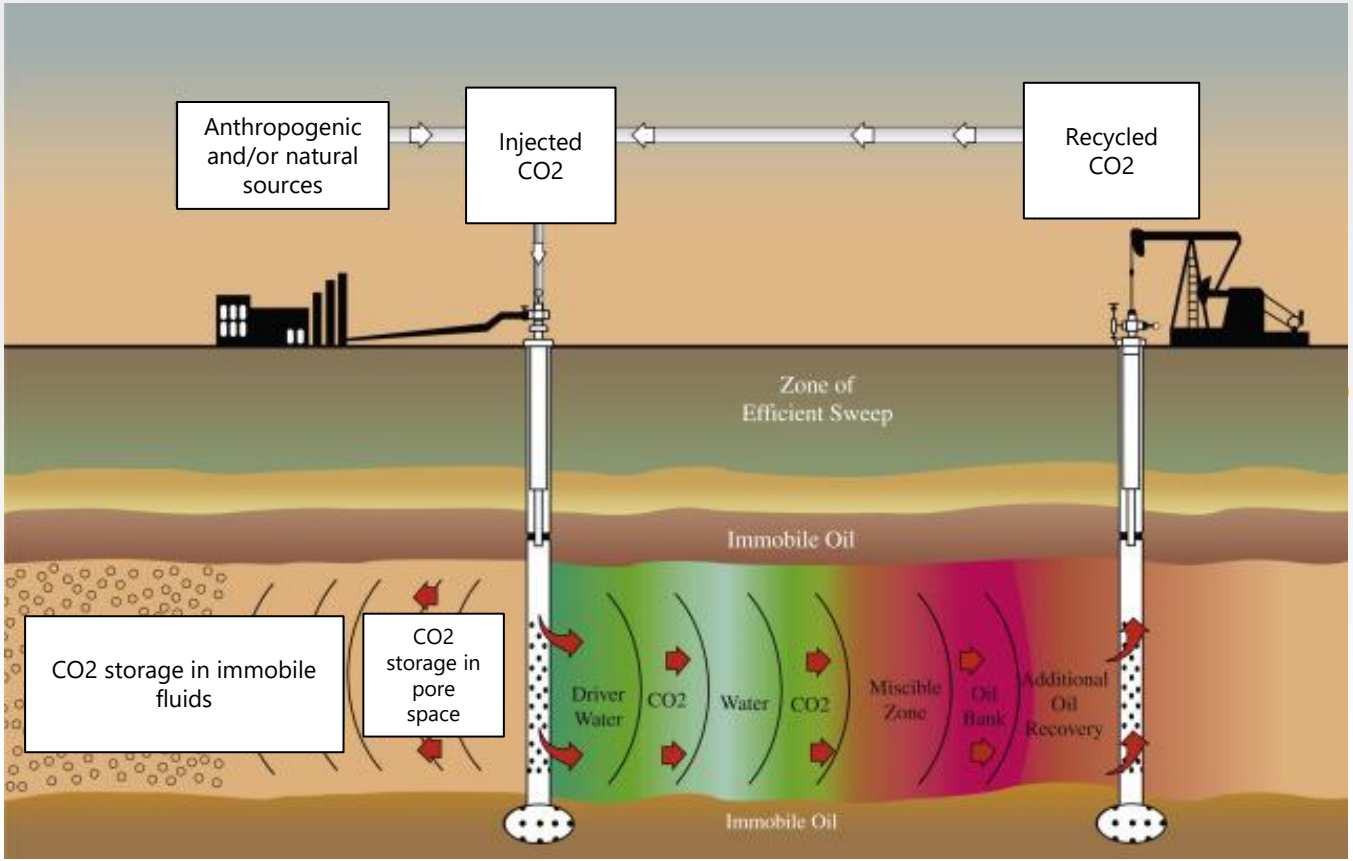
CO_2 Utilization and Storage





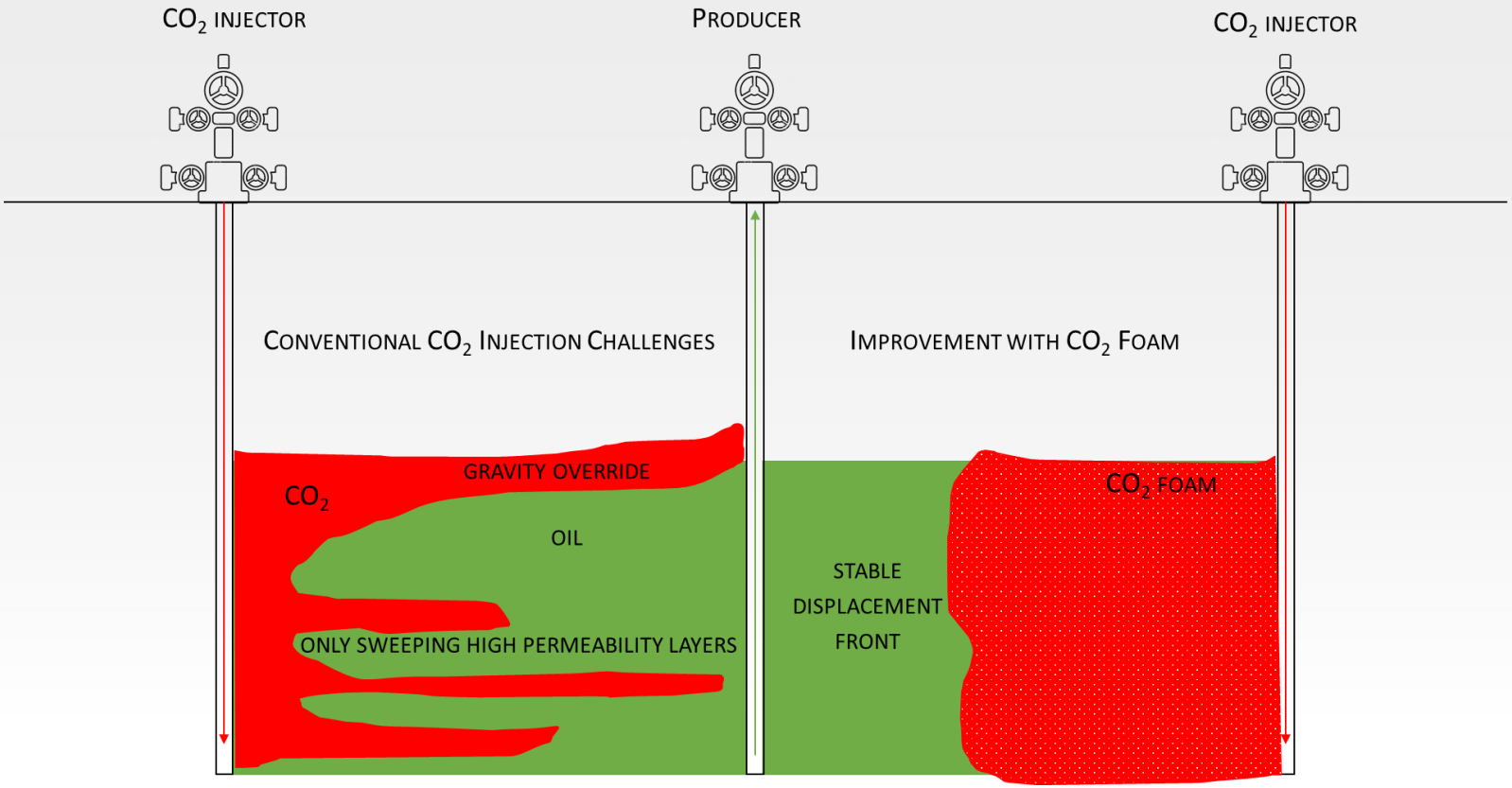
Mac Dowell et al. 2017

CO_2 Utilization and Storage

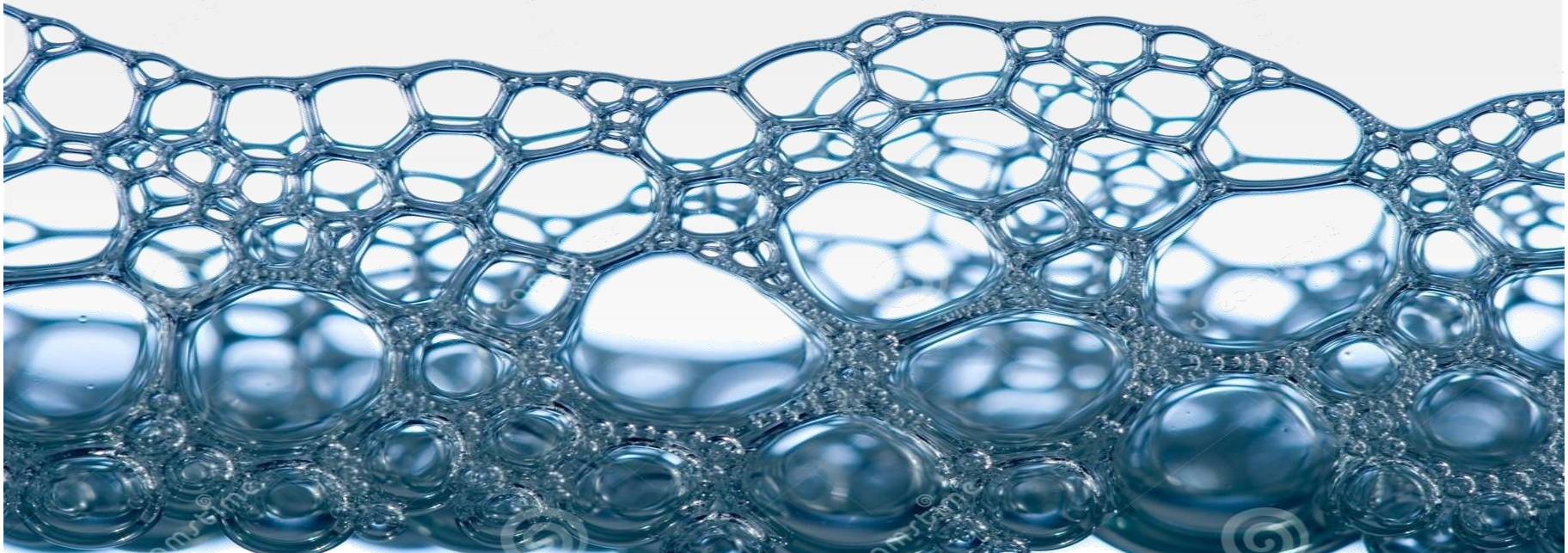


Modified from Lake et al. 2019

CO_2 Utilization and Storage



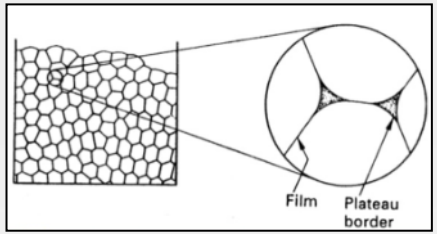
CO_2 Foam



CO_2 Foam Fundamentals

What?

