Department of Physics and Technology

# $CO_2$ Foam for Enhanced Oil Recovery and $CO_2$ Storage

## Field Pilots in Texas

Zachary Paul Alcorn, Sunniva B. Fredriksen, Mohan Sharma, Tore Føyen, Michael Jian, and Arthur Uno Rognmo

CCUS Student Week
Golden, Colorado
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The National IOR Centre of Norway

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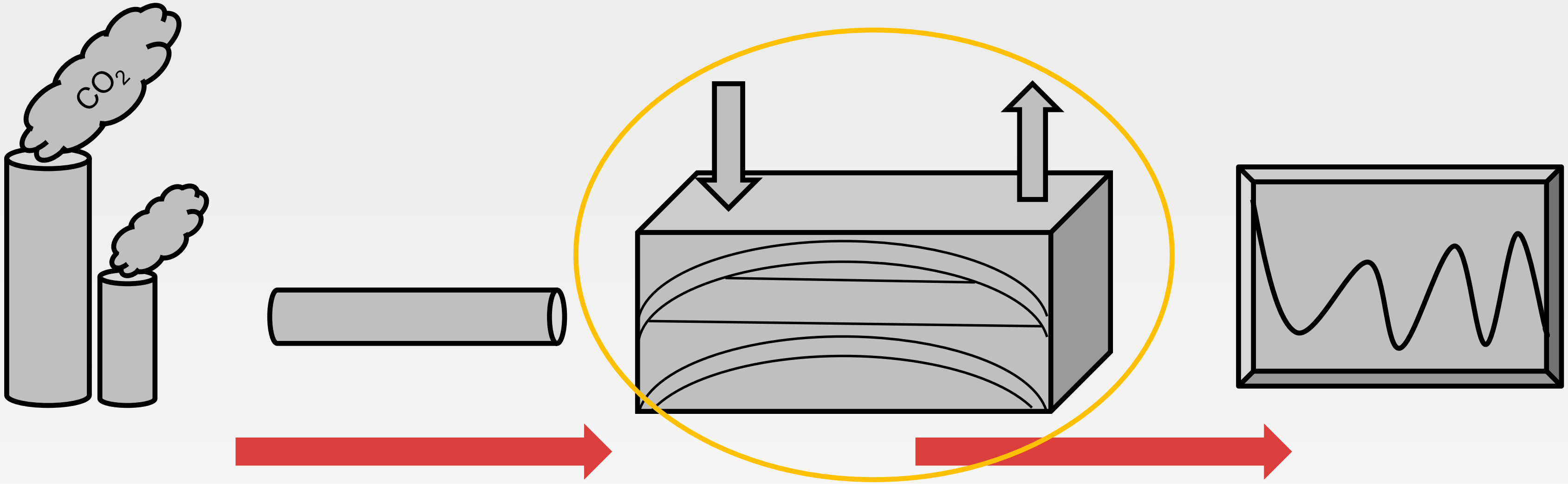
# Carbon Capture, Utilization, and Storage (CCUS)




Capture $CO_2$

Transport

Injection into subsurface reservoirs for energy production and $CO_2$ storage

Monitoring

# $CO_2$ EOR and $CO_2$ Storage

| Advantages | Disadvantages |
| --- | --- |
| Low MMP | Corrosion |
| Oil Viscosity | Low Availability |
| Swelling | High Mobility |
| Emissions | |

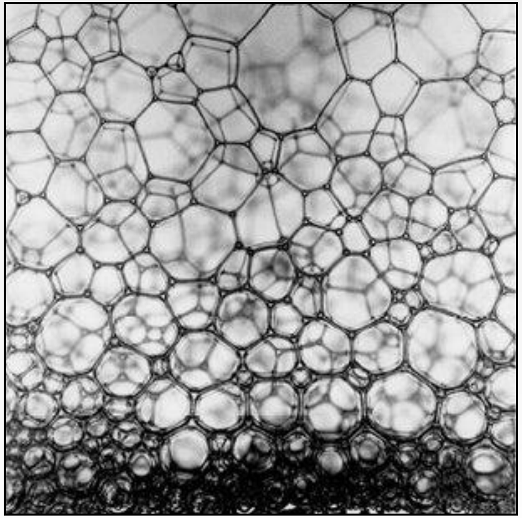
# $CO_2$ Mobility Control Agents

Direct Thickeners

Polymers/Polymer Gel

Foams

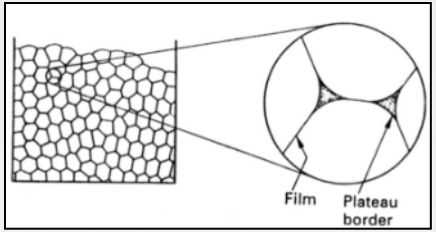
From Kuraray

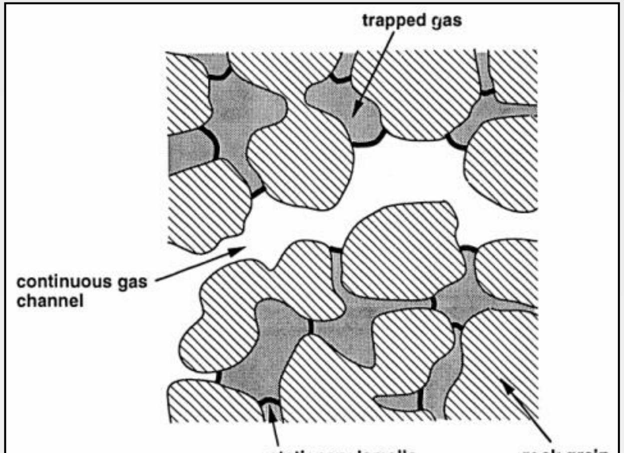


From European Space Agency

# $CO_2$ Foam

- **What?**
  - Dispersion of gas in liquid
  - Stabilized by surfactant

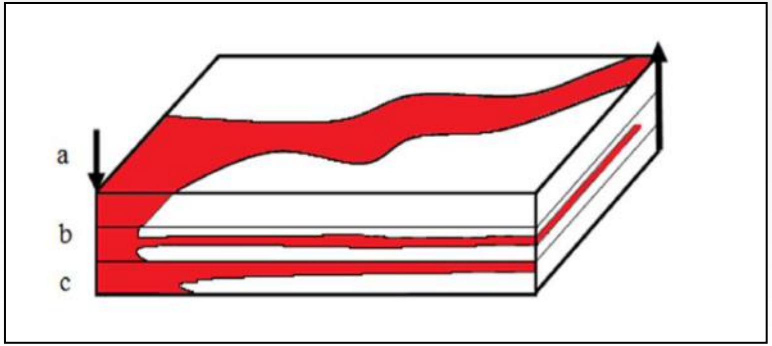



After Kovscek and Radke

- **How?**
  - Decreases relative permeability
  - Reduces IFT
  - Injection: SAG or Co-injection

- **Why?**
  - Mobility control
  - Increase reservoir sweep
  - Improve $CO_2$ utilization



