

Experimental Studies of Halite Precipitation and Implications for Flow Assurance in CO₂ Injection Wells

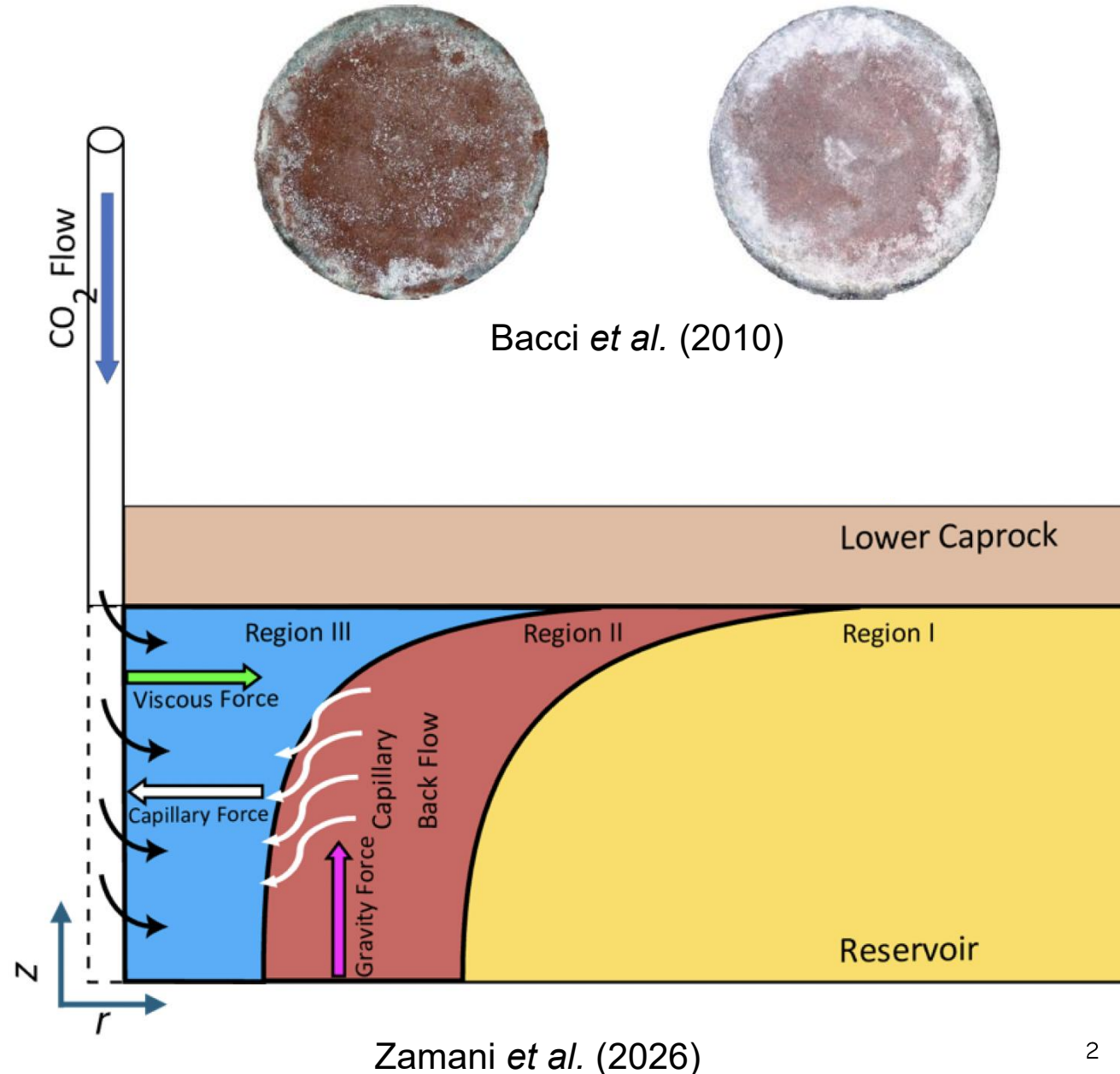
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Professor Myles Jordan
SLB

Main Messages

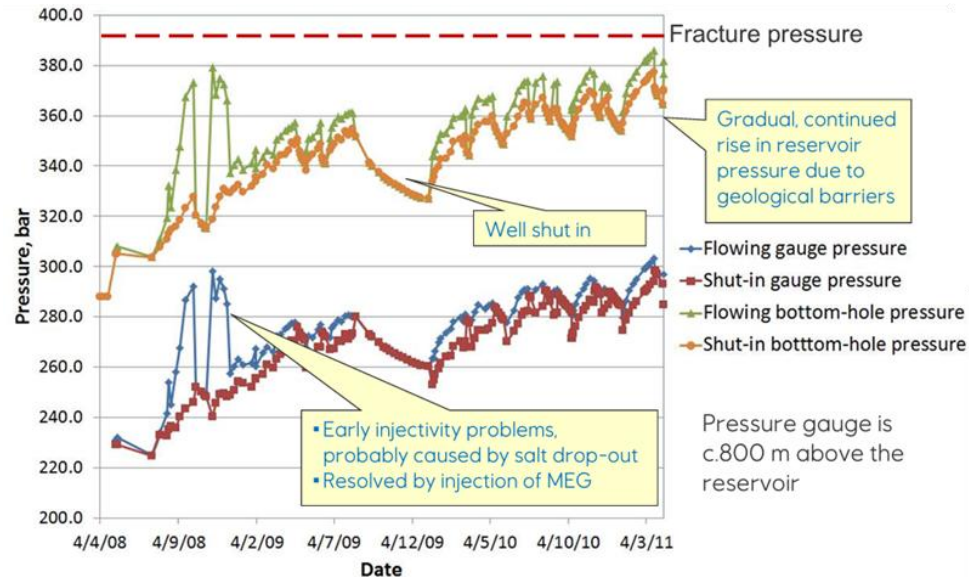
- Salt may precipitate **whenever** dry CO_2 injected into wet porous medium
- **Amount** depends on
 - Balance of viscous, capillary and gravitational forces
 - Brine supply
 - Salinity
- Damage significant if brine flux into:
 - Near well zone
 - Well itself
- Avoided if injection rate high enough that CO_2 flows across entire completed interval
- If halite forms, it may be removed by batch water (+ MEG) treatments



Context

Context of Study – Field Observations

- Halite precipitation observed at
 - Quest
 - Aquistore
 - Snøhvit
- Also occurs in natural gas production
 - 10% of Dutch gas wells



Ringrose & Sæther (2020)



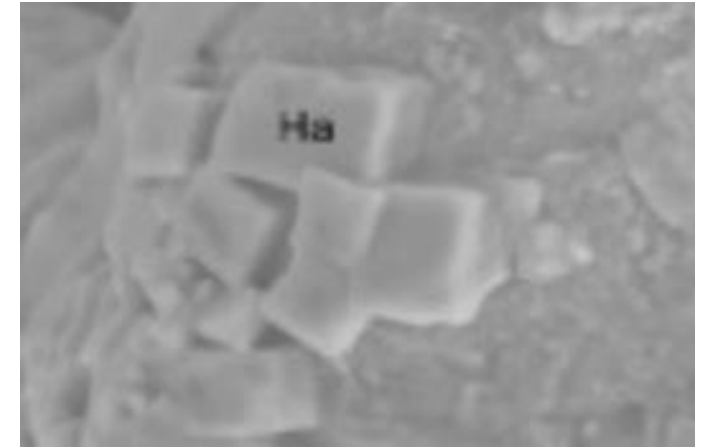
Smith *et al.* (2022)