- Dispersion of gas in liquid
- Stabilized by surfactant

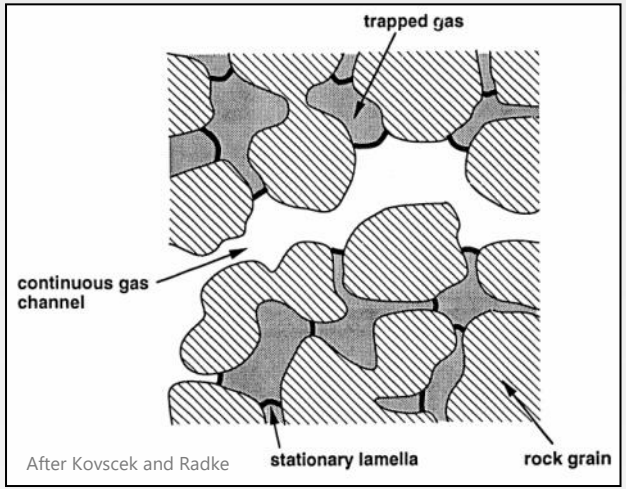


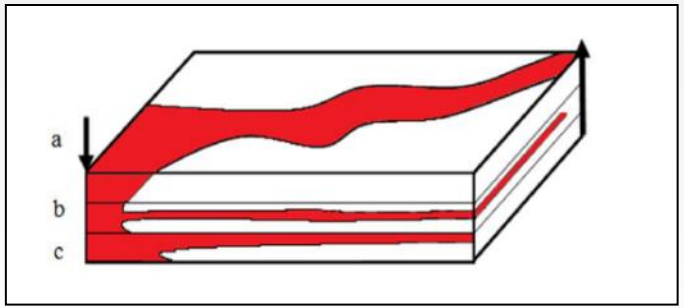
How?

- Decreases relative permeability
- Increases viscosity
- Injection strategy: SAG or co-injection

Why?

- Conformance and mobility control
- Increase reservoir sweep and displacement
- Additional CO_2 storage

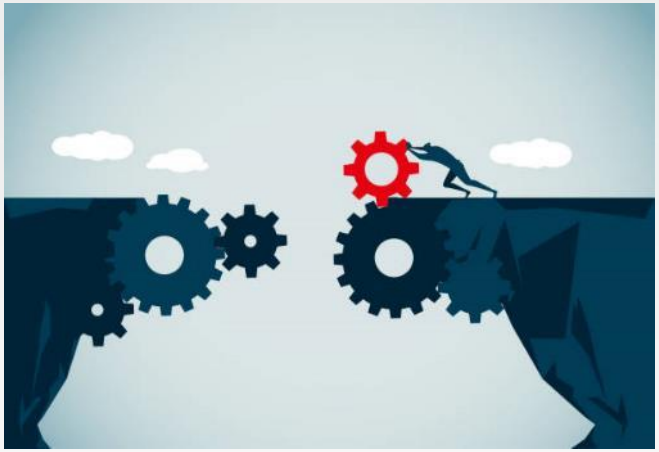




Sc-CO_2 EOR mobility challenges: a) poor aerial sweep, b) gas channeling, c) gravity override
(Hanssen et al., 1994)

The Foam Challenge

- Complex flow behavior
- Foam mobility depends on bubble density, which changes continuously during generation and coalescence.
- Opaque core-scale systems
- Foam generation and stability are impacted by the presence of oil.



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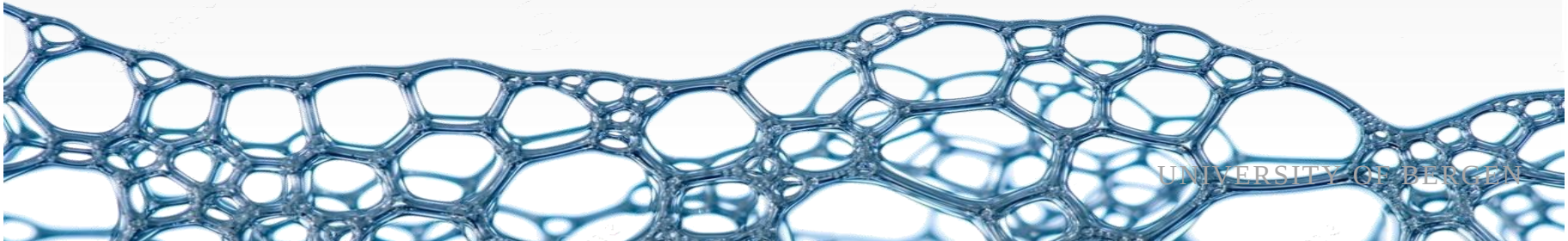
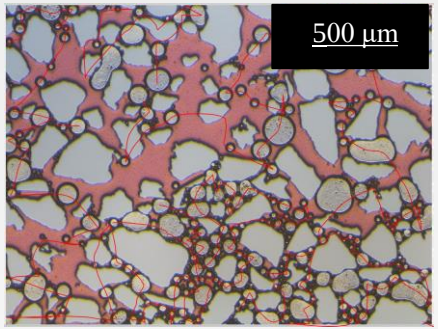
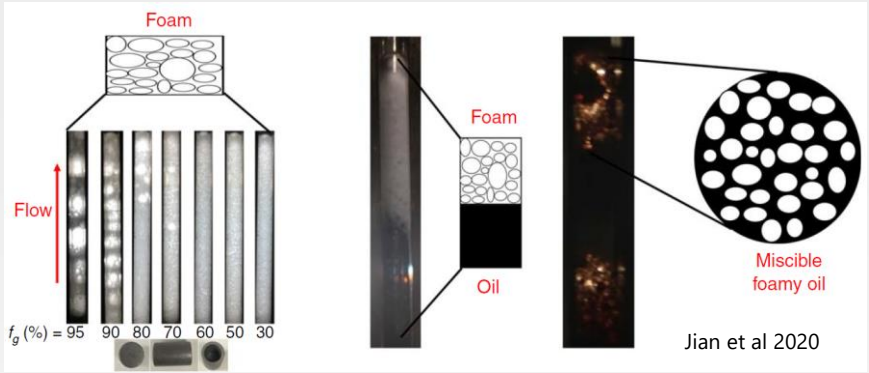