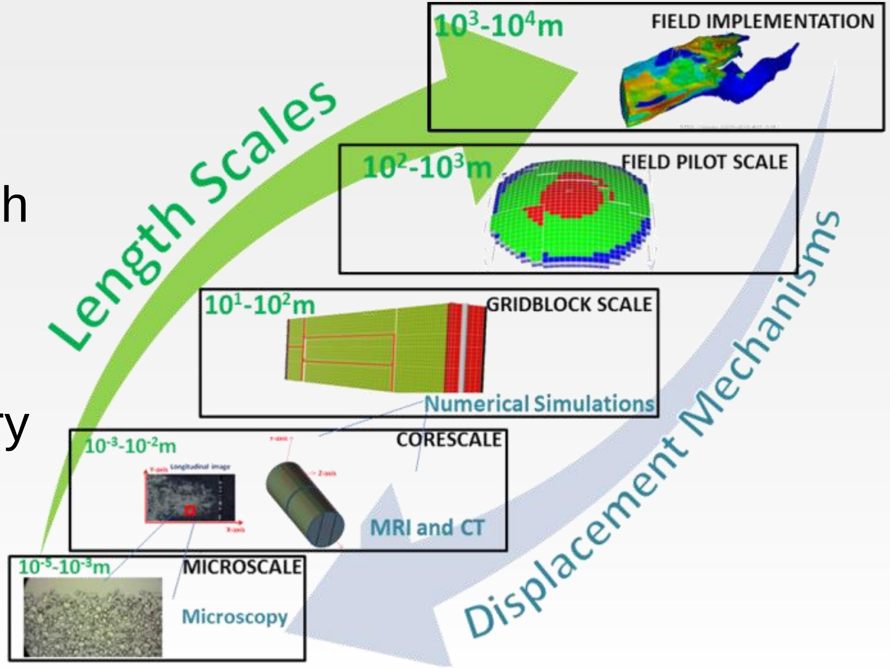

Sc-$CO_2$ EOR mobility challenges: a) poor aerial sweep, b) gas channeling, c) gravity override (Hanssen et al., 1994)

# Motivation

Discrepancies arise between scale dependent $CO_2$ foam displacement mechanisms associated with laboratory and field scale processes.

- A further understanding of dominant displacement forces occurring at each scale is needed

- Field trials offer unique insight to bridge the gap between the laboratory and the field



# Approach

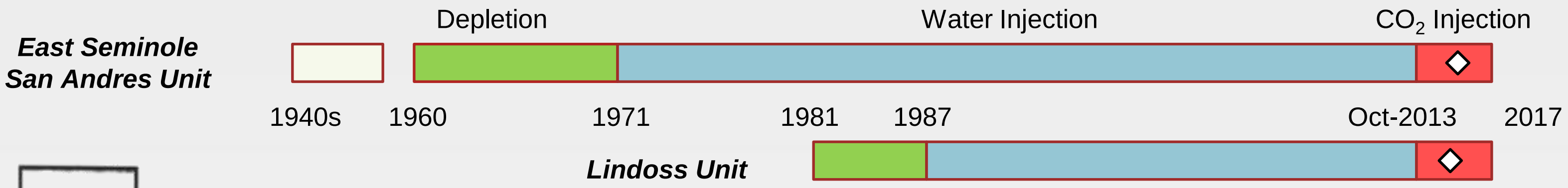
Combining verified laboratory $CO_2$ foam technology with a field scale demonstration test. Project objectives are twofold:

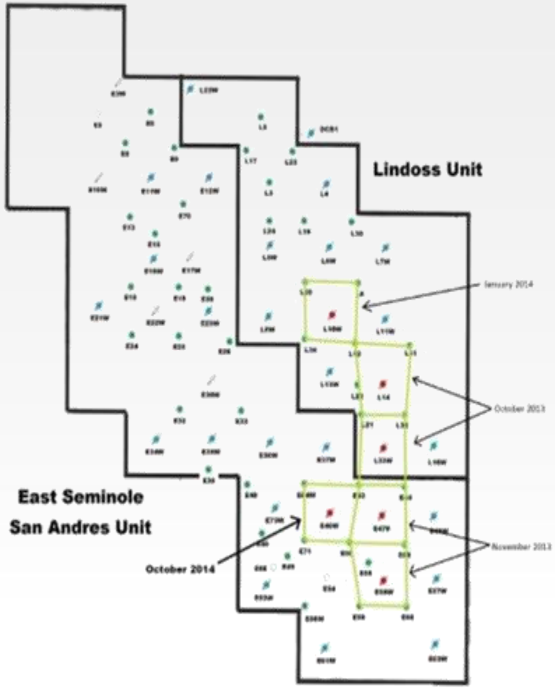
1) Identify multiscale $CO_2$ foam displacement mechanisms during EOR and associated $CO_2$ storage

2) provide transferrable knowledge for the design of similar projects where foam is appropriate to mitigate $CO_2$ flood challenges

# Pilot Design

# Field Development History




| Reservoir Characteristic | Value |
|---|---|
| Depth | 5200 ft |
| Permeability | 1 – 300 mD<br>Ave. 13 mD |
| Porosity | 3 – 28 %<br>Ave. 12- 15 % |
| Pay Thickness | 110 ft |
| Reservoir Pressure (initial) | 2500 psig |
| Reservoir Pressure (current) | 3200 psig |
| Temperature | 104ºF |
| Oil Gravity | 31º API |
| Initial Oil Saturation | 0.65 |
| Initial Water Saturation | 0.35 |
| Oil viscosity (reservoir conditions) | 1.20 cP (at 2500 psig and 104 ºF) |
| Bubble Point Pressure | 1805 psig |
| Formation Brine Salinity | 70,000 ppm |
| $S_{orw}$ | 0.40 (Gray, 1989) |
| ROZ $S_{orw}$ | 0.25 (Honarpour et al. 2010) |
| ROZ ROS, waterflood | 0.32 (Honarpour et al. 2010) |
| ROZ $S_{orm}$ | 0.12 (Honarpour et al. 2010) |