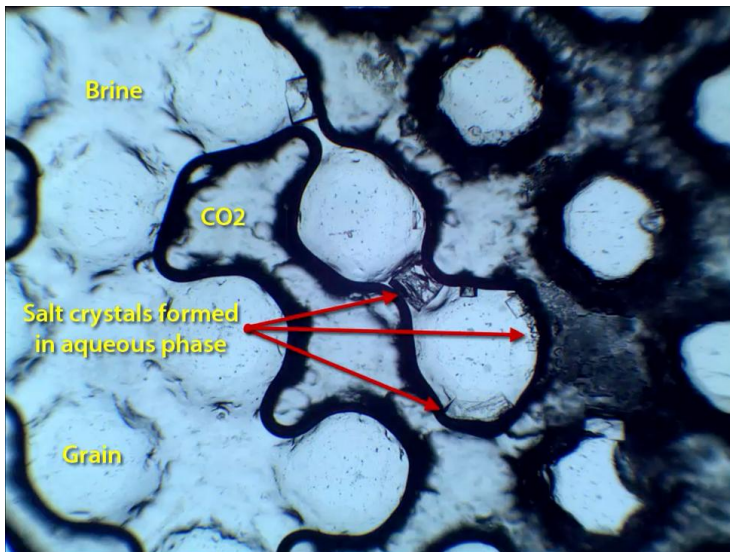
Talman *et al.* (2021)

Context of Study – Laboratory Studies

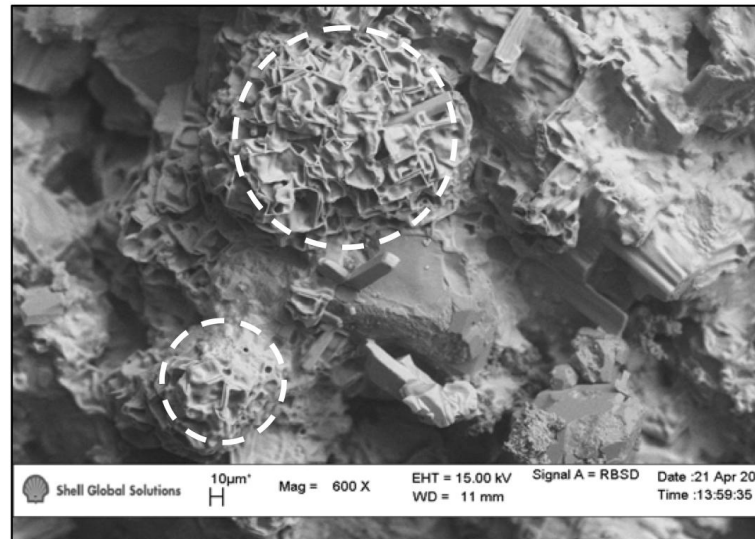
- Existing studies have focused on pore-scale, with some core-scale also
- Pore scale difficult to upscale, but observations can aid understanding
- Core flooding often entails multiple injection cycles



Narayanan *et al.* (2023)



Miri *et al.* (2015)



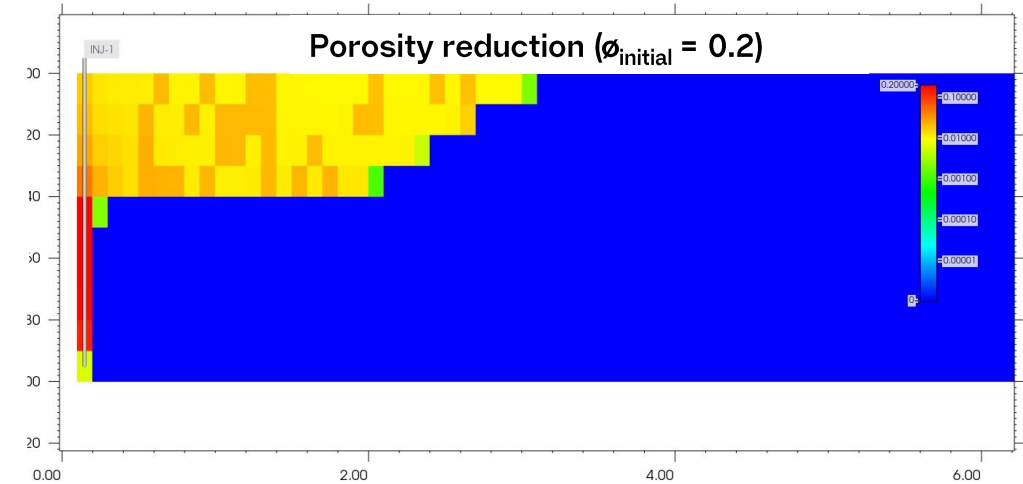
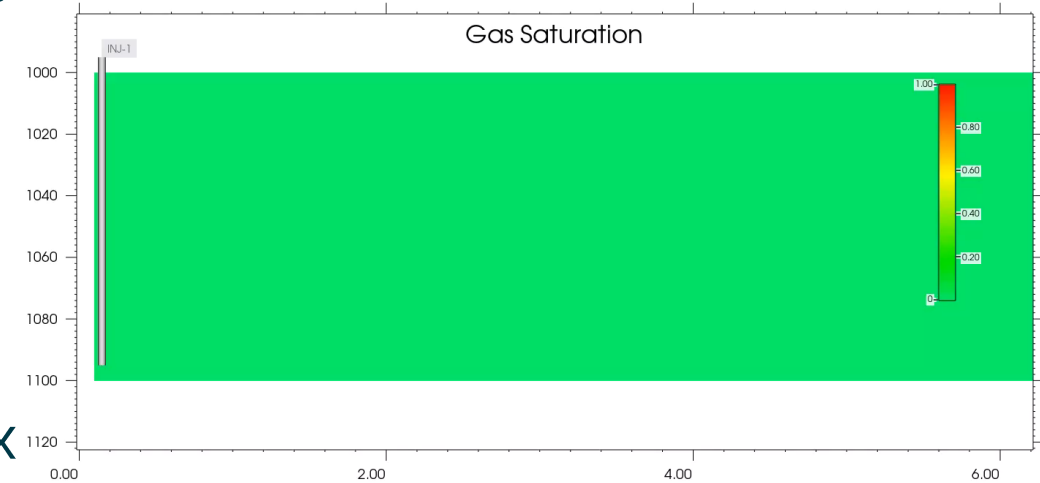
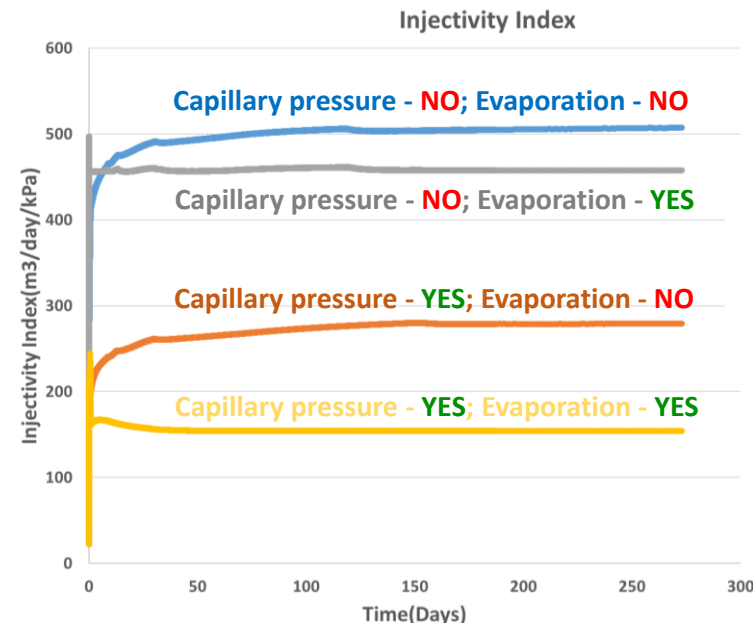
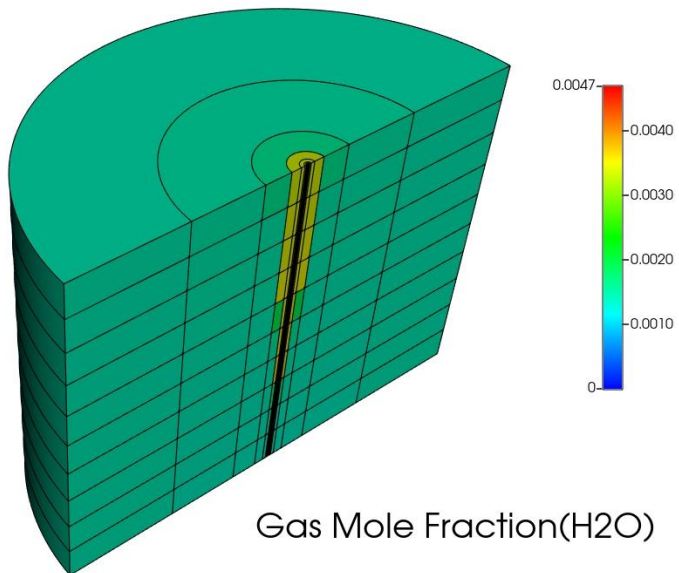
Wang *et al.* (2009)