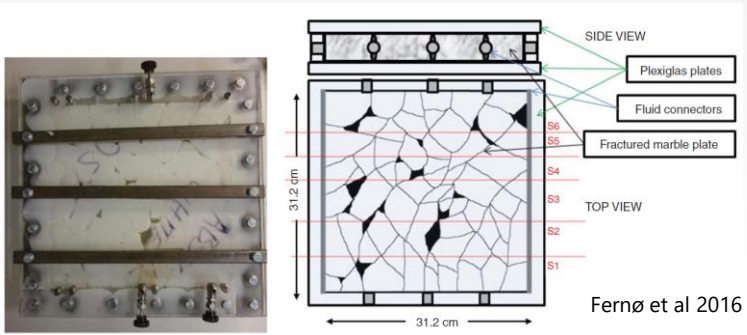
Laboratory Scales

- Bulk
- Pore
- Core
- Block

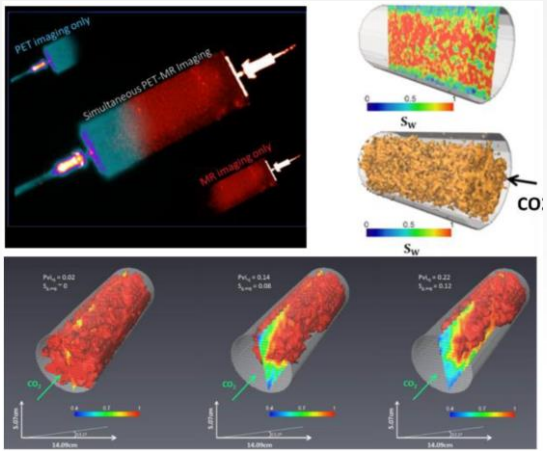




Jian et al 2020

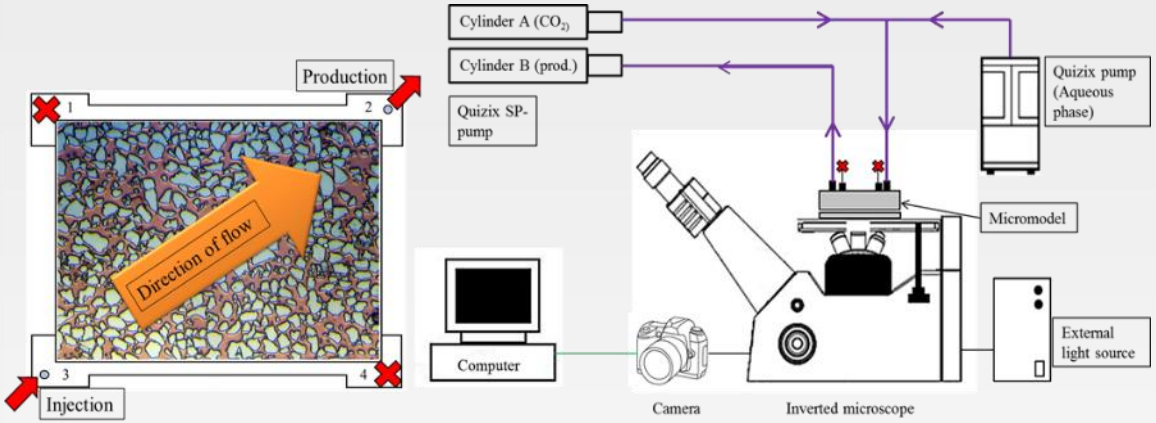


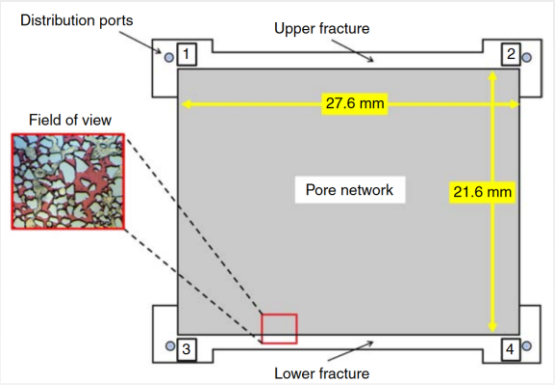
Fernø et al 2016



Pore-scale CO_2 Foam

Set-up and Properties



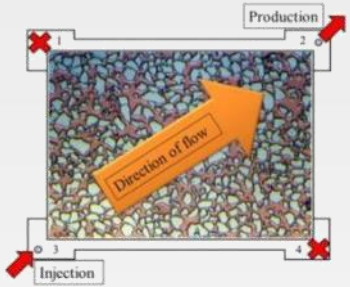


Rognmo et al. 2019

Porosity (%)	Permeability (md)	Avg. Grain Size (μm)
≈60	2.9	99.3

1305 psi, 20ºC

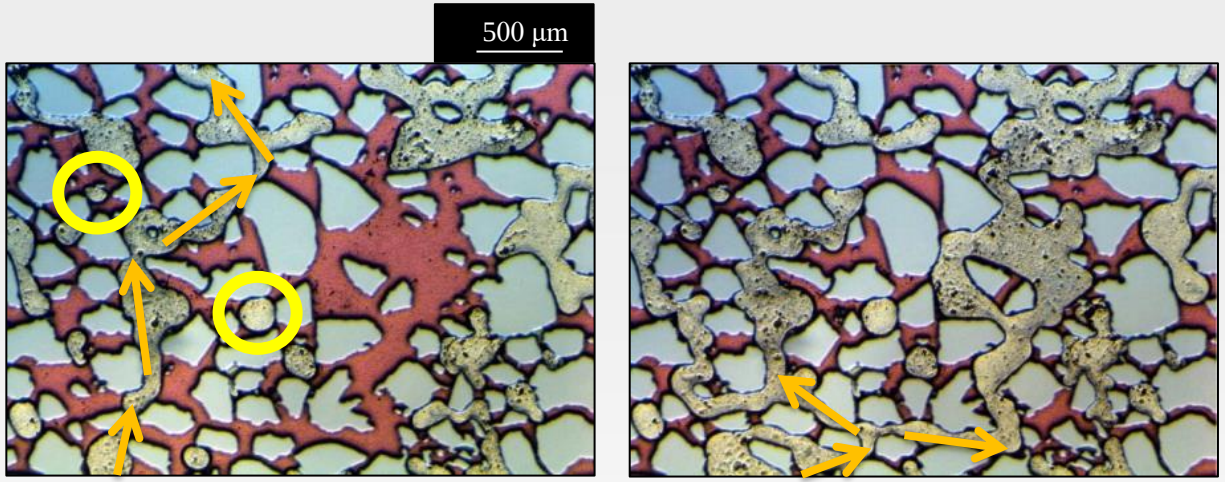
Pore-Scale Baseline (no surfactant)



1305 psi, 20ºC

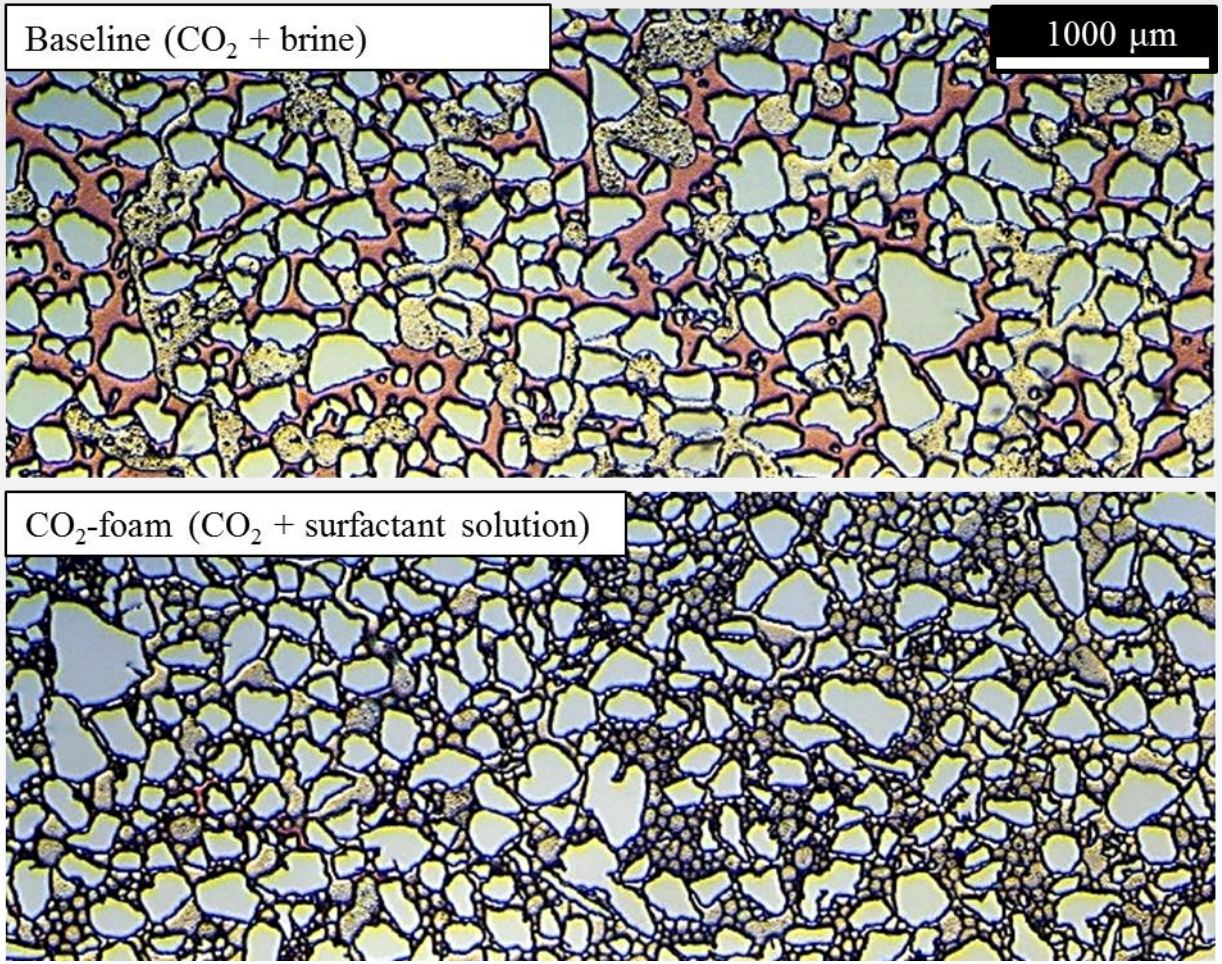
100% brine saturated

Gas fraction (f_g) = 0.70



Red is water, **light blue uniform areas are grains,** **brown textured areas are CO_2**

CO_2 phase spanning over several pores without being separated by liquid films, indicating low CO_2 mobility reduction

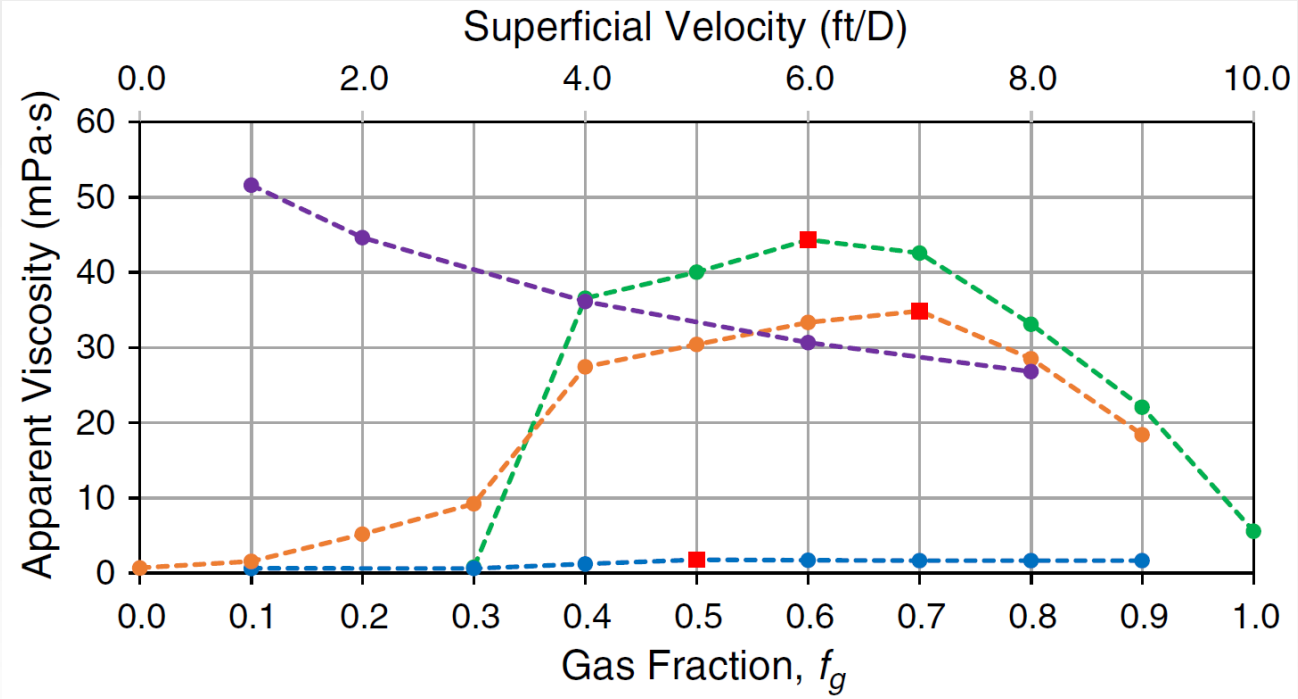


Red is water, light blue uniform areas are grains, brown textured areas are CO_2

Core-scale CO_2 Foam

Steady- and unsteady-state flow

Steady-state Foam Quality and Rate Scan



2500 psi and 40C
Injection rate: 1 ft/day
100% brine-saturated
1 wt% surfactant solution

- Foam-quality scan–reservoir plug
- Foam-quality scan–baseline
- Foam-quality scan–outcrop plug
- Optimal gas fractions
- Foam-rate scan–reservoir plug