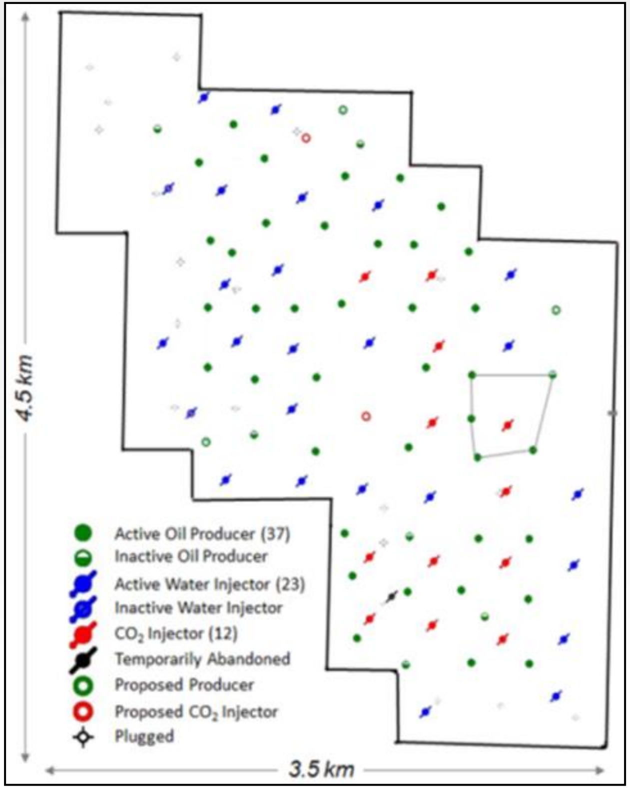
# Pilot Design

## Identify Problems – ongoing $CO_2$ injection

- Poor sweep efficiency
- High producing gas oil ratio (GOR)
- $CO_2$ channeling

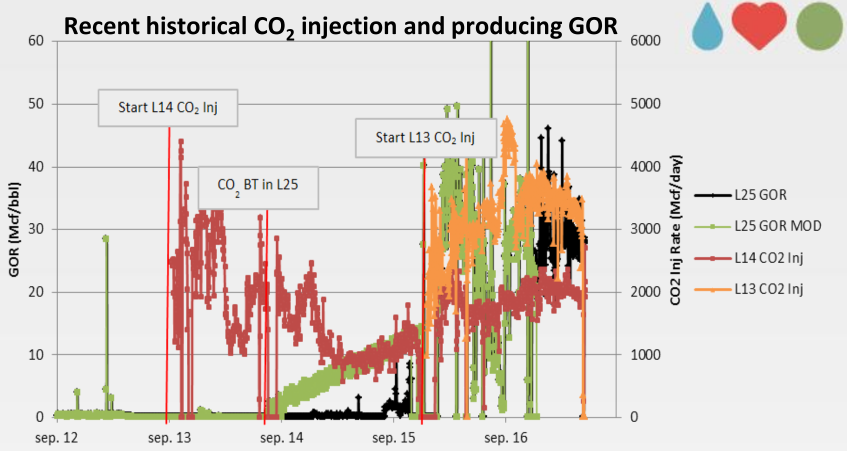
## Potential Opportunities for Foam

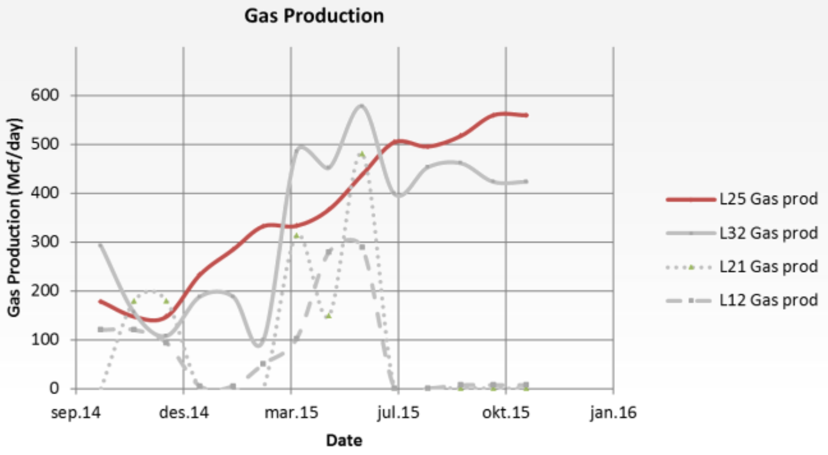
- Conformance Control
- Mobility Control
- Combination
- Reservoir Heterogeneity



# Pilot Well Selection Criteria

- Rapid gas breakthrough
- An high GOR in the selected producer
- Lower injection well head pressure
- Wells in close proximity to minimize geological uncertainty and maximize interwell connectivity.

