Relative Permeability for Offshore EOR

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Project Description and Objectives

Relative Permeability (k_r) for Offshore EOR

- Relative permeability (k_r) is the description of **multiphase transport through porous media** that is most widely accepted and utilized to scale relationships up to the field scale through simulations.
- Previous research at NETL has shown a **dependence of k_r on the flow rates and porous media structure** that is poorly captured in most descriptions of this process.
- Our project was originally scoped to be a 3-year project to (2019-2021)
  1. Determine if this poor literature description is true for offshore EOR.
  2. Collect data on the generation of relevant k_r curves for offshore EOR.
  3. Distribute this collected data, methodology and resultant curves.

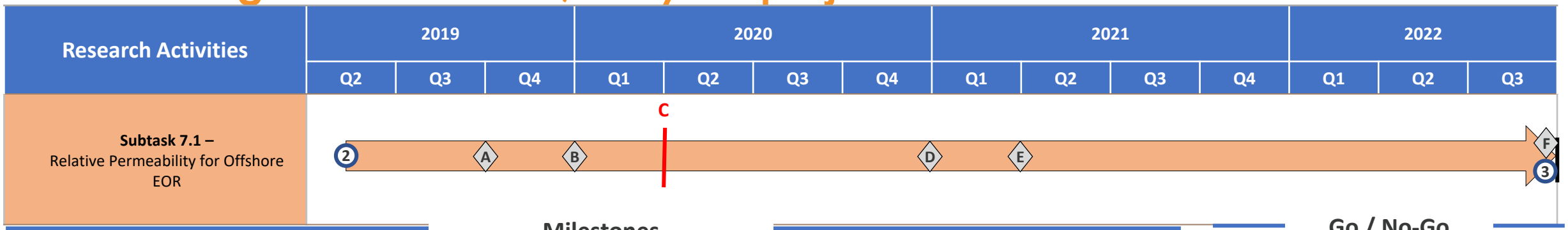
Project Description and Objectives

Relative Permeability (k_r) for Offshore EOR

- **The primary thrusts of this research are to**
  - Provide improved modeling parameters for enhanced offshore recovery
  - Which will result in more product getting out of the well
- **Technology benchmarking**
  - Comprehensive literature review was completed in year 1
- **<u>Current Status of project</u>**
  - Roughly halfway through the data collection phase
  - Slight delays due to COVID; should be ok
  - **Industry/input or validation**
    - discussing fundamental experimental questions with several majors
    - will leverage existing platform in 2021 to distribute for review

Project Timeline Update

Due to budget constrictions, 3.5-year project



Milestones

7.A – Complete gas/oil and water/oil k_r curves developed for a minimum of two flow rates through two different representative offshore cores. Eight k_r curves total. (Sept '19)

7.B - Complete literature review of available and most used k_r curves for EOR simulations in offshore environments. Will include fluids, flow rate, methods that have been used to derive these curves, and curve types. Required for following Go/No-Go decision point. (Dec '19)

7.D - Perform a minimum of 4 additional gas/oil and water/oil tests to determine variations in the k_r curves based of different representative offshore environments. (Dec '20)

7.E – Develop beta tool, populate and make available for industry review. Anticipating ~1/2 of tests completed and seek feedback from industry to direct work towards the highest priority missing data. (March '21)

7.F – Publish offshore EOR k_r tool. Fully functioning tool that offshore planners can access and utilize to reduce the uncertainty in their reservoir simulations of Offshore EOR projects. (Sept '22)

Go / No-Go

7.C – March '20 Go/No-Go Decision

No-Go: If existing k_r curves for water/oil and gas/oil flows in the literature, and within industrial knowledge, accurately describes the results obtained with the unsteady state methodology the project will be halted.

Go: If the unsteady state methodology shows that existing data is lacking in accuracy.