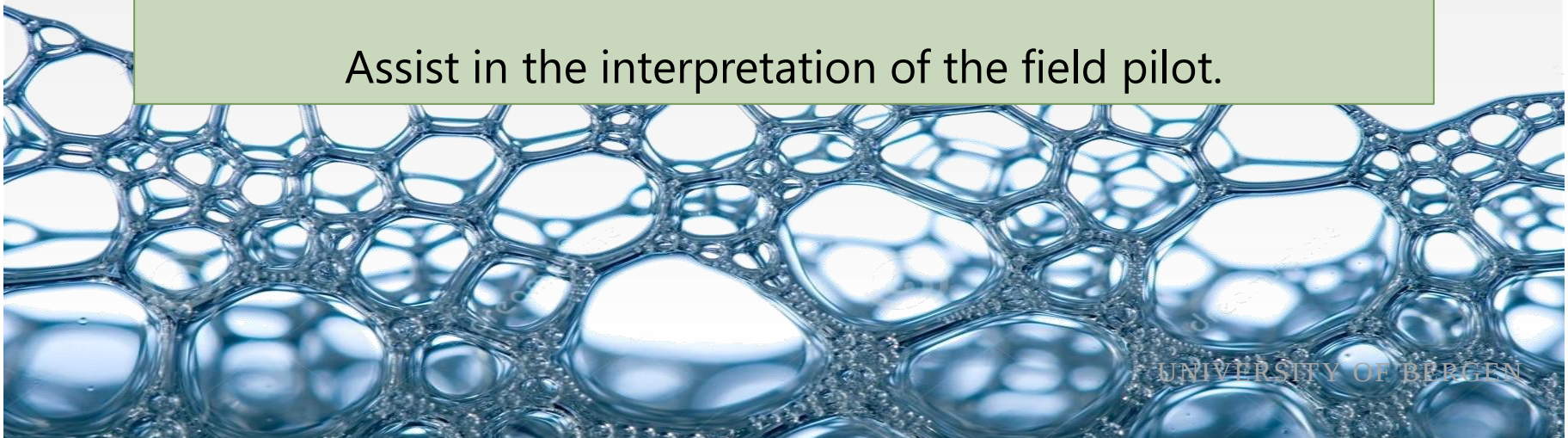
Core Identity	Length (cm)	Diameter (cm)	Pore Volume (mL)	Porosity (%)	Permeability (md)
Reservoir	5.7	5.0	15.2	13.8	22.1
Outcrop	7.5	5.0	35.3	24.2	20.5

Unsteady-state

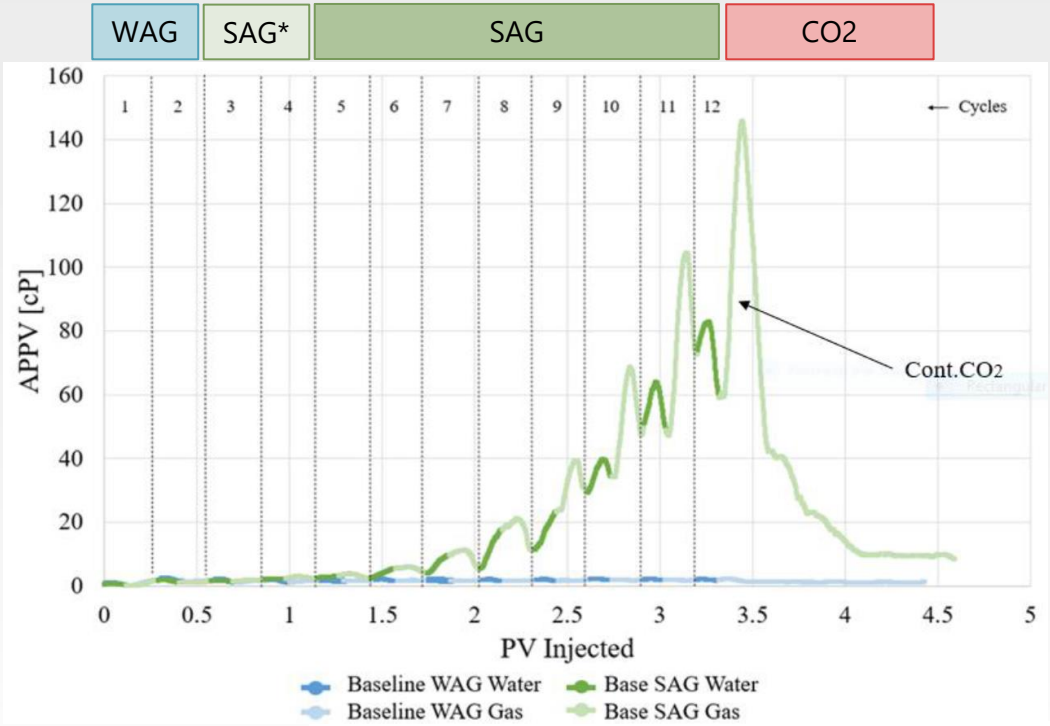
Foam generation, strength and stability during unsteady-state alternating slug injection of surfactant solution and CO_2.

Develop a methodology for evaluating CO_2 foam during unsteady-state injection.

Assist in the interpretation of the field pilot.



Unsteady-state: Baseline WAG vs SAG



2800 psi and 40C
100% brine saturated
0.5 wt% surfactant solution
Injection rate: 4 ft/day
Gas fraction: 0.60

Properties	Value
Length [cm]	24.40 ± 0.01
Diameter [cm]	3.88 ± 0.01
Permeability [D]	2.14 ± 0.03
Pore Volume [ml]	62.16 ± 0.01
Porosity [%]	21.54 ± 0.10

CO_2 Foam EOR and CO_2 Storage

Evaluate EOR and CO_2 storage potential of CO2 foam systems

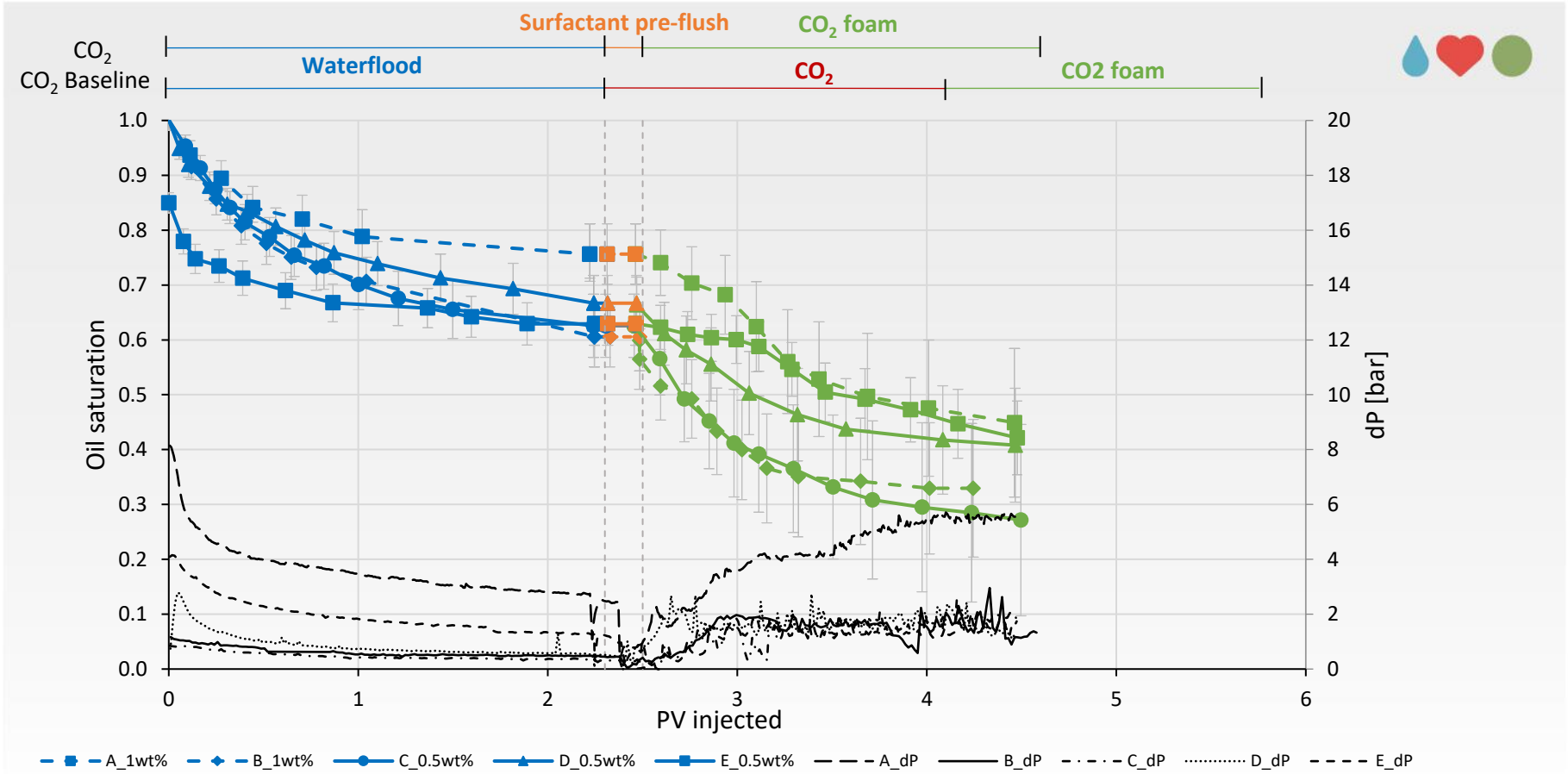
- water-soluble nonionic Surfonic L24-22 (0.5 wt% and 1 wt%)