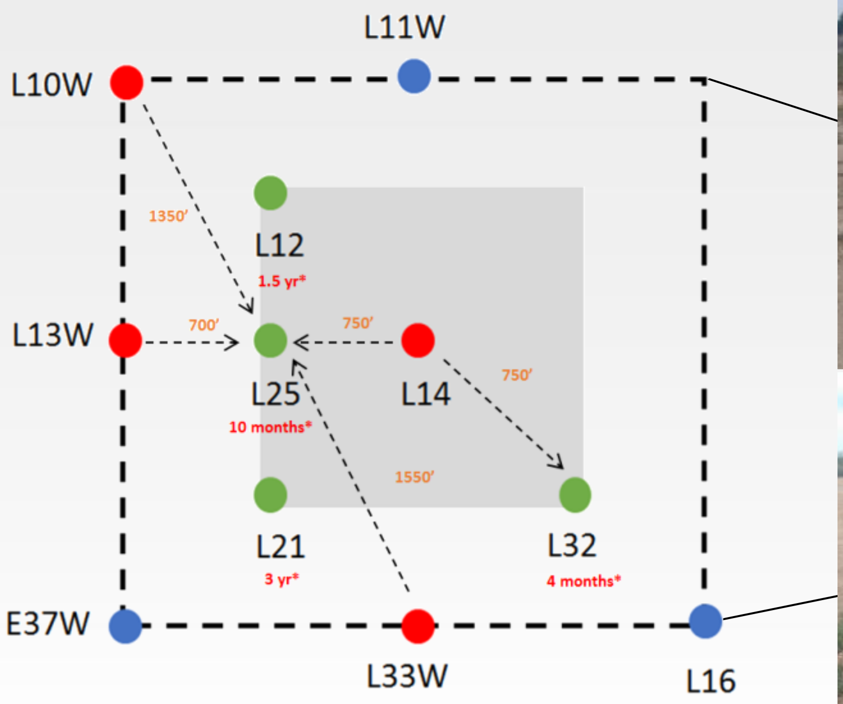


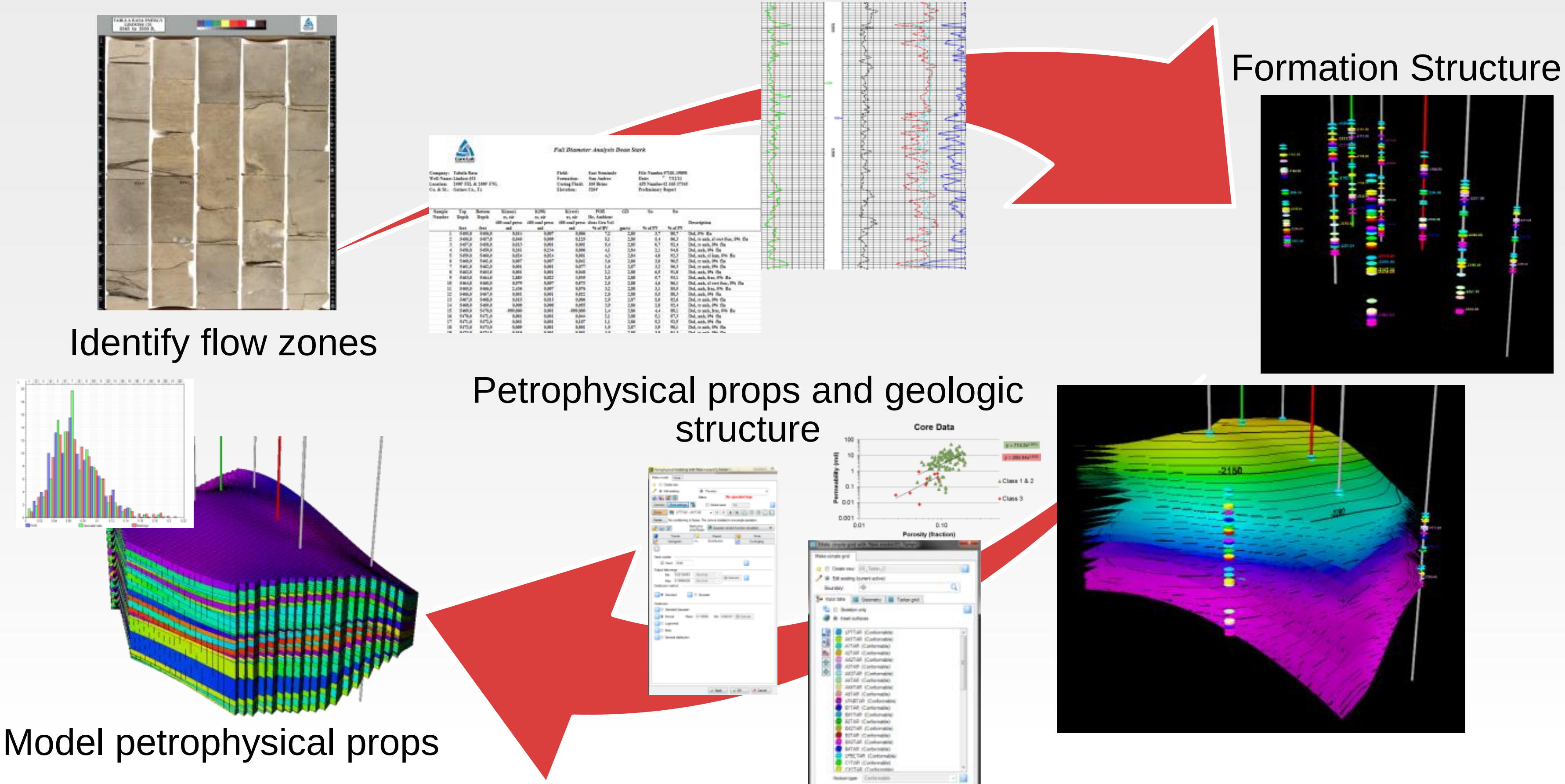
# Pilot Design - Objectives

- Increase incremental oil production through improved $CO_2$ sweep efficiency
- Reduce the producing GOR while maintaining injectivity
- Improve $CO_2$ utilization
- Verify $CO_2$ storage and mobility control

# Pilot Pattern




# Field Scale: Geologic and Reservoir Modeling



# Laboratory Scale:
# Technology Testing and Verification

Foam System Design

$CO_2$ Foam Enhanced Oil Recovery (EOR)

$CO_2$ Storage

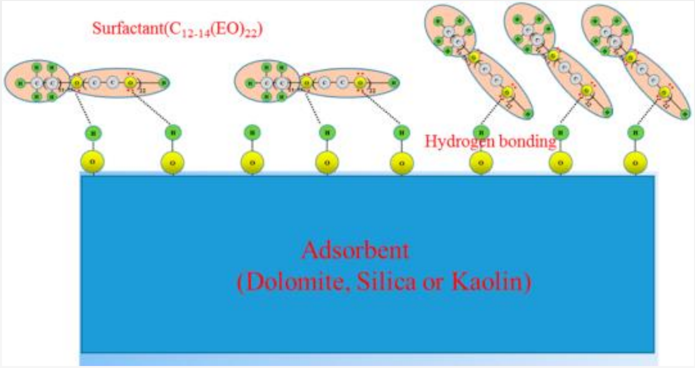
# Foam System Design

Surfactant Screening
Surfactant Concentration
Foam Quality

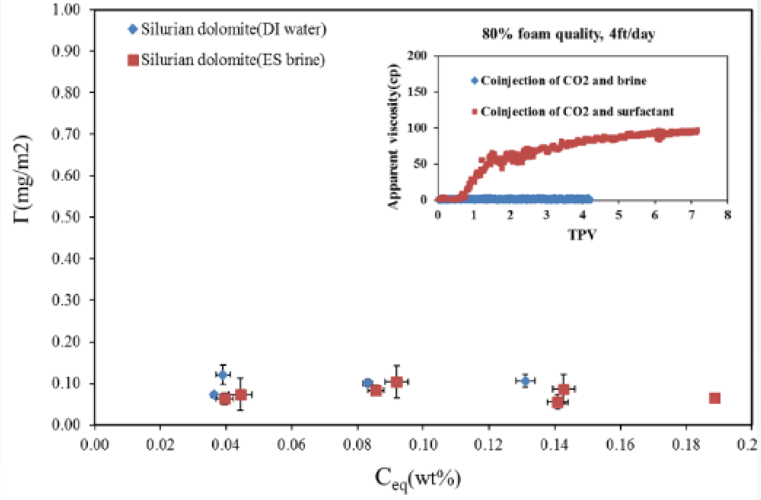
# Surfactant Screening

## Objective

Surfactant with least amount of adsorption on reservoir material, in presence of $CO_2$



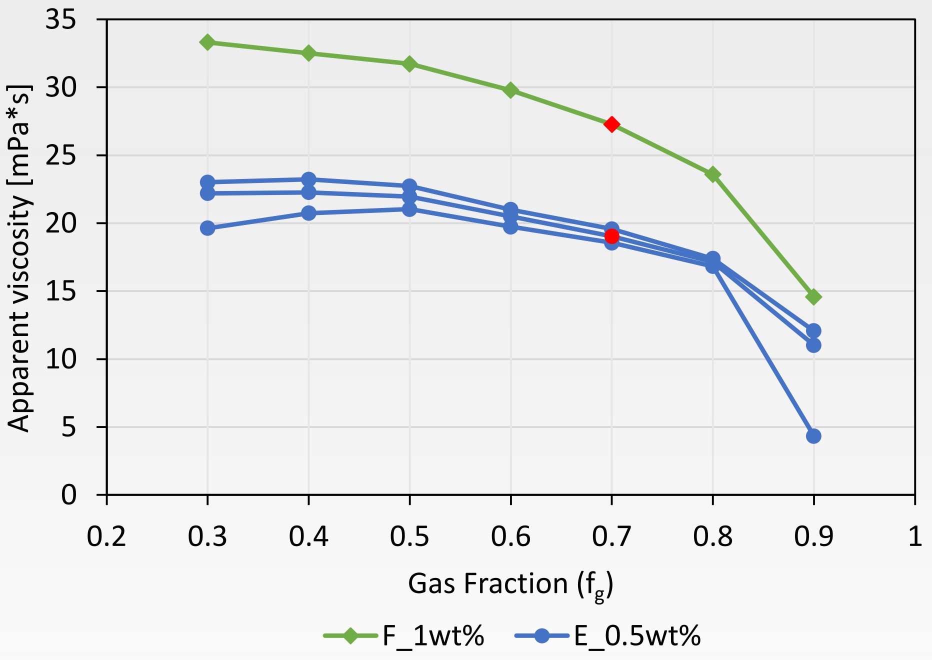

Jian et al., 2016




Results:

- Non-ionic Huntsman L24-22 surfactant (highly ethoxylated surfactant)
- Low surfactant adsorption on pure calcite and dolomite (0.05-0.1mg/$m^2$)
- Adsorption remained unchanged in experiments with $CO_2$

# Foam Quality Scans




Results:

- Gas Fraction ($f_g$) of 0.70 is recommended based upon the highest apparent viscosity at economically feasible $f_g$
- The relatively small reduction in foam strength between $f_g$ = 0.30 to 0.70 does not justify the choice of a more expensive $CO_2$ to surfactant solution ratio.