Sokama-Neuyam *et al.* (2019)

Context of Study – Modelling Studies

- Radial models required to model near well zone
- Predict loss of injectivity due to precipitation towards lowest part of completion in which CO_2 being injected
- Capillarity necessary to cause brine flow into dry out zone
- Evaporative flux must be greater than brine flux

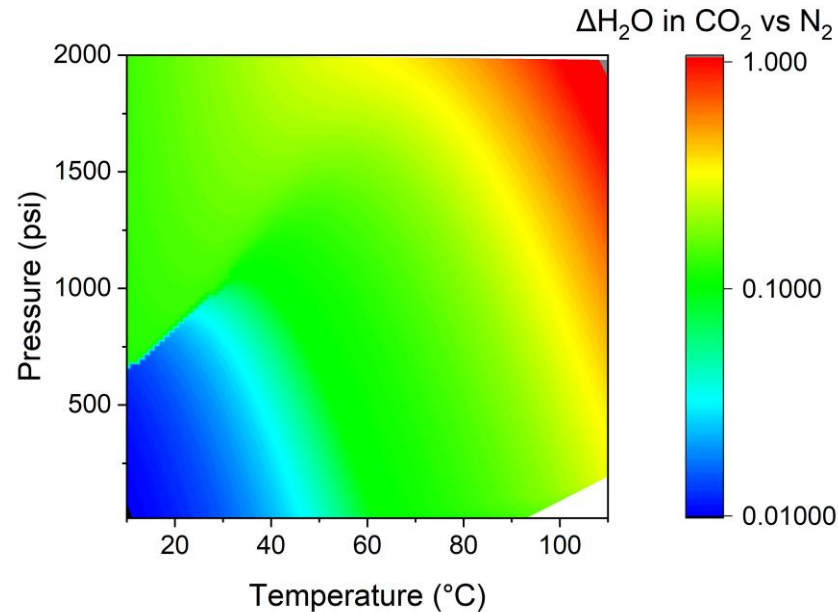


Ogundipe & Mackay (2023)

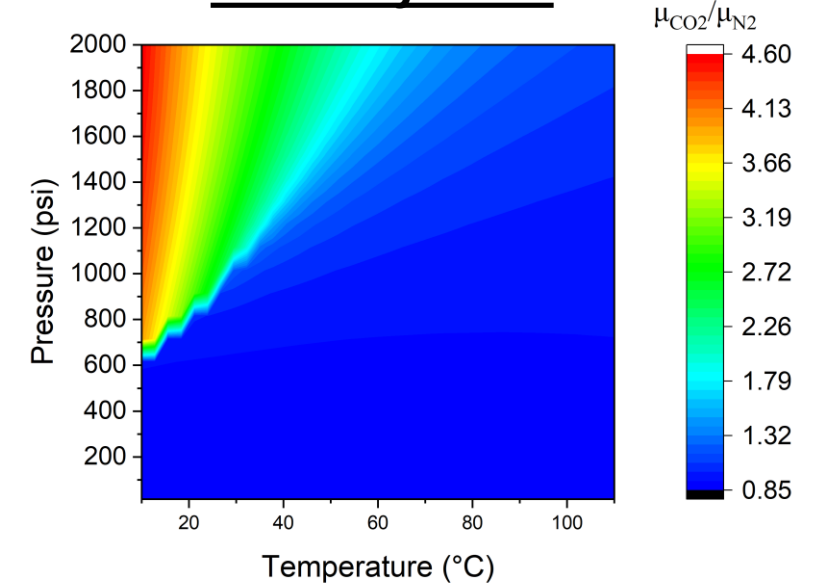
Aside: CO₂ vs N₂ Properties

- Fluid properties are relatively similar under the studied conditions (20°C, 1 atm)
- Viscosity and density from Winprop (right)
- Evaporative capacity via ScaleChem (below)