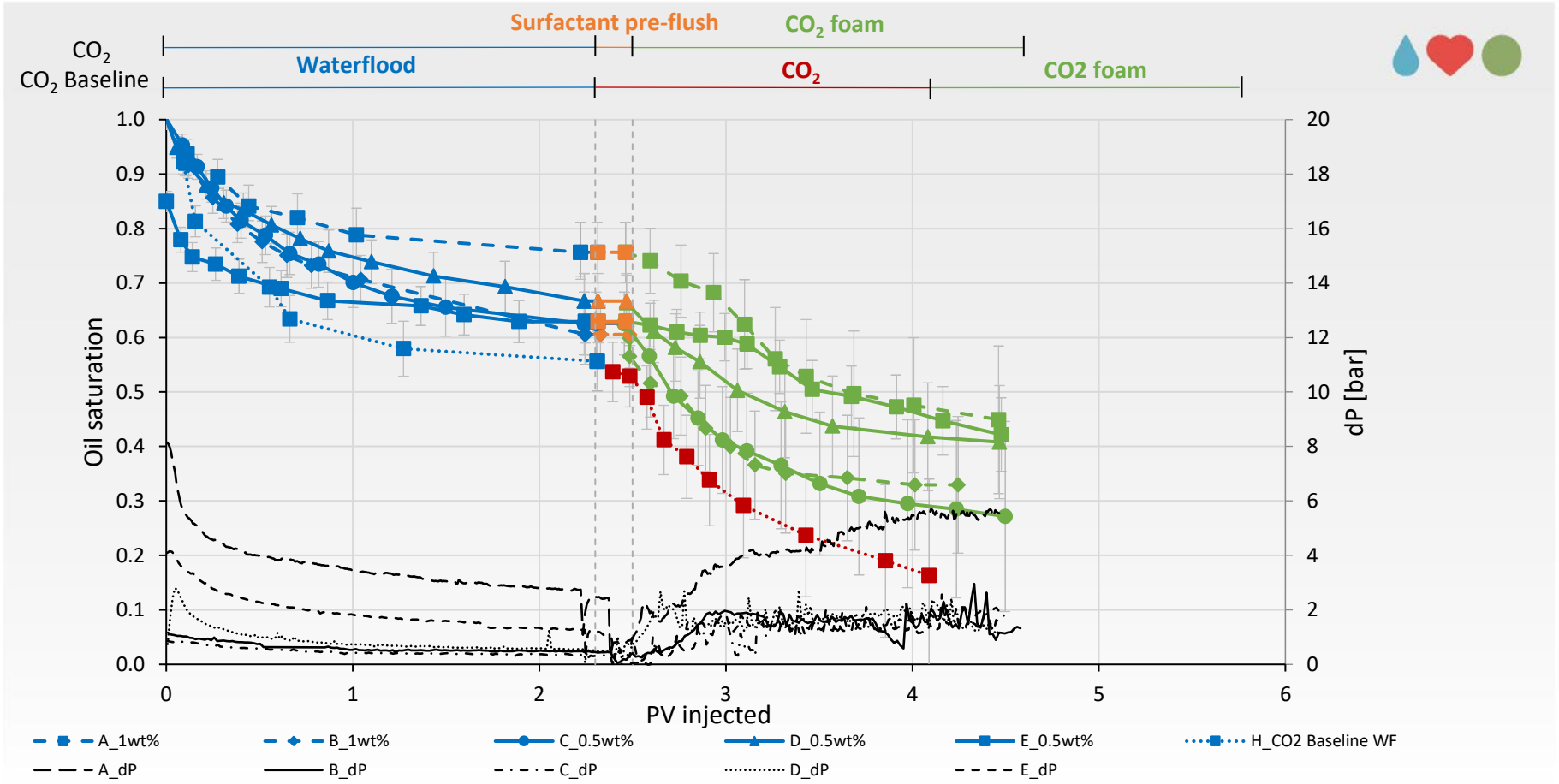
Experimental conditions and procedure:
2500 psi at 40^{0}C

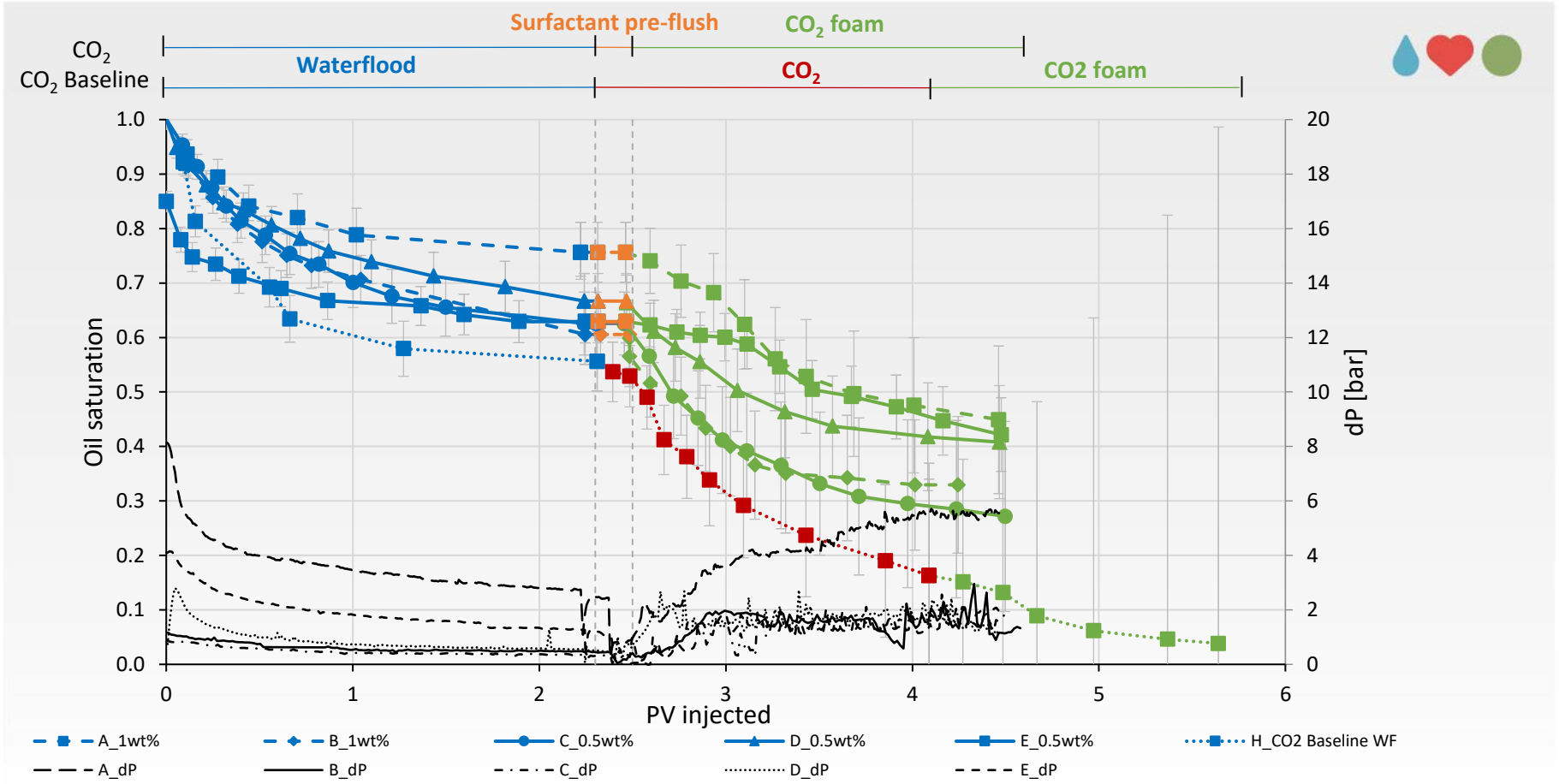
Reservoir-core was restored to reservoir conditions and 100% oil saturated.

Initial **waterflood**, **surfactant pre-flush**, **CO_2 flood**, and a final **CO_2 foam** flood.

All rates were 1 ft/D, at a gas fraction of 0.70.


Surfactant pre-flush
CO_2 foam
CO_2
Waterflood
CO_2 Baseline
CO_2
CO2 foam
Oil saturation
dP [bar]
PV injected
A_1wt%
B_1wt%
C_0.5wt%
D_0.5wt%
E_0.5wt%
A_dP
B_dP
C_dP
D_dP
E_dP


Surfactant pre-flush
CO_2 foam
CO_2
Waterflood
CO_2 Baseline
CO_2
CO2 foam
Oil saturation
dP [bar]
PV injected
A_1wt%
B_1wt%
C_0.5wt%
D_0.5wt%
E_0.5wt%
H_CO2 Baseline WF
A_dP
B_dP
C_dP
D_dP
E_dP


Surfactant pre-flush
CO_2 foam
CO_2
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CO_2 Baseline
CO_2
CO2 foam
Oil saturation
dP [bar]
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C_0.5wt%
D_0.5wt%
E_0.5wt%
H_CO2 Baseline WF
A_dP
B_dP
C_dP
D_dP
E_dP

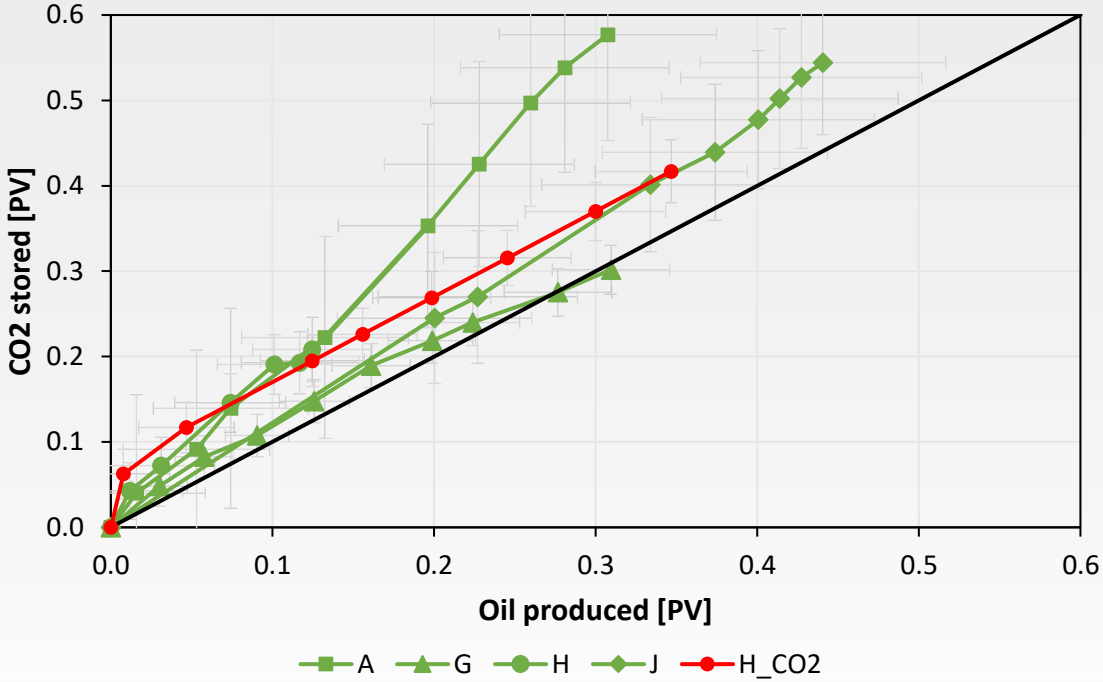
Associated CO_2 Storage – Reservoir Cores