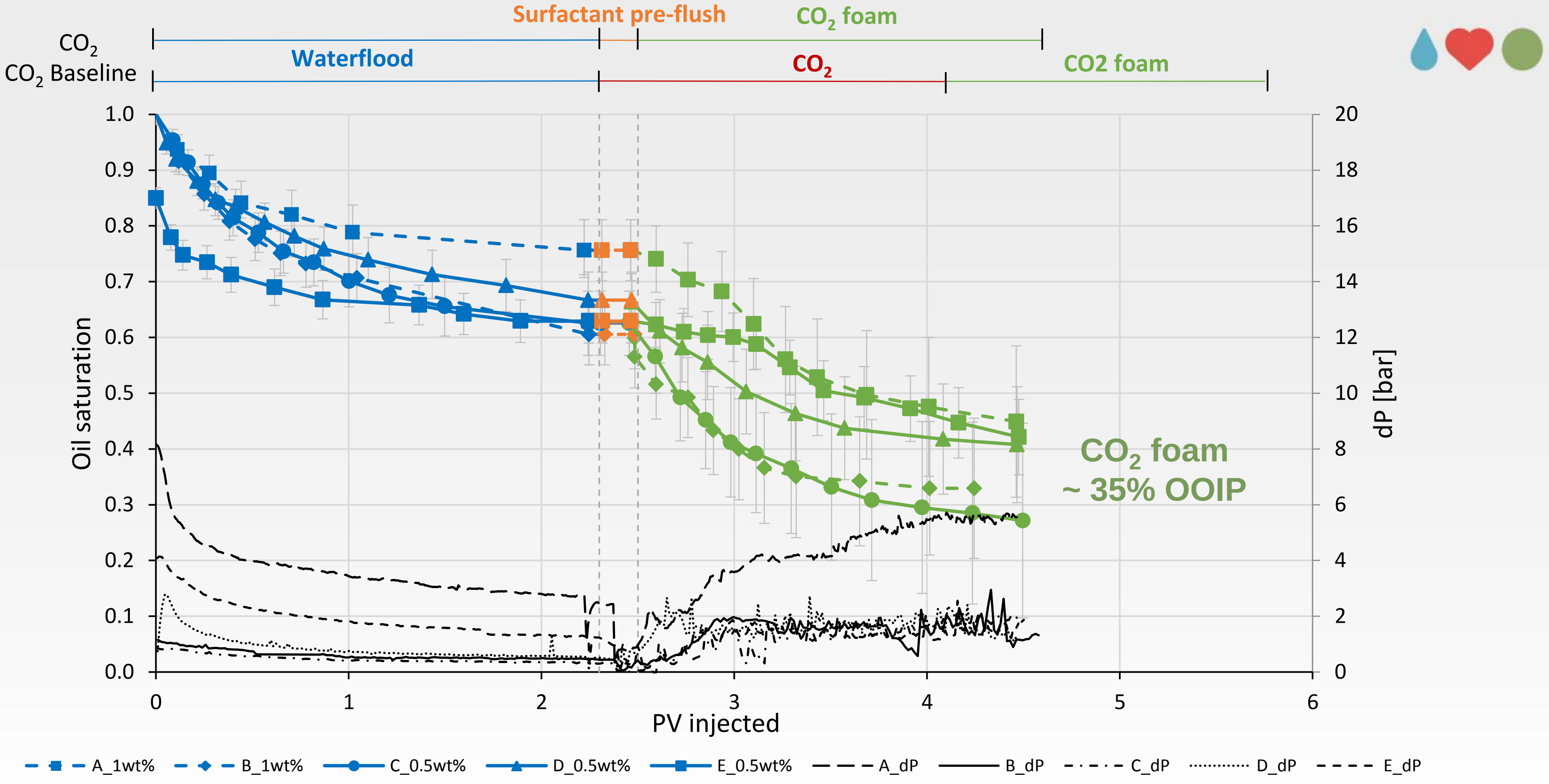
1wt% surfactant solution (green curves) and **0.5 wt% surfactant solution (blue curves)**

# $CO_2$ Foam
# Enhanced Oil Recovery (EOR)

EOR and $CO_2$ storage potential

Surfactant concentration

Foam in the presence of oil

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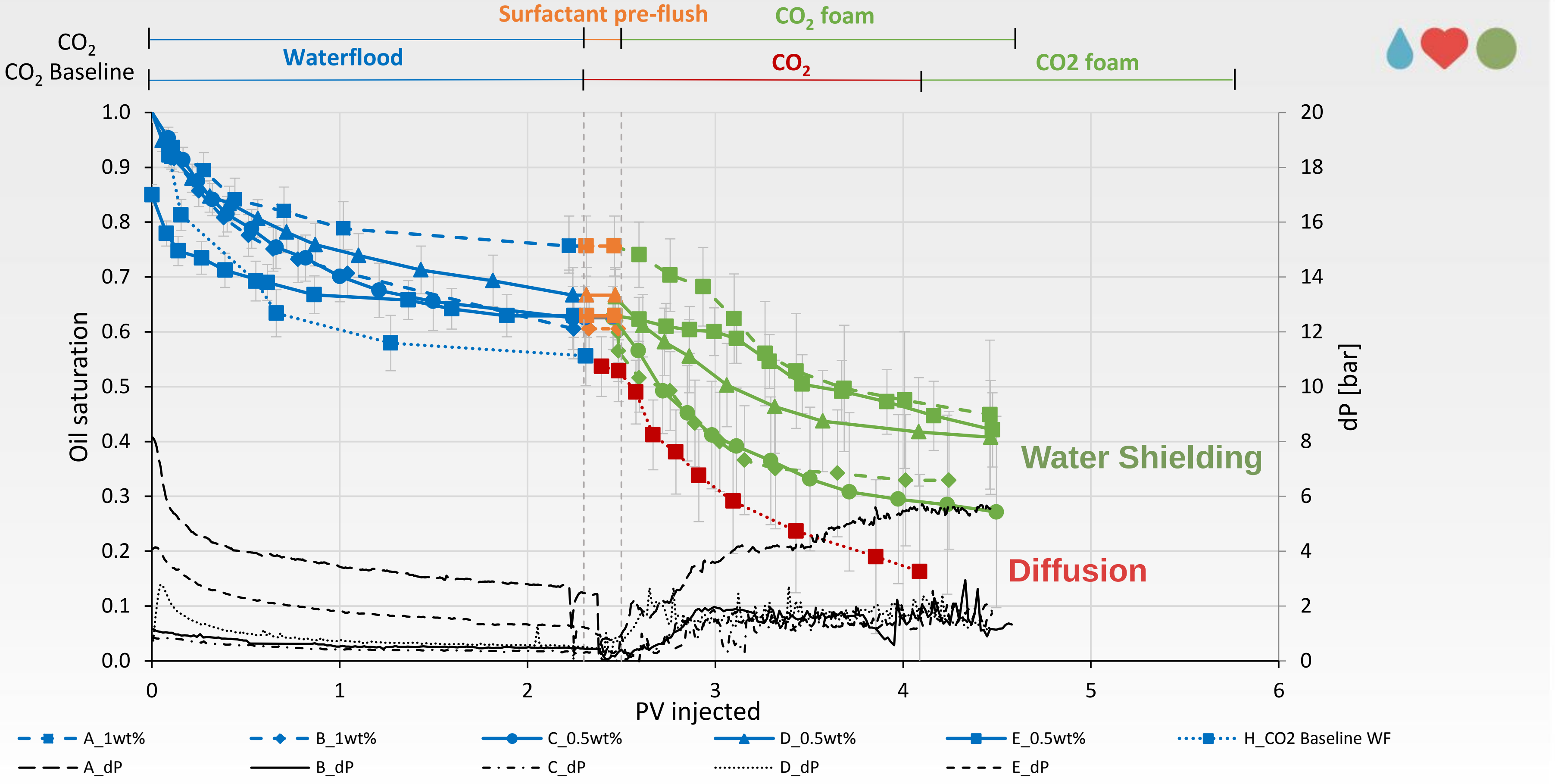
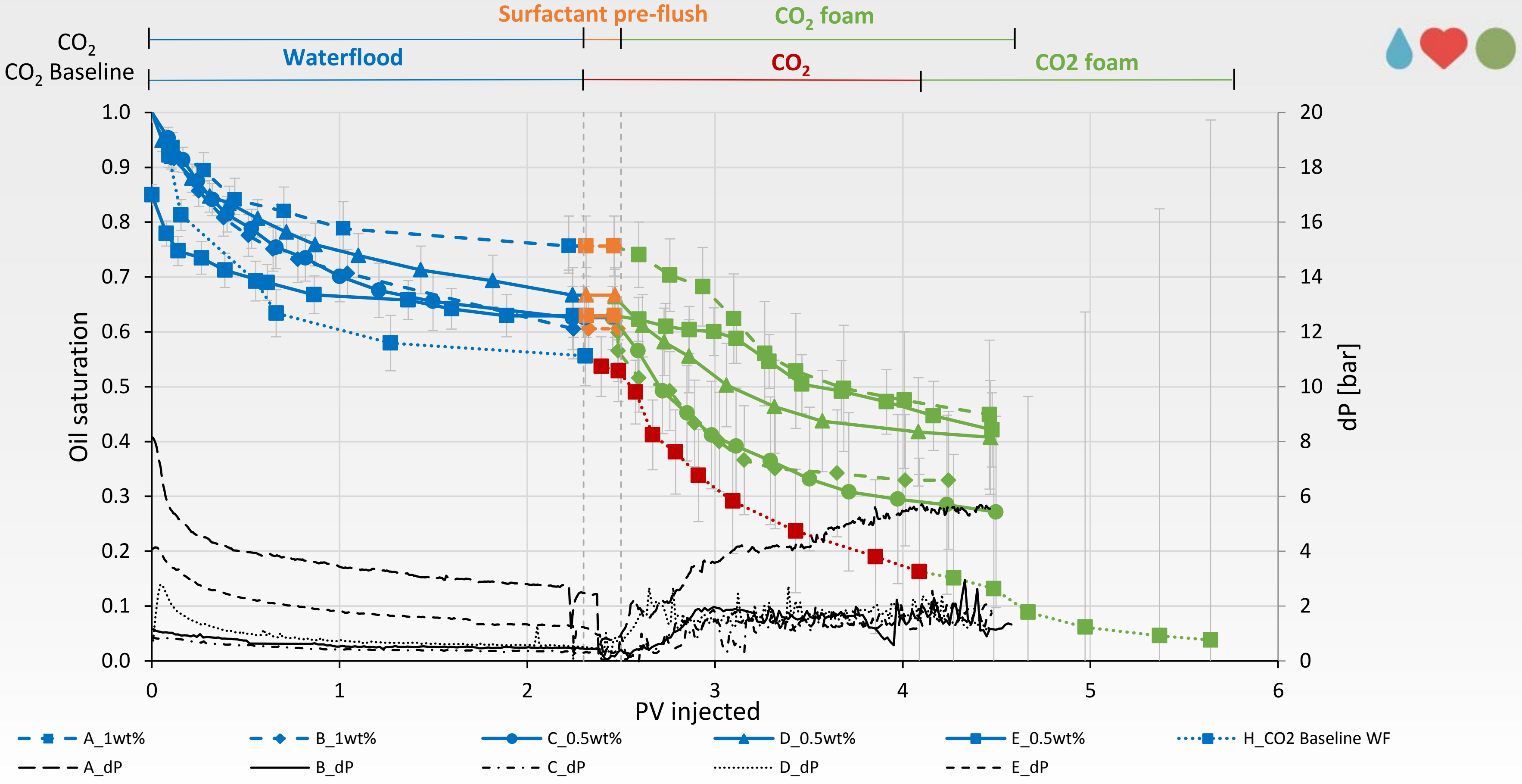