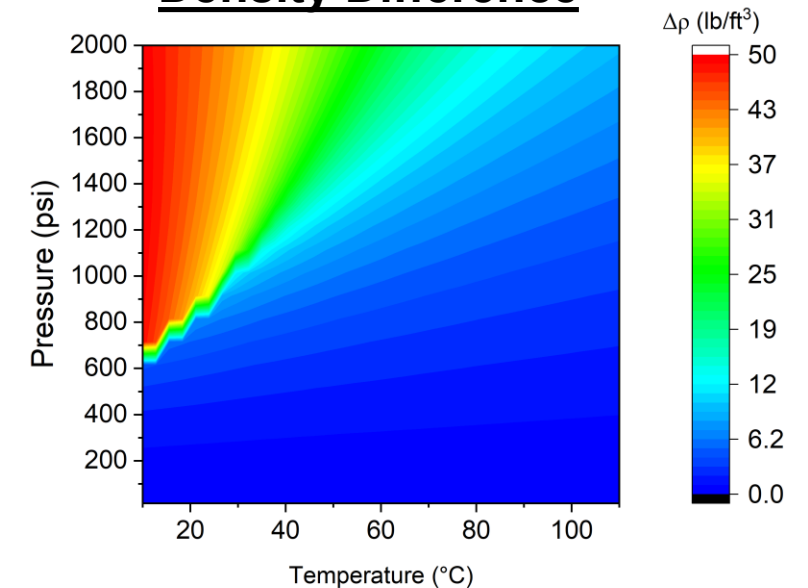
Difference in Evaporative Capacity



Viscosity Ratio



Density Difference

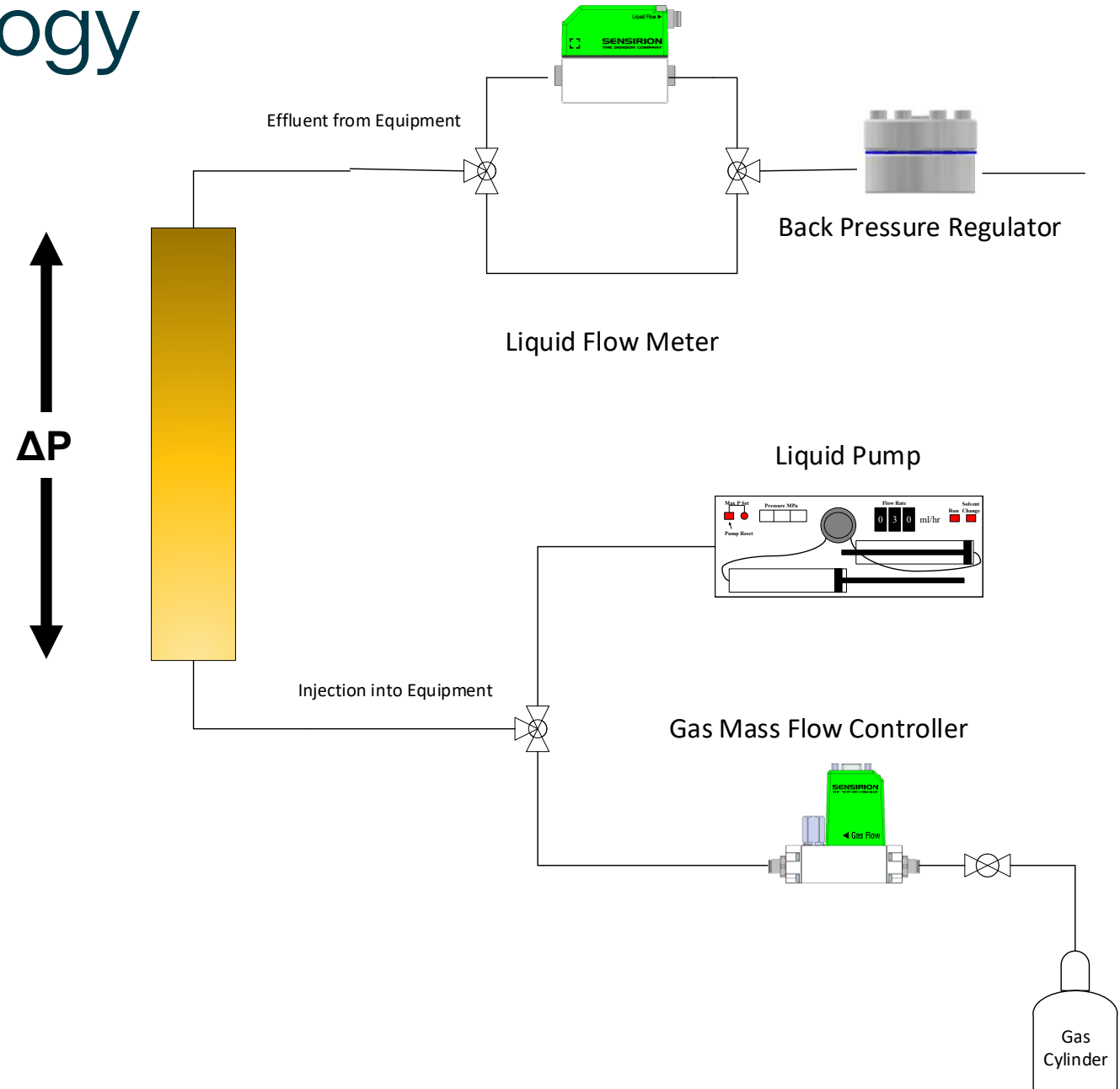


Thanks to Dr Guilia Ness for her help with the ScaleChem calculations

Core Flood Experiments

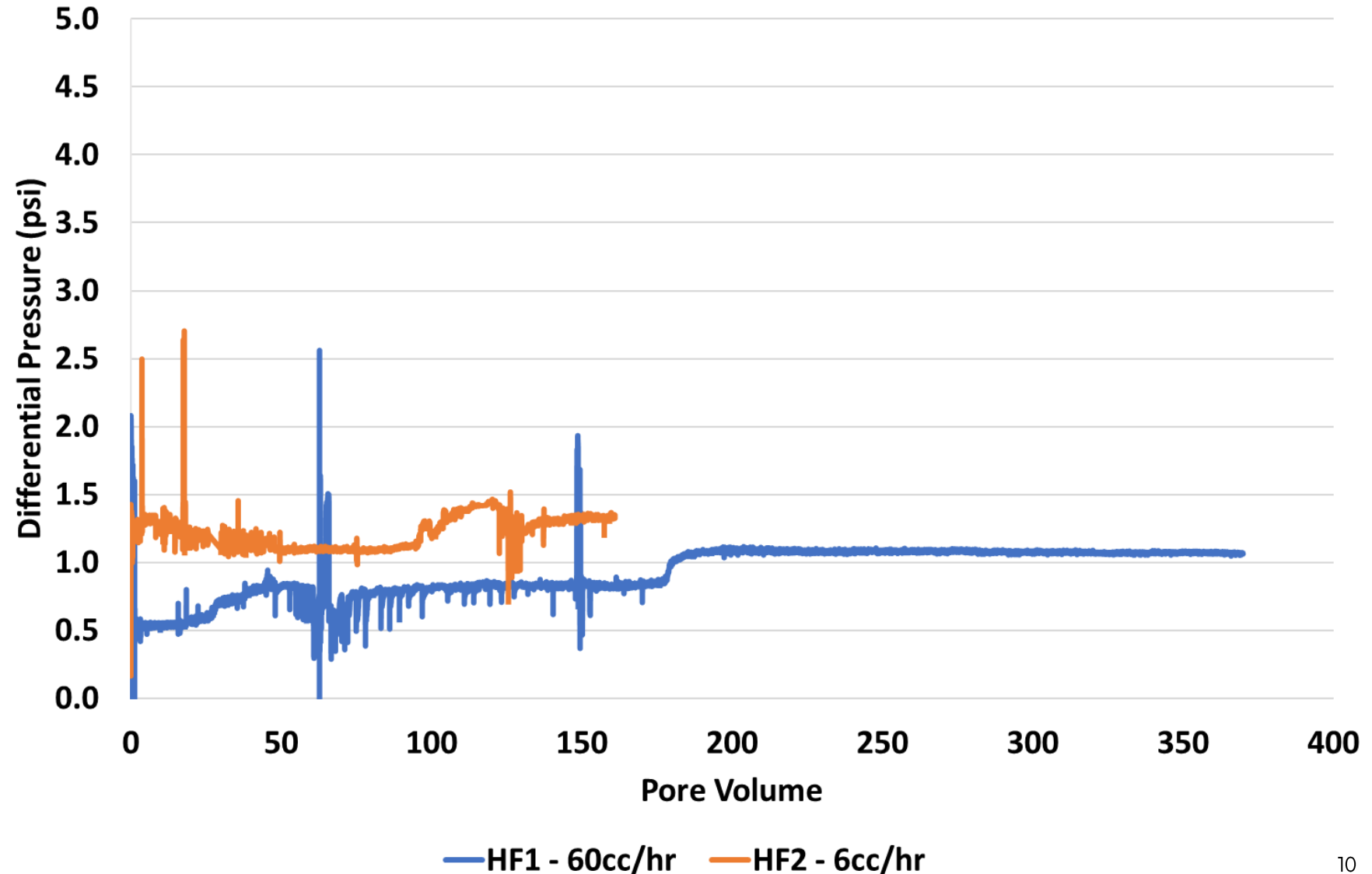
Core Flood Methodology

- Bentheimer core
 - 10"x1.5"
 - flooded vertically with N₂
 - i.e. gravity is acting with flow (unstable)
- Gas injection via mass flow controller at a fixed *volumetric* flow rate
- Measure differential pressure along core vs time