CO_2 storage during CO_2 foam displacement (after WF)

40^0C, 2500 psi

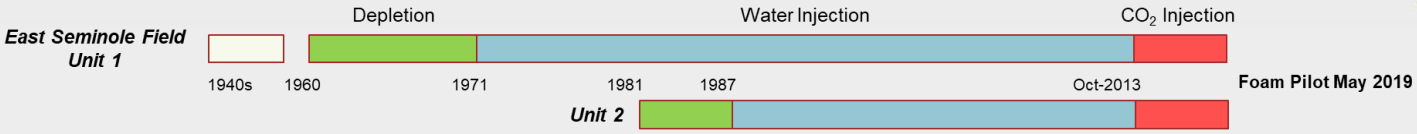
Oil-wet

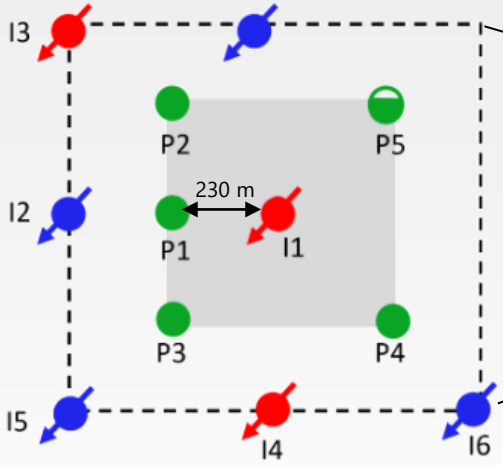
Foam displaces water in favor of CO_2 storage

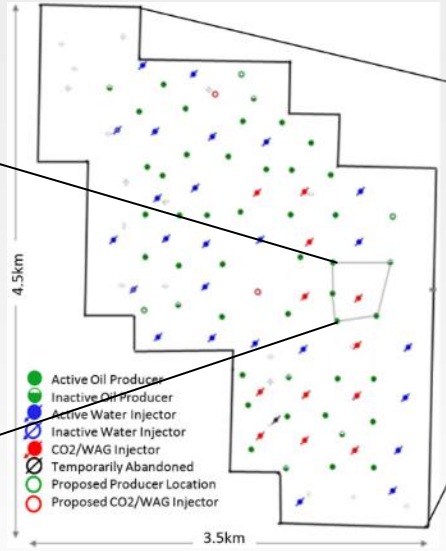


The Pilot

Pilot Pattern







Rapid CO_2 Breakthrough
High producing GOR

San Andres Dolomite

Reservoir Characteristic	Value
Depth	5200 ft
Permeability	1 to 250 md (avg: 13 md)
Porosity	3% to 28% (average: 12%)
Pay thickness	110 ft
Reservoir pressure (initial)	2500 psig
Reservoir pressure (current)	3400 psig
Fracture pressure	3900 psig
Reservoir temperature	104°F
Oil gravity	31 °API
Formation brine salinity	70,000 ppm

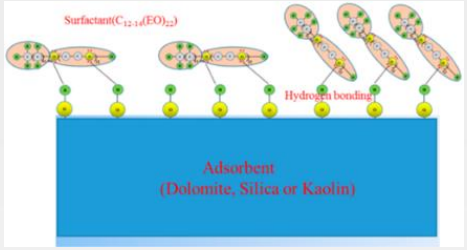
Pilot Design

Foam Formulation

- Minimal adsorption
- Adequate foam strength
- Chemical stability

Nonionic Surfonic L24-22, a linear ethoxylated alcohol ($C_{12-14}E_{22}$)

Foam quality: 60% to 70%
Surfactant concentration: 0.5 wt%



Injection Strategy

Surfactant alternating gas (SAG):
10 days surfactant, 20 days CO_2
Half the historical injection rate

San Andres

Reservoir Characteristic	Value
Depth	5200 ft
Permeability	1 to 250 md (avg: 13 md)
Porosity	3% to 28% (average: 12%)
Pay thickness	110 ft
Reservoir pressure (initial)	~~2500 psig~~
Reservoir pressure (current)	3400 psig
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Reservoir temperature	~~104°F~~
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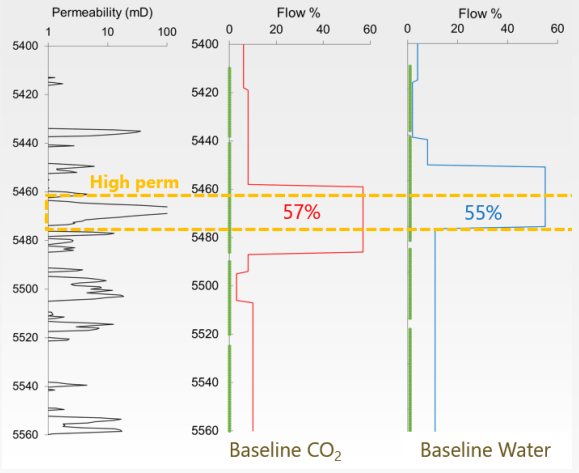
Formation brine salinity	70,000 ppm

Baseline (pre-pilot) injection profiles



Pilot start: May 2019

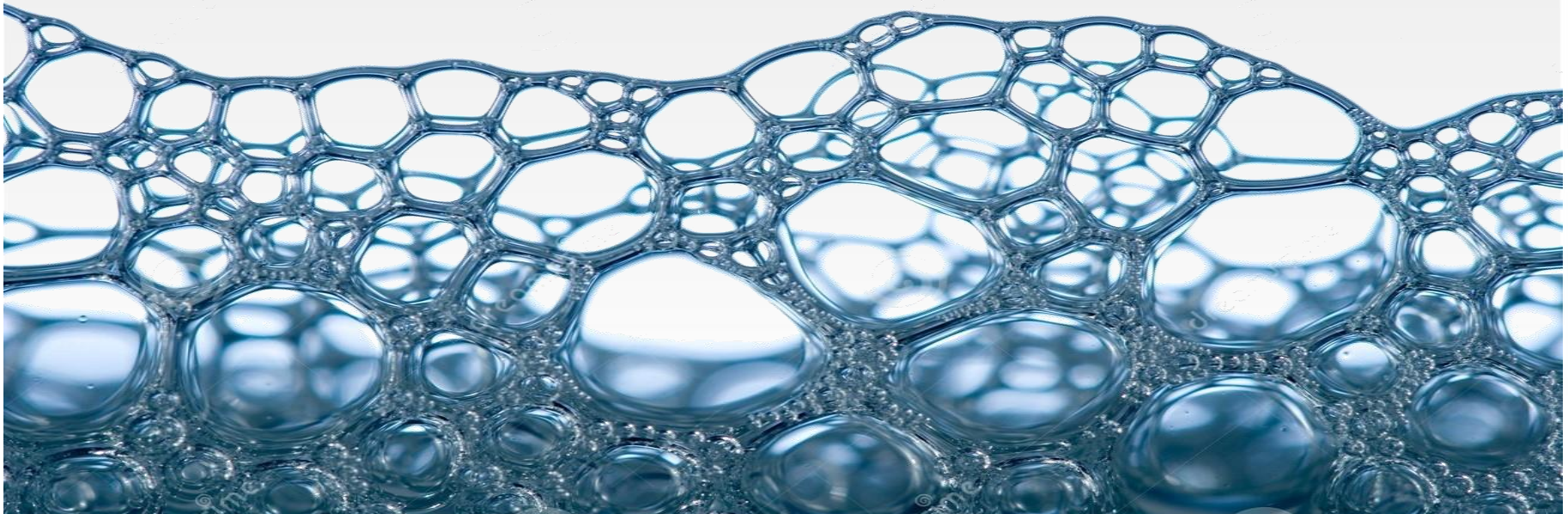
Pilot end: August 2020

May 2021

Pilot Objectives

In-depth CO_2 mobility control

Improve CO_2 sweep efficiency, oil recovery and CO_2 utilization



Data Collection and Monitoring

Data Collection and Pilot Monitoring

- Obtain baseline and monitor pilot performance to evaluate reservoir response to foam injection.

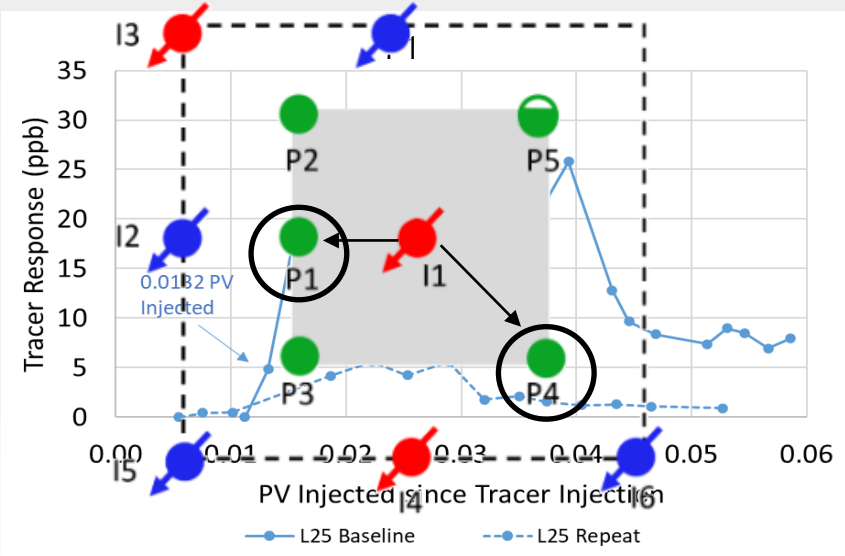
- Characterize **interwell connectivity** and CO_2 and water injectivity.