Surfactant pre-flush
CO2 foam
CO2
CO2 Baseline
Waterflood
CO2
CO2 foam
Oil saturation
dP [bar]
PV injected
Water Shielding
Diffusion
A_1wt%
B_1wt%
C_0.5wt%
D_0.5wt%
E_0.5wt%
H_CO2 Baseline WF
A_dP
B_dP
C_dP
D_dP
E_dP

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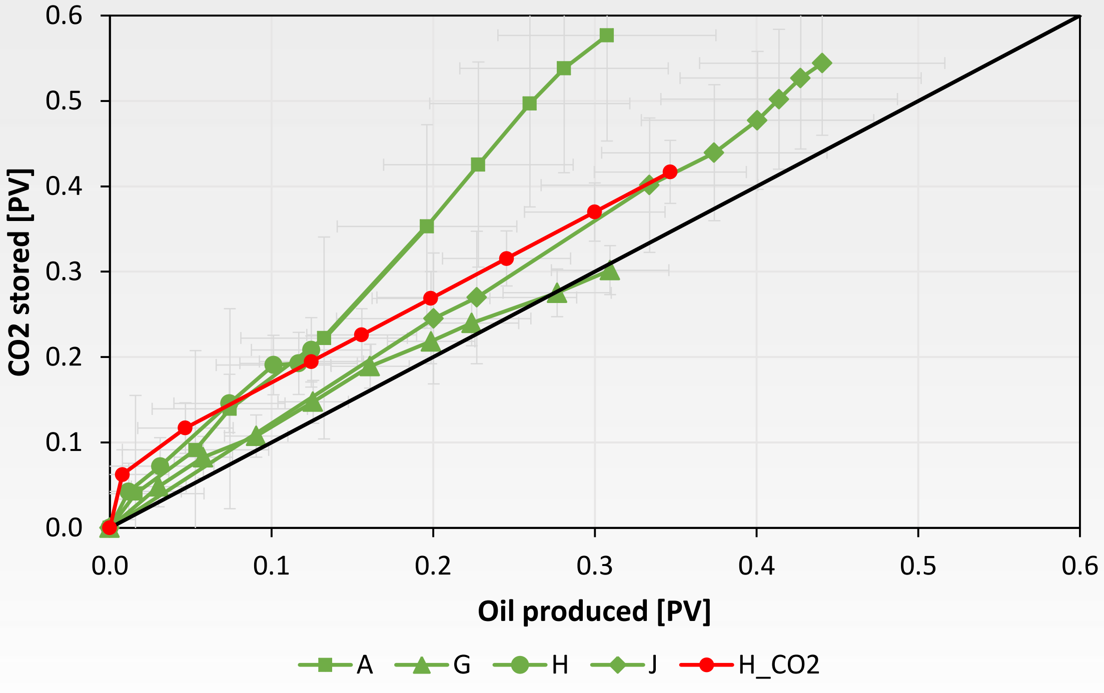
# Associated $CO_2$ Storage