Low Rate Core Flood Results

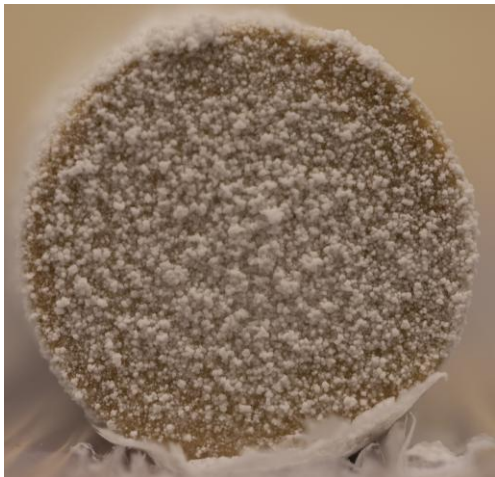
- No distinct pressure increase resulting from gas injection at
 - 6 cc/hr
 - 60 cc/hr
- Gave up on 6 cc/hr case after 170 PV throughput
- Gave up on 60 cc/hr case after 370 PV throughput



Low Rate Flood – State of Core after Experiment



On removal after 75 days of flooding @ 6 cc/hr

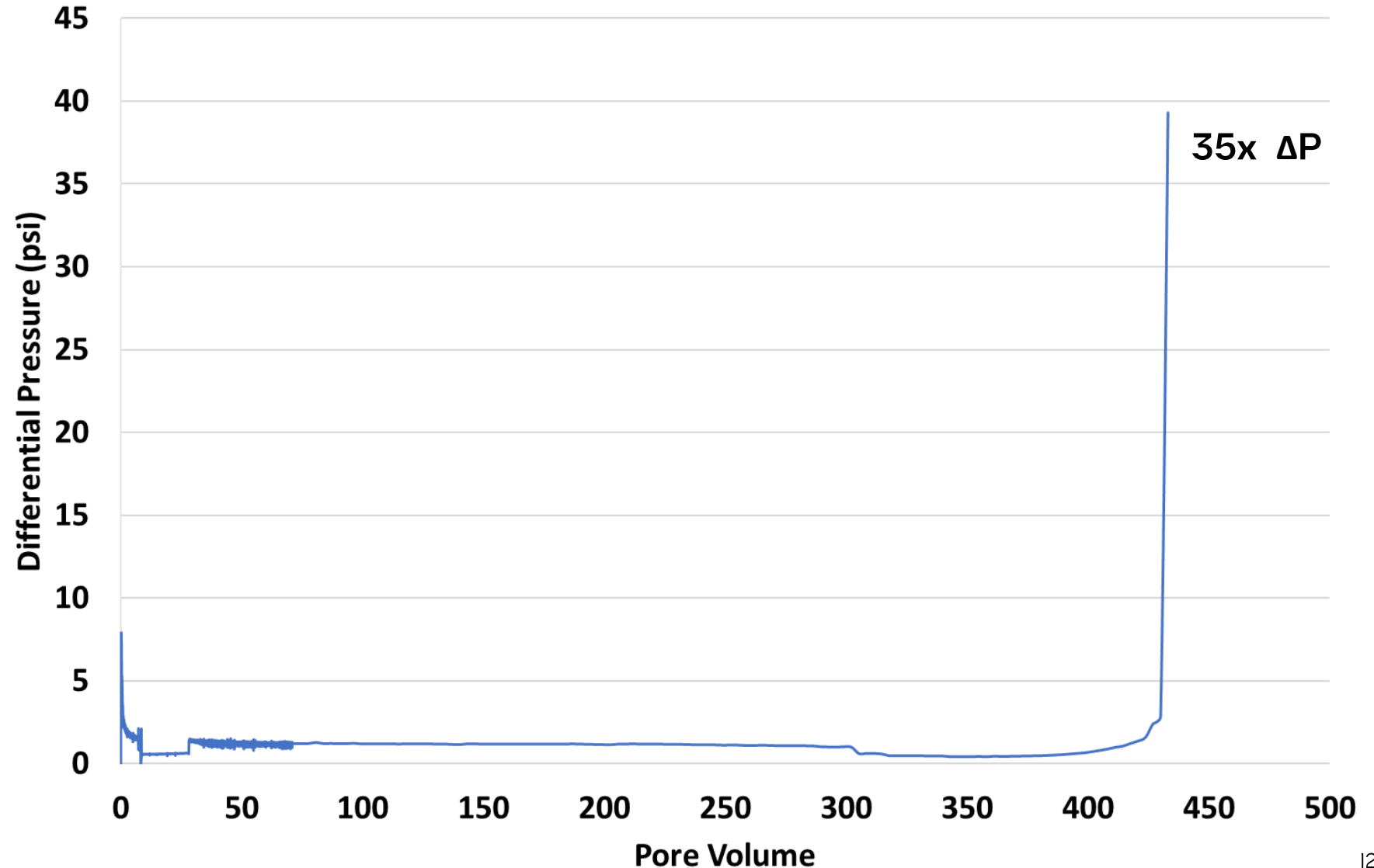


After sitting on lab benchtop for further 120 hrs



High Rate Core Flood Results

- Pressure increase resulting from gas injection
 - at 1200 cc/h
 - after 430 PV throughput
- There is blockage!
- 60 PV greater throughput than previously
- A matter of throughput?