	SAG Cycle																							
	Pre		1		2		3		4		5		6		7		8		9		10		11		Post
Slug																								
IWTT		x																					x	
Injection Profiles	x	x			x	x					x	x			x	x			x	x			x	x	x
Produced water collection			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x							x
DHPG reading		x			x							x				x							x	x	x

Water CO2 Surfactant

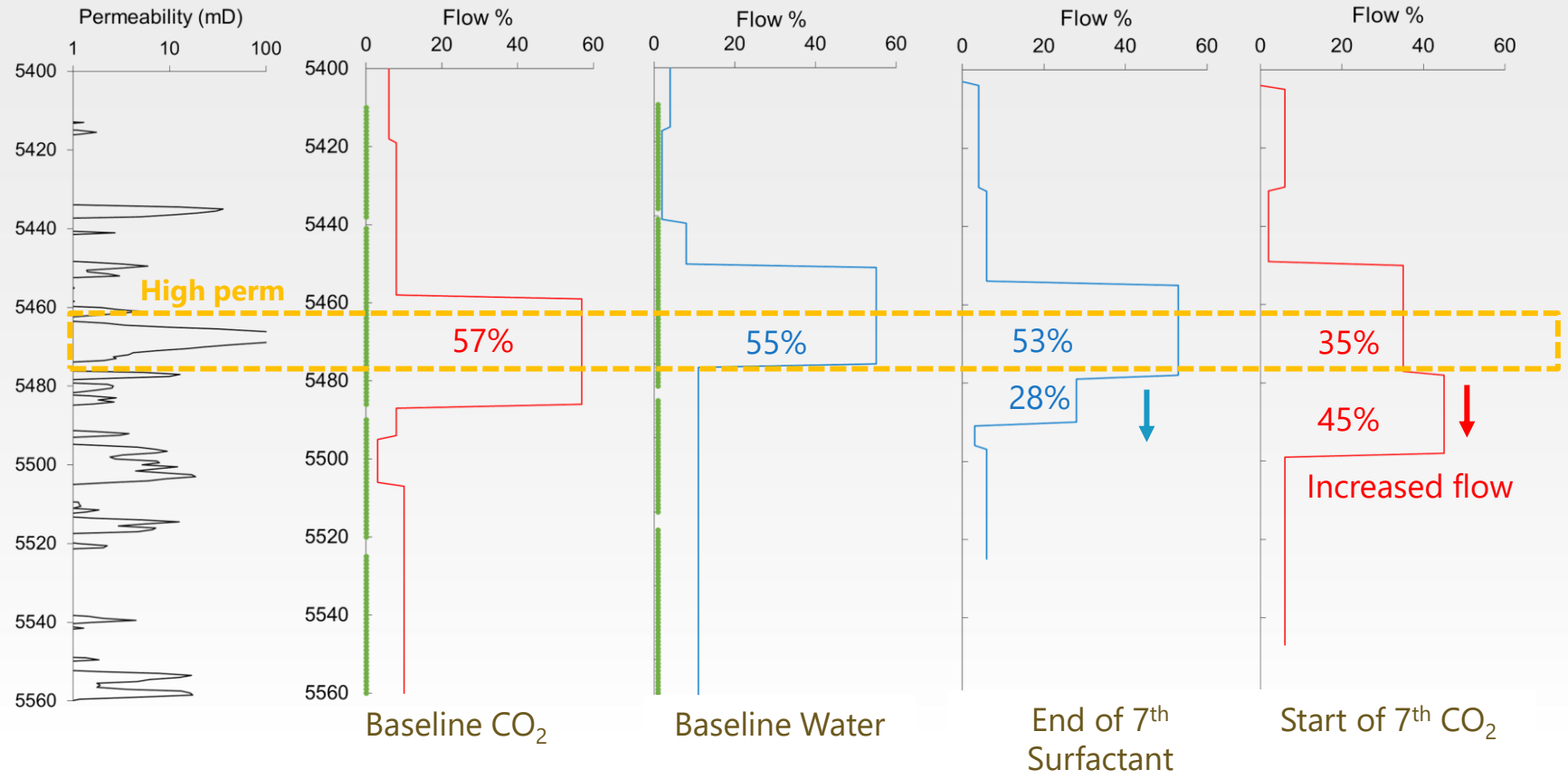
CO_2 Interwell Tracer Test (IWTT)

- Determine baseline CO_2 breakthrough time (BT) and migration rate
- Compare it to BT time after foam injection



- CO_2 breakthrough from I1 to P1 delayed by 43% during the foam pilot
- Baseline tracers broke through at a higher concentration
  - Tracers during foam injection mostly went through matrix due to reduced CO_2 channeling in a high-permeability zone

Injection Profiles – Foam Injector



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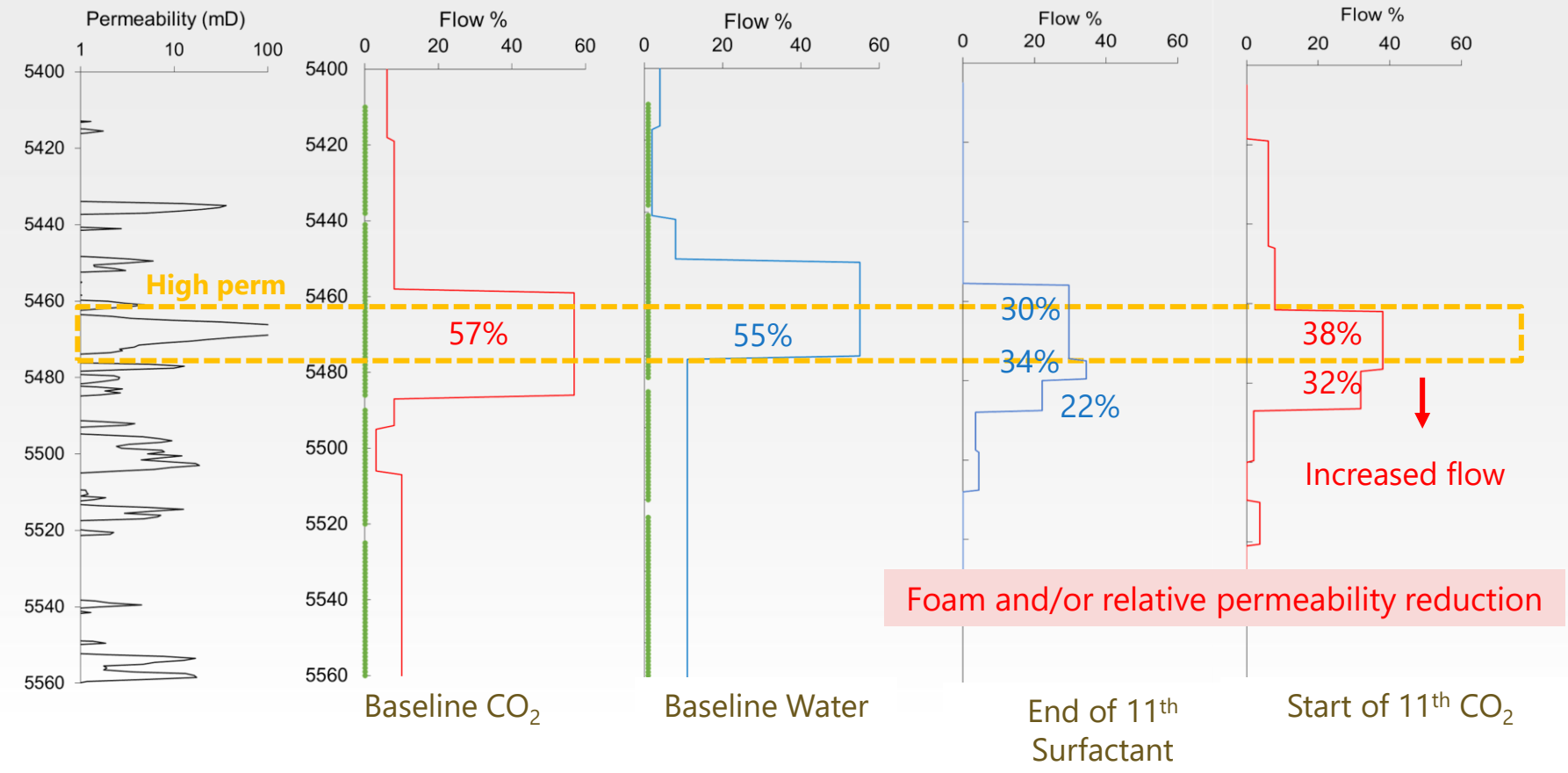
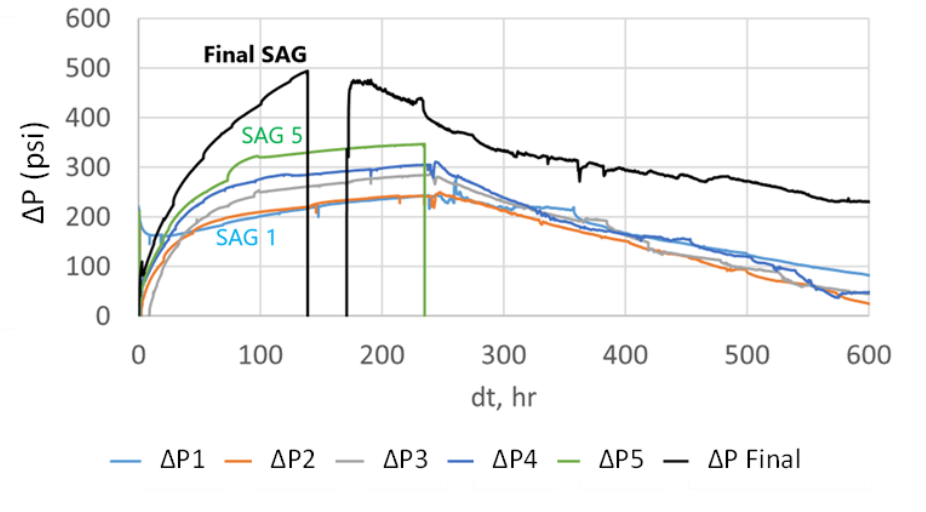
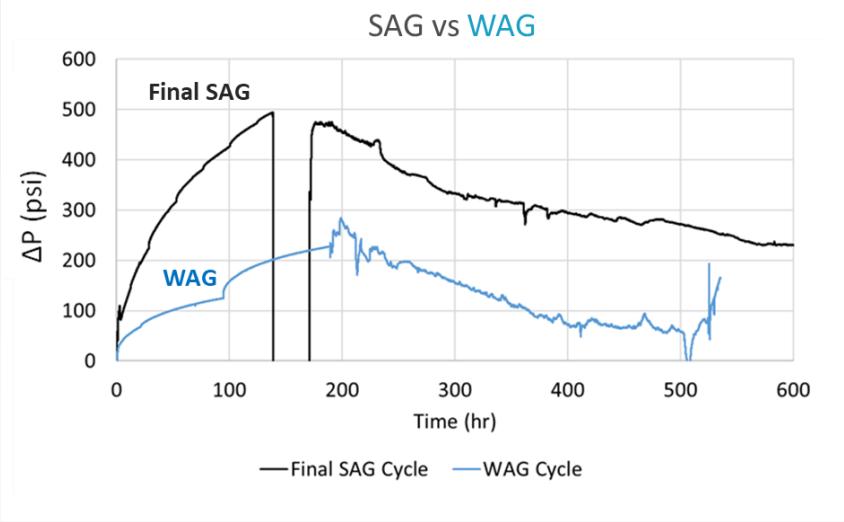


Transient Analysis





Reduced mobility of each cycle, indicating a foam bank developing further into the reservoir.