# Field Scale:
# Technology Demonstration

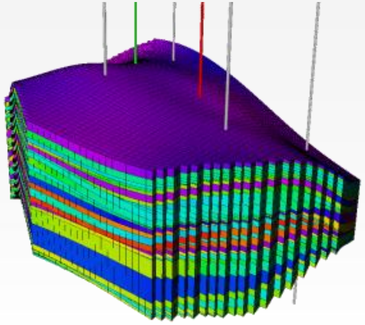
Reservoir Simulation

Surface Facilities

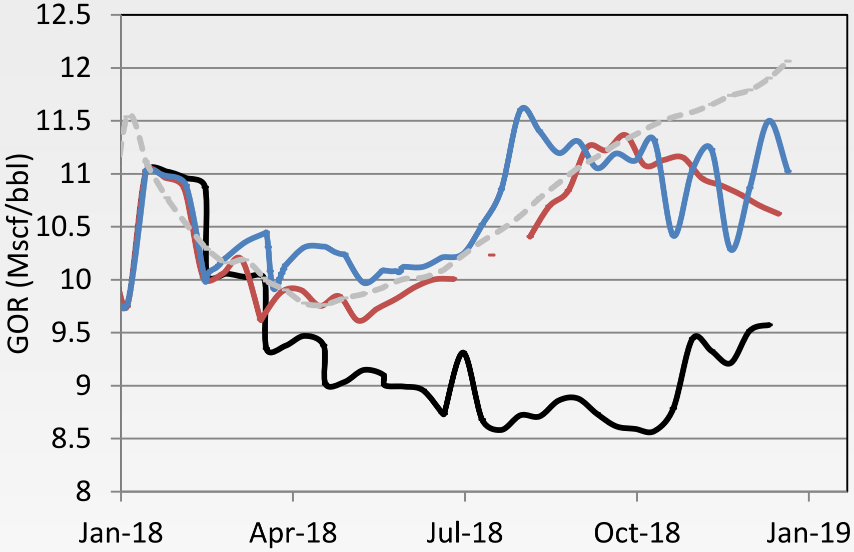
Data Collection and Monitoring

# Reservoir Simulation

Foam injection strategy impacts on
oil recovery, GOR, $CO_2$ mobility, and $CO_2$ utilization

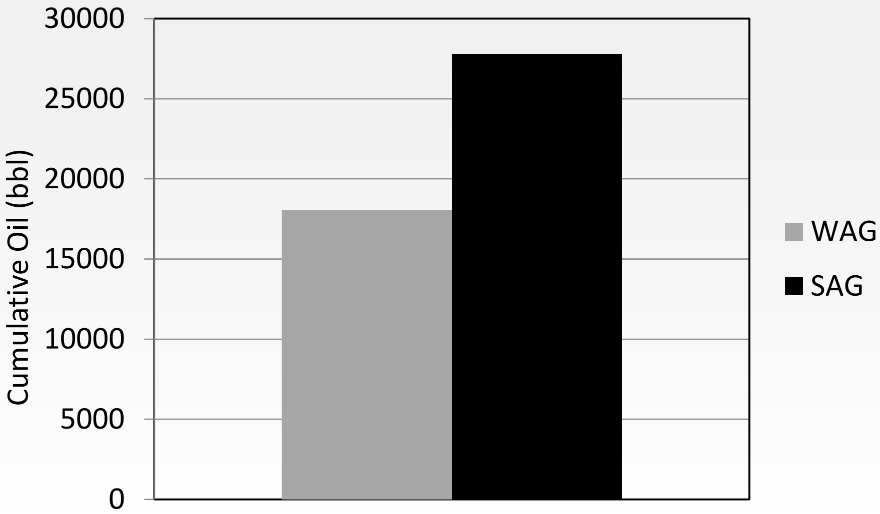


# Foam Injection Strategy



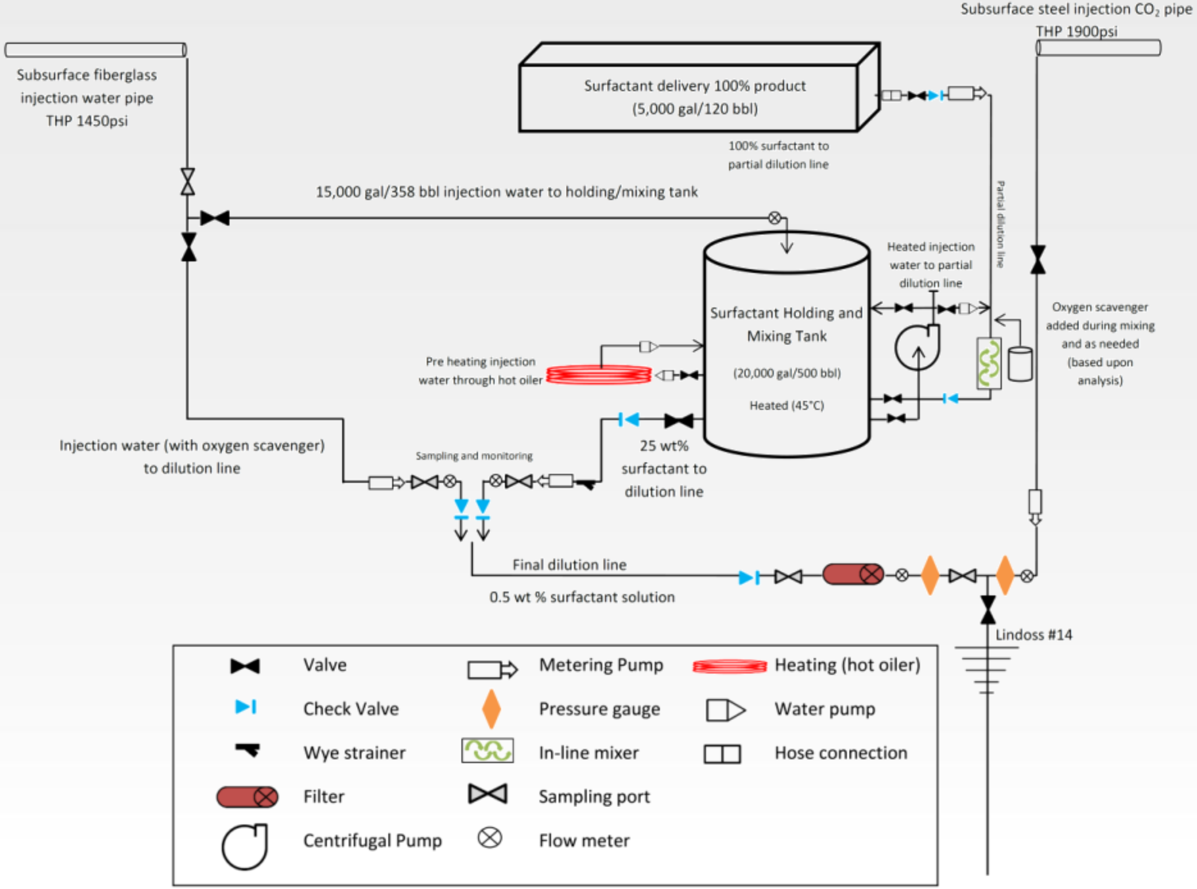

Field GOR of WAG , multi-cycle SAG, single cycle SAG, and rapid SAG.

| Case | $CO_2$ Utilization factor (Mscf/bbl) |
|---|---|
| WAG | 30.14 |
| SAG | 19.26 |
| Single Cycle SAG | 20.47 |
| Rapid SAG | 21.30 |