High Rate Flood – State of Core after Experiment

Core length



Inlet platen



Inlet core face



Outlet core face

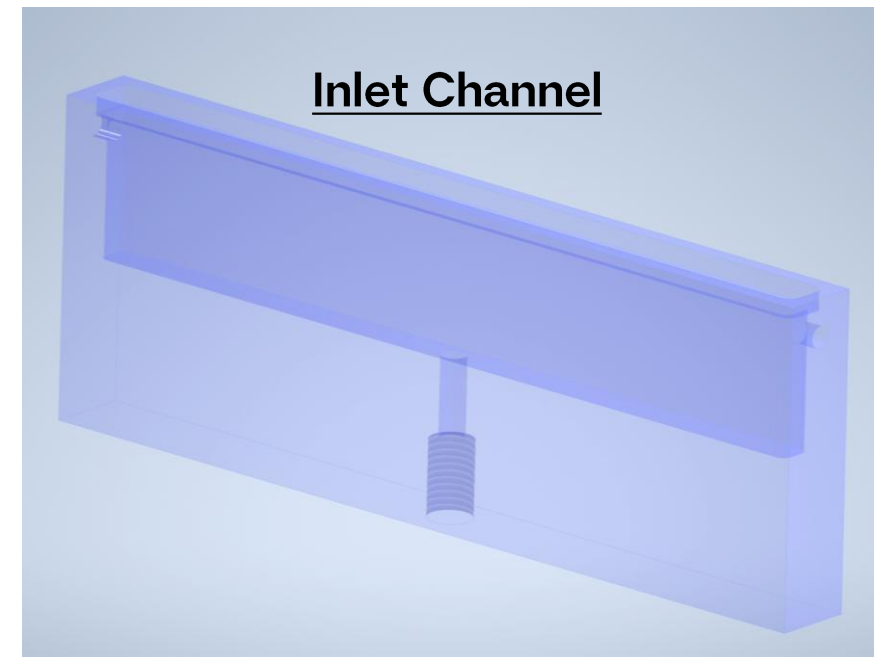


Glass Bead Pack Visualisation Experiments

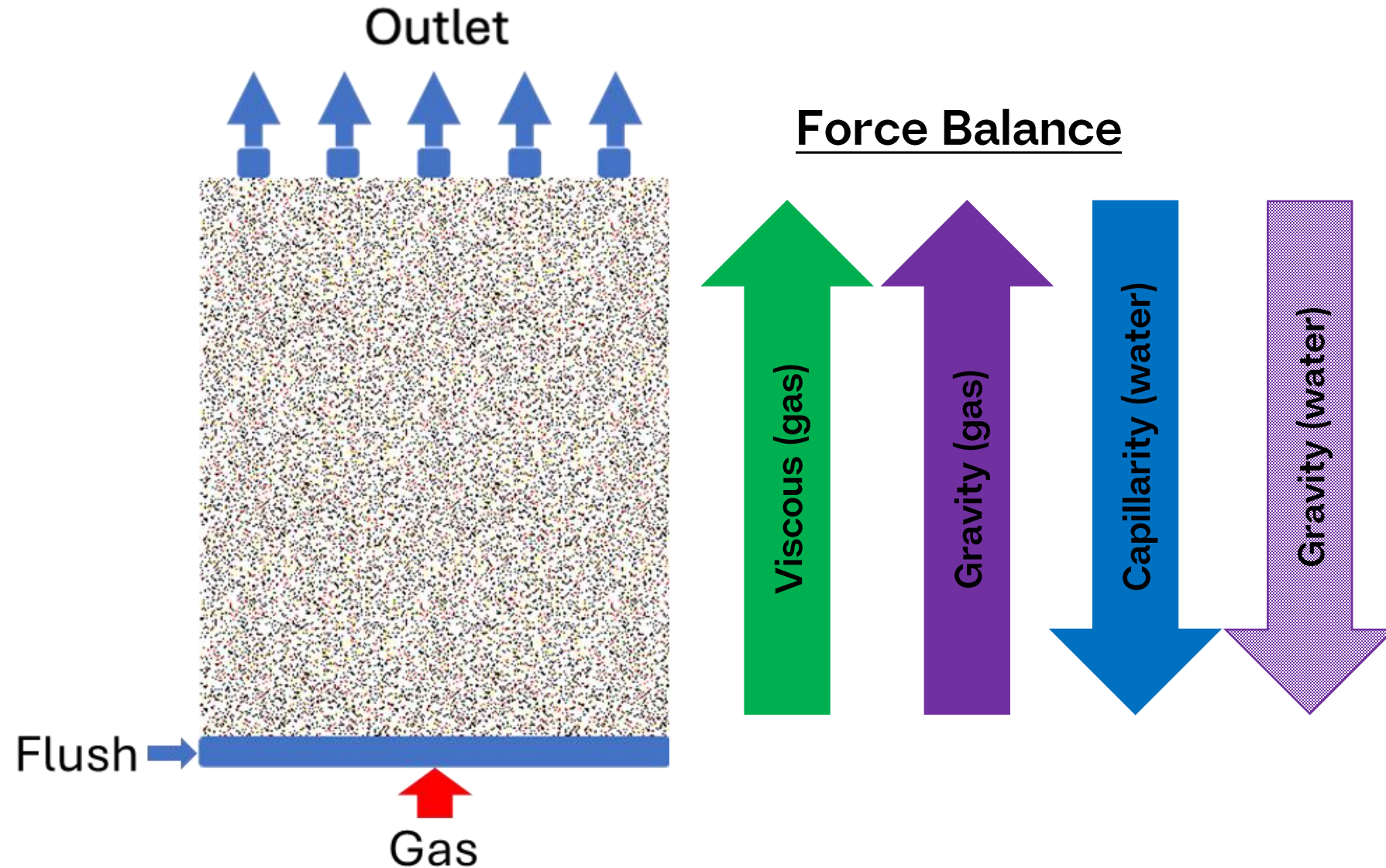
Glass Bead Pack – Methodology

- Large glass bead pack (120-315 μm) saturated with 200 g/L NaCl + blue dye
- Visualise porous medium + *inlet distribution channel*
- N_2 injected via mass flow controller (MFC) at fixed volumetric rate of 2,700 cc/hr
- 308 ft/day (previous core flood was 376 ft/day)
- Residence time – 2.8 min/PV vs. 3.1 min/PV

Property	Value
Dimensions (cm)	18x14x1.5
Porosity, ϕ	0.33
Pore Volume (ml)	125
Permeability (D)	9.5