Reduced mobility during the SAG cycles compared to the WAG

Pilot start: May 2019

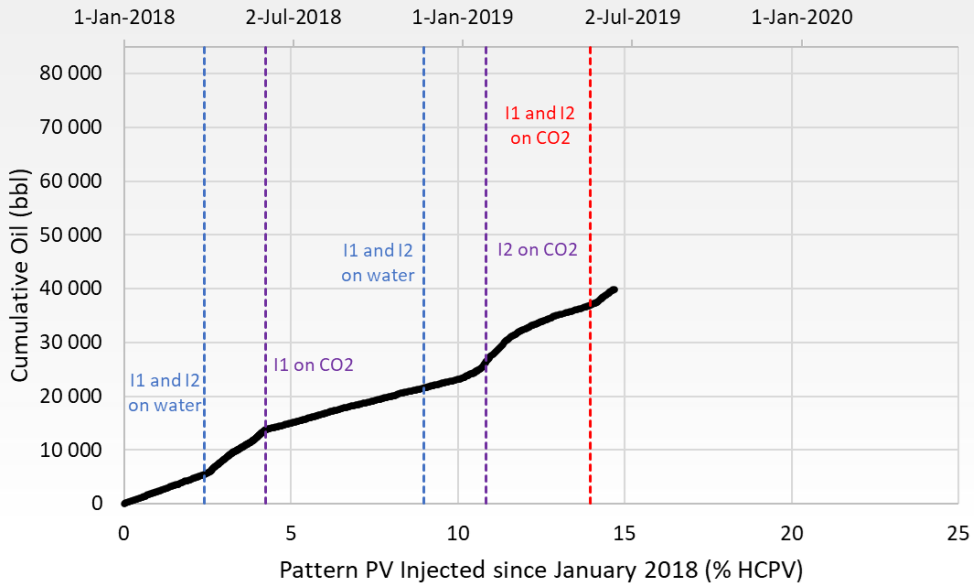
Pilot end: August 2020

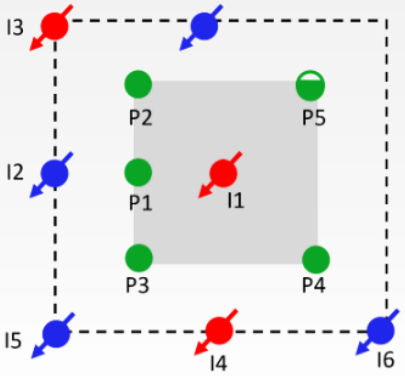
May 2021

Production Analysis

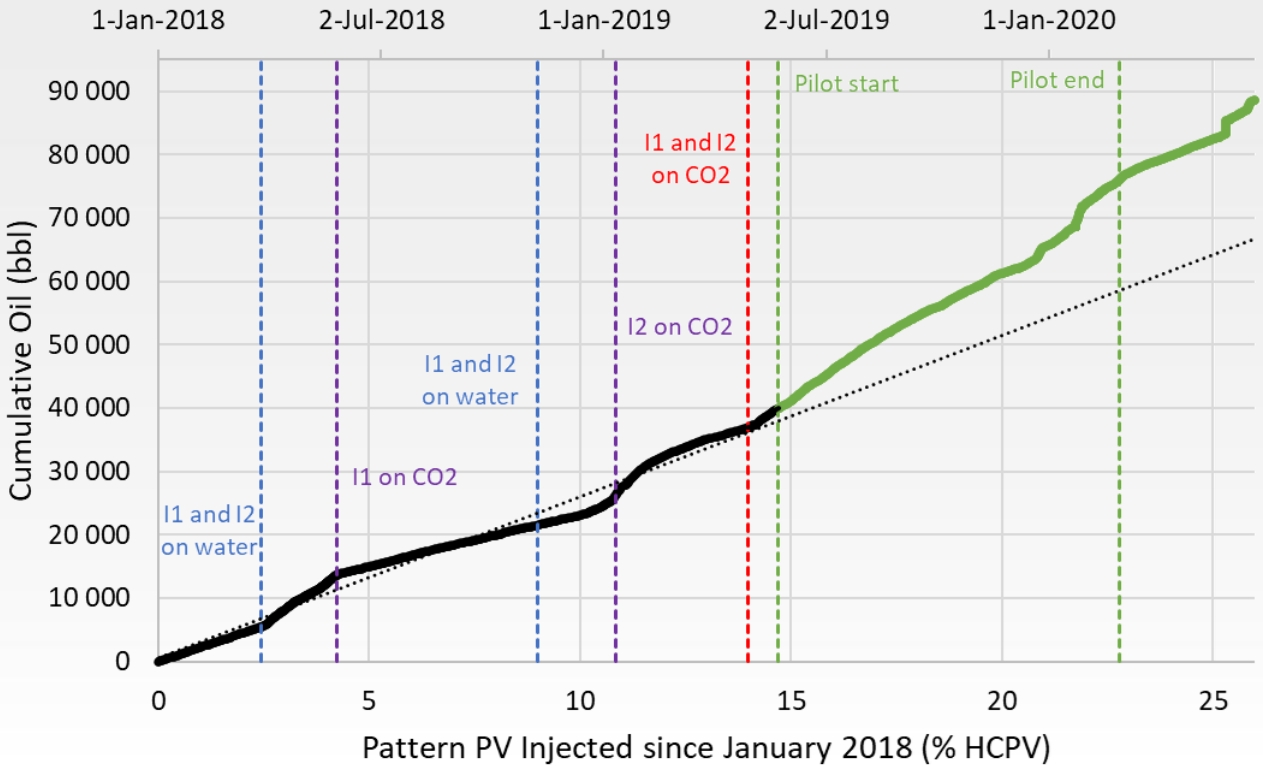
Production Analysis

- Cumulative oil recovered as a function of pore volume injected.
- Projection of the baseline performance.
  - 1.5 years prior to the start of the pilot (January 2018 to May 2019) with consistent data and minimal operational disruptions in the pattern.

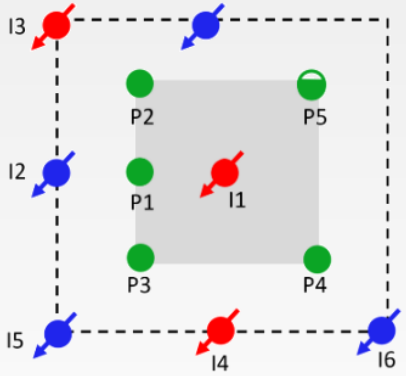




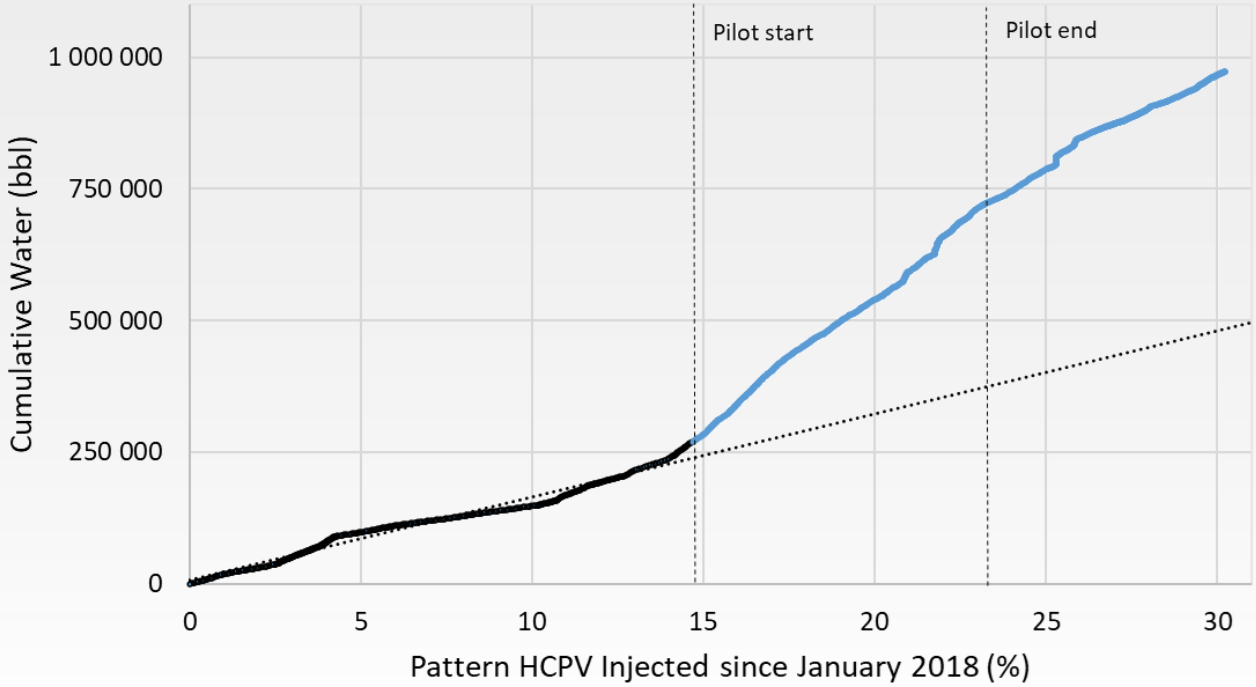
Production Analysis – Pilot Pattern

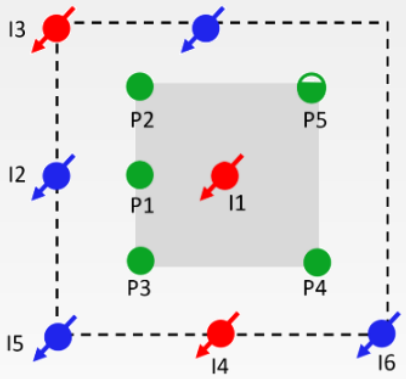


+25,000 bbls



Production Analysis – Pilot Pattern





Conclusions

Reduced CO_2 mobility

Increased sweep efficiency

Improved oil recovery

Increased CO_2 storage volumes

Ongoing monitoring and analysis

Acknowledgements

CLIMIT Program for financial support under grant **249742** - *CO_2 Storage from Lab to On-Shore Field Pilots Using CO_2 Foam for Mobility Control in CCUS* and **Gassnova** project **618069**.

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From Laboratory to Field-scale

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October 18, 2022

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