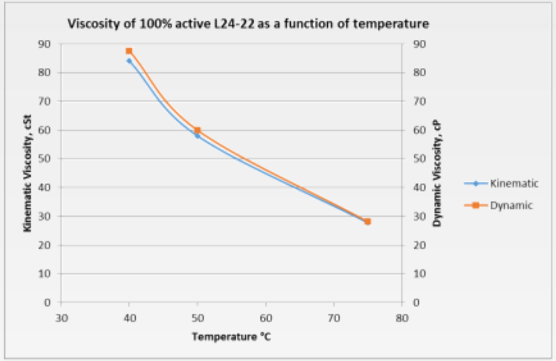

## Multi-cycle SAG

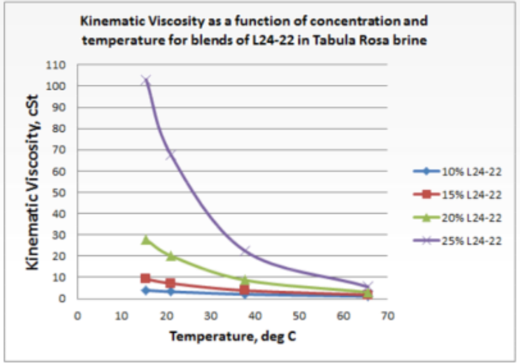
# Field Injection Unit




Bulk properties, 100% active

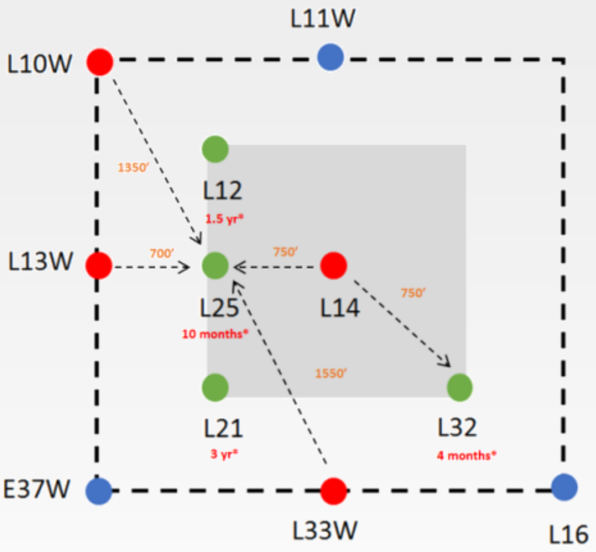
| Temperature °C | Kinematic viscosity, cSt | Density, g/ml | Dynamic viscosity, cP |
|---|---|---|---|
| 40 | 84.111 | 1.0419 | 87.635 |
| 50 | 58.021 | 1.034 | 59.994 |
| 75 | 27.809 | 1.0147 | 28.218 |



# Data Collection and Monitoring

- Demonstrate creation of stable foam in reservoir
- Monitor the propagation of $CO_2$, water, and surfactant
- Establish baseline interwell connectivity



# Data Collection and Monitoring

- Interwell Connectivity
- Injection Profiling
- Reservoir Characterization and Fluid Monitoring
- Recovery and Production Monitoring
- Corrosion

| Stage | Pre SAG (baseline) | Pilot Phase (3 SAG cycles) | | | | | | Post SAG |
|---|---|---|---|---|---|---|---|---|
| Slug | Ongoing $CO_2$ Injection | Surfactant | $CO_2$ | Surfactant | $CO_2$ | Surfactant | $CO_2$ | |
| Tracers | $CO_2$, water | | | | | | | $CO_2$, water |
| Injection Profiles (L14) | X | | X | | | | | X |
| Fall off test | X | | X | | | | | X |
| Crosswell Seismic | X | | | | | | | X |

# Conclusions

| | Laboratory | Field |
|---|---|---|
| Site | reservoir cores | 40 acre 5-spot |
| Surfactant | nonionic Huntsman L24-22 | |
| Foam System | 0.5 wt% at $f_g$= 0.70 | foam model input |
| EOR | 35% Incr. OOIP | |
| $CO_2$ Storage | water and oil | unswept zones |
| Injection Strategy | multi-cycle SAG | |

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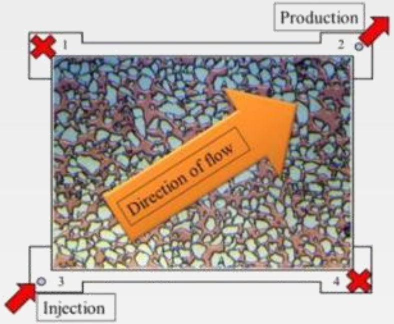
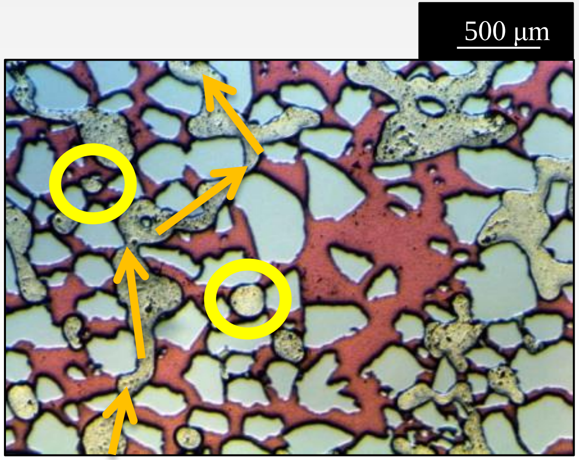
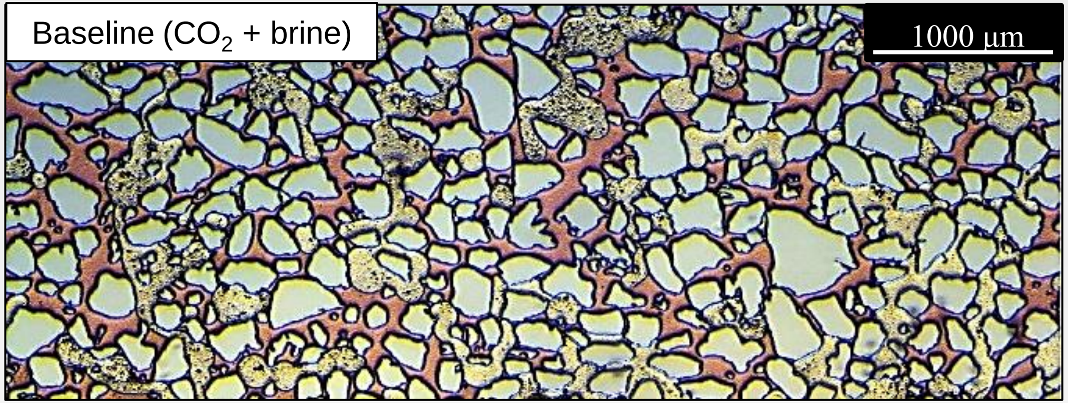
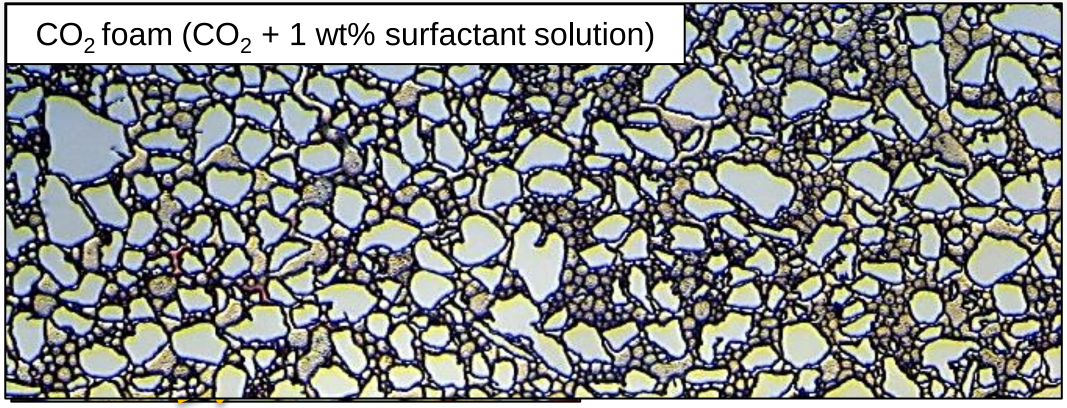
# $CO_2$ Foam: Pore Scale



# $CO_2$ Displacement Mechanisms