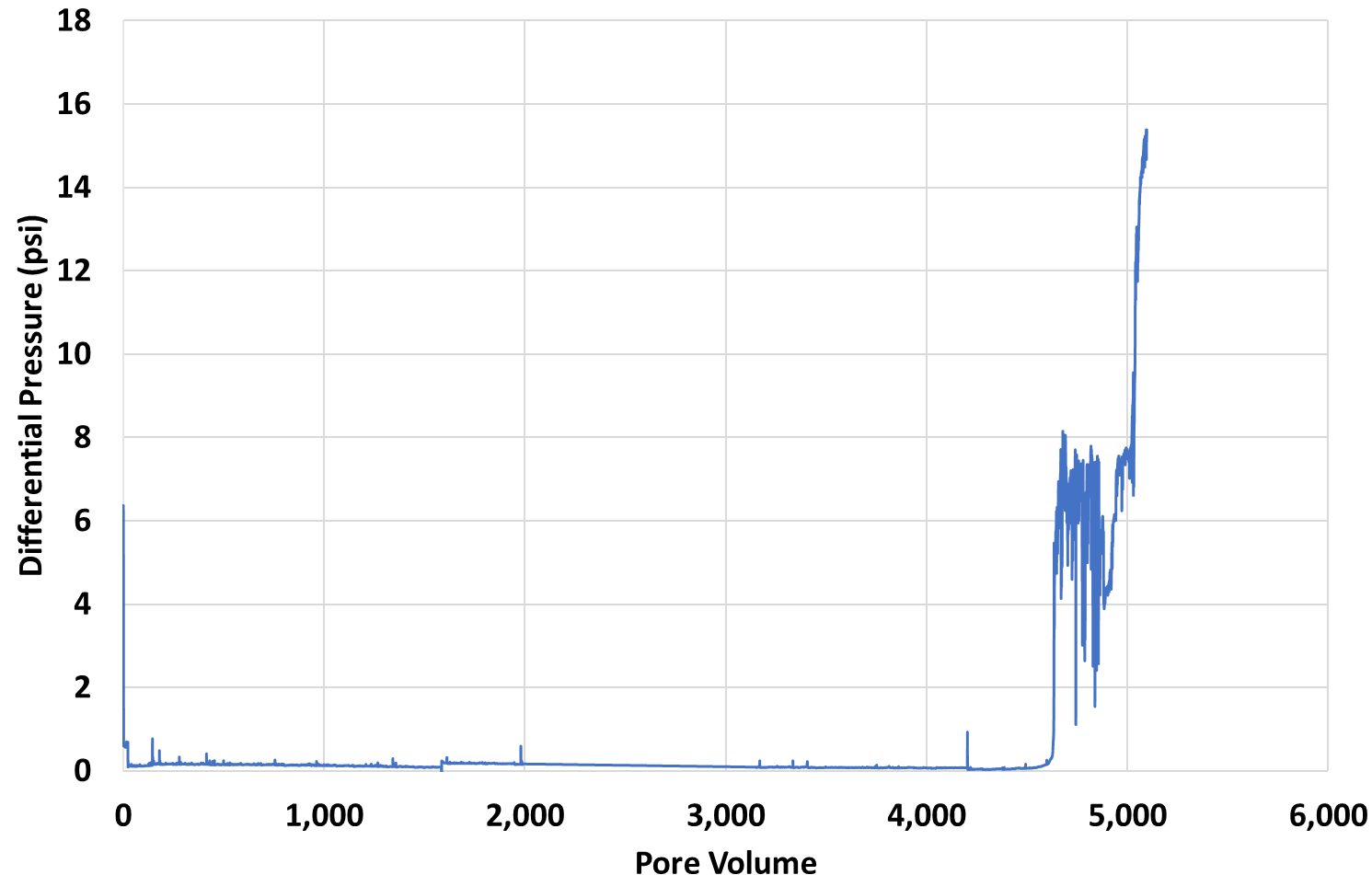


Bead Pack Experiment 1 – Vertical Flow



Bead Pack Experiment 1 – Vertical – ΔP

- Similar result to equivalent core flood
- But greater pore volume throughput
- Injection area 2x core flood
- Impact of capillarity?
 - Lower P_c in high k pack



Bead Pack Experiment 1 – Vertical – Porous Medium

- Fingers rapidly propagate
- Appear darker than brine
 - light scattered
- Dominant fingers remain in place throughout experiment
- Increasing gas saturation at top of pack
- Final finger development due to blockage of inlet
- Evaporation at bottom of pack driving water downwards (capillary + gravity)

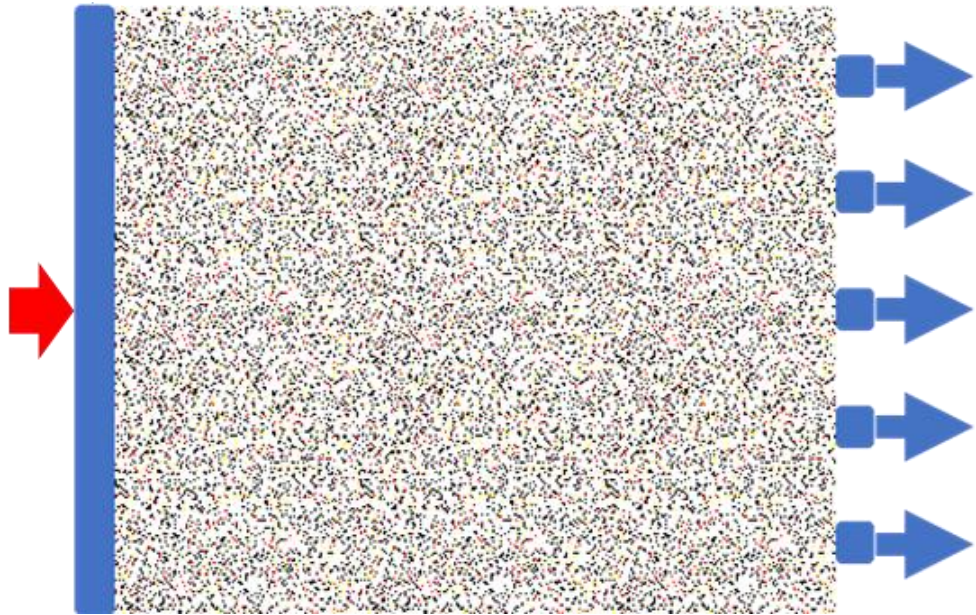


Bead Pack Experiment 1 – Vertical – Inlet

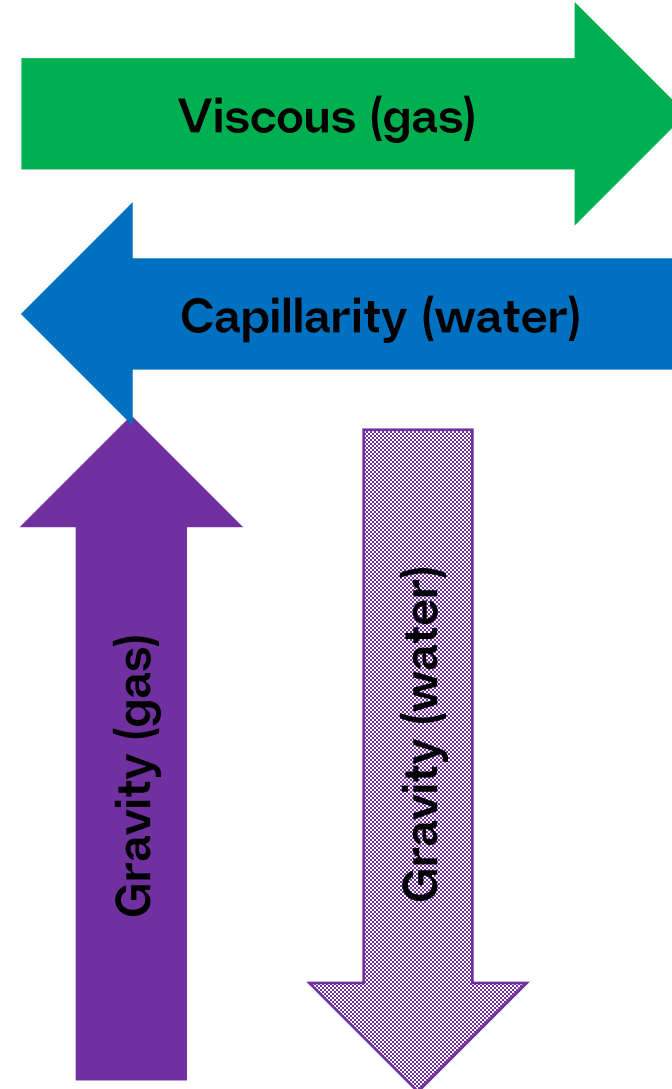
- Initial drying of residual water in inlet
- Salt forms on front and back of channel, then bridges
- Gravity and capillarity act to bring more brine into salt aggregate
- Salt hydrophilic: once formed enhances capillary imbibition



Bead Pack Experiment 2 – Horizontal Flow

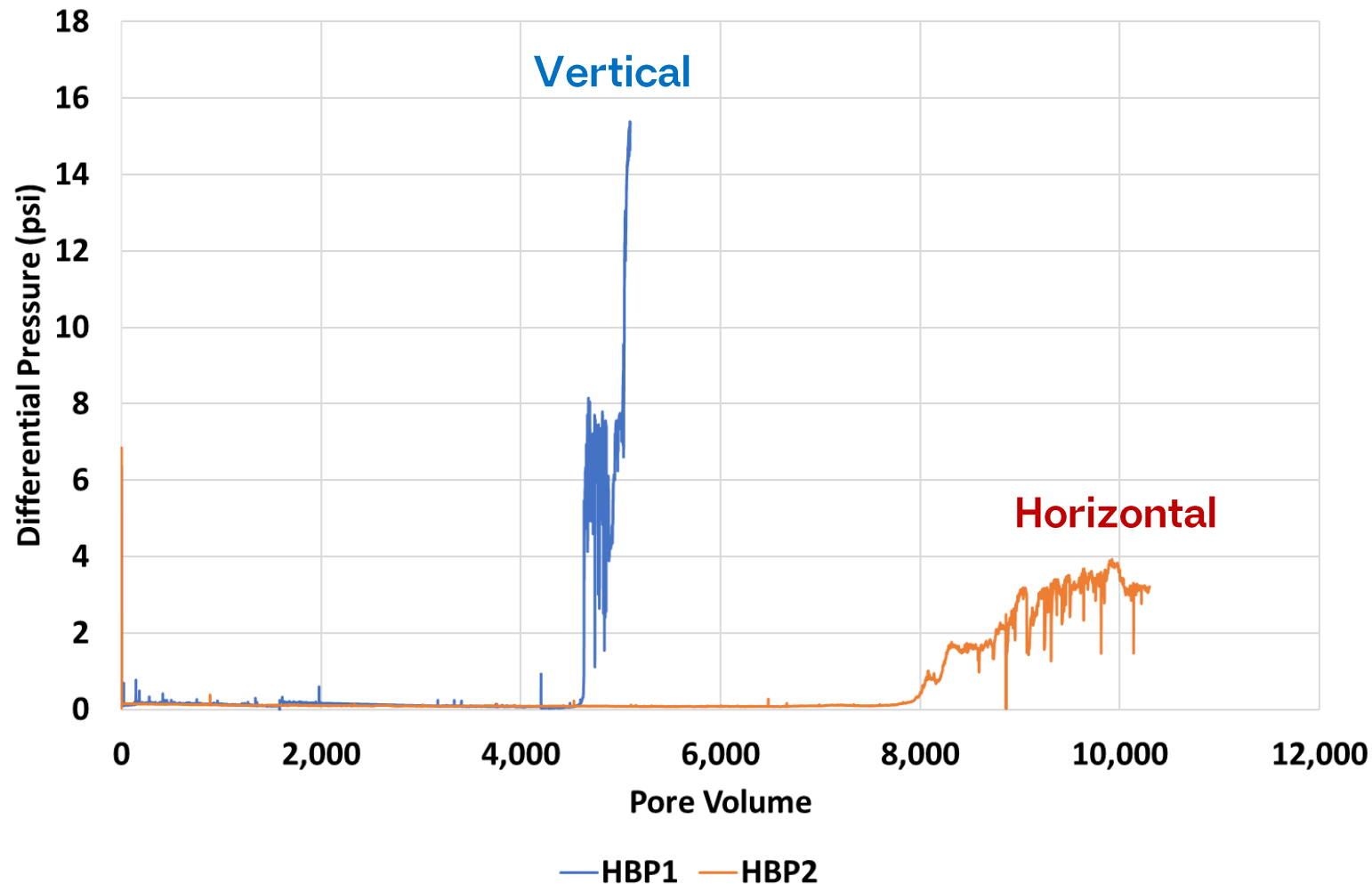


Force Balance



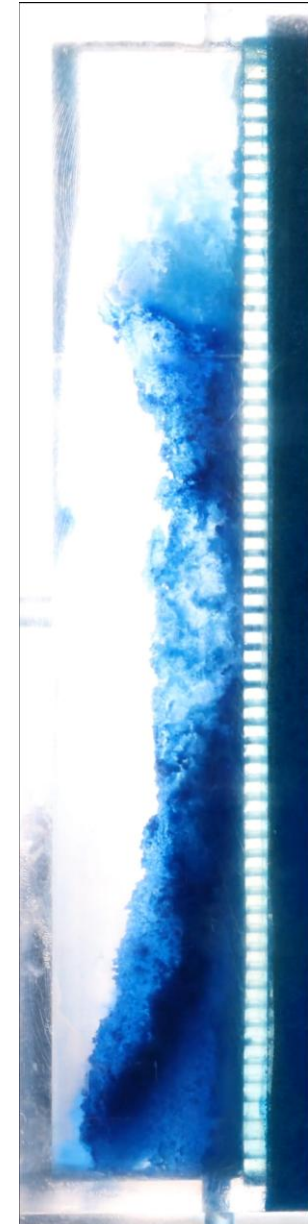
Bead Pack Experiment 2 – Horizontal – ΔP

- Pack re-orientated to give flow across system, perpendicular to gravity
- Approximating a 2D vertical cross section
- Slower build resulting from “self-healing”?
- Plateau is lower but still $>50\times$ higher ΔP



Bead Pack Experiment 2 – Horizontal – Inlet

- On initial drying, salt deposits on upper $\frac{3}{4}$ of inlet
- Imbibition of brine in swept upper region
- NaCl progressively forms in lower section of “wellbore”
- Imbibed water transports (capillary and gravity) into larger aggregate at bottom of “wellbore”
- Partial self-healing mechanism – imbibed brine not super saturated:
- Some imbibition into upper section
- Salt in that location is dissolved
- Re-precipitates lower in channel



Conclusions

- In both cores and packs, greatest precipitation of salt is in injection “wellbore”
 - Field observation: camera tools show salt in perforations, more so to bottom of well
 - Simulation: greatest precipitation in cells closest to well, more so to bottom of well
- “Wellbore” is driest part of system
- Precipitated salt agglomerates to form a hydrophilic porous medium
 - Salt further imbibes brine, which then evaporates depositing more salt
- In vertical configuration, deposition is constant across interface
 - Capillarity and gravity counteract viscous flow
- In horizontal system, more gas at top and more brine at bottom
- If brine not supersaturated, it may partially dissolve halite in upper section of wellbore and re-precipitate in lower section
 - Halite precipitates when brine flows, so long as not so much brine as to exceed evaporative capacity of CO₂

Acknowledgments

- Sponsors of **FAST JIP** at Heriot-Watt University

Baker Hughes 

 **CHEMISERVIS**

CLARIANT 



equinor 

HALLIBURTON

 **Harbour Energy**



Y-TEC

- **CMG Ltd** for use of **GEM** reactive transport reservoir simulator

CMG

- **Energi Simulation** for funding the chair in *CCUS and Reactive Flow Simulation* at Heriot-Watt University

energi
SIMULATION

'a foundation for the future'



- **PTDF** for funding scholarship held by Oluwatosin Ogundipe

What is Effect of Imbibition?

- Brine continuously re-invades dry out zone due to capillary pressure
- As brine evaporates
 - Halite deposits
 - More brine is imbibed
 - Deposition greatest where rate of evaporation and rate of imbibition are matched
- What about gravity?