Impact

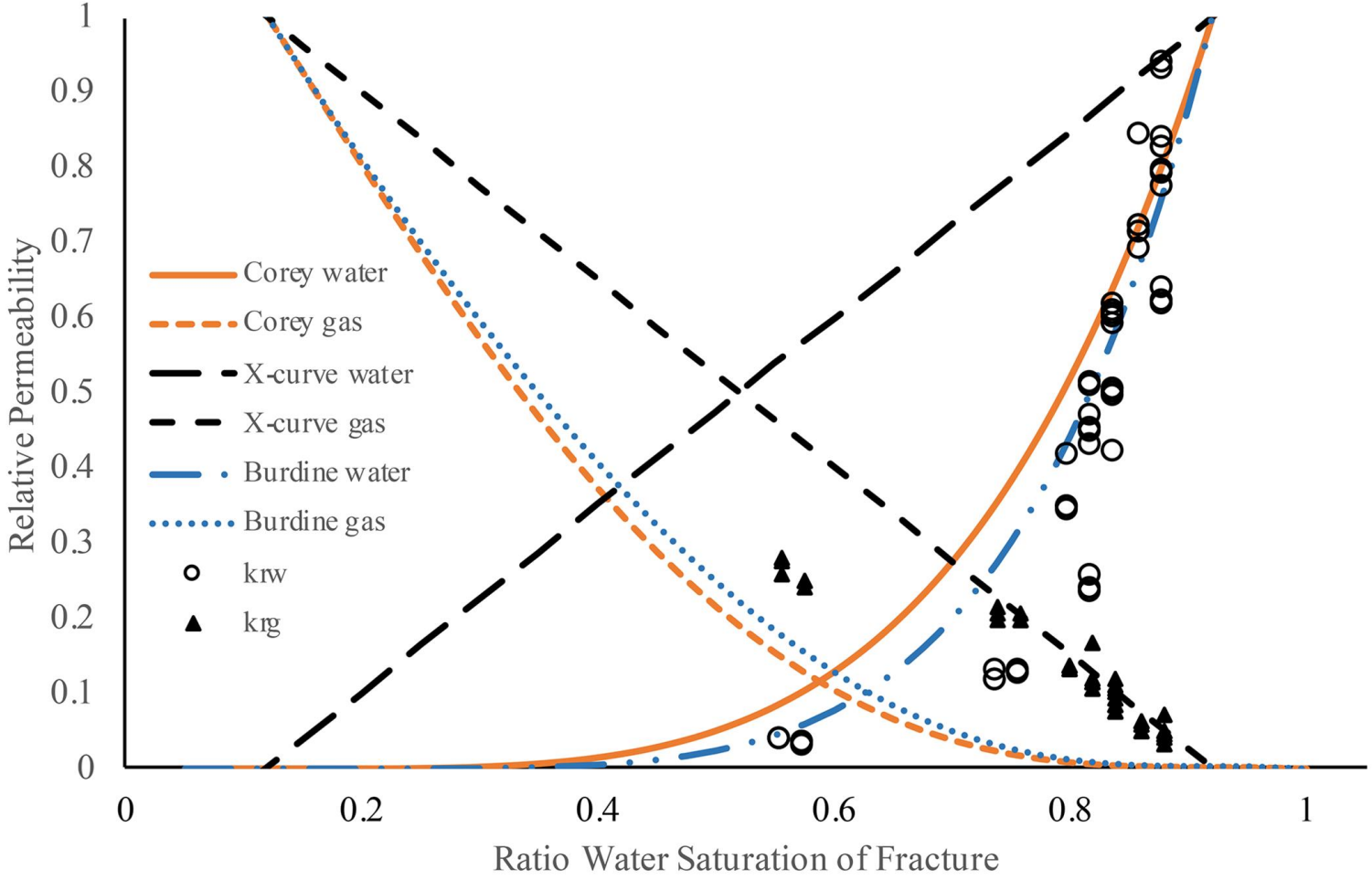
Key Accomplishments/Deliverables	Value Delivered
• New start in the Offshore FWP, building upon techniques and tools developed in the FE Coal/Carbon Storage FWP, to directly measure variations in water/oil and gas/oil k_r curves within representative offshore cores and subsurface temperature and pressure.	• The product of this work is to deliver a database with measurements of relative permeability, residual saturation, and wettability for offshore EOR simulations, and accessible tools for reservoir modelers to access this data and reduce uncertainty in their estimates.

So What is Relative Permeability?

- Relative permeability (k_r) is the ratio of effective permeability of a fluid with saturation less than 100% to absolute permeability

$$k_{rx} = {k_x}/{k}$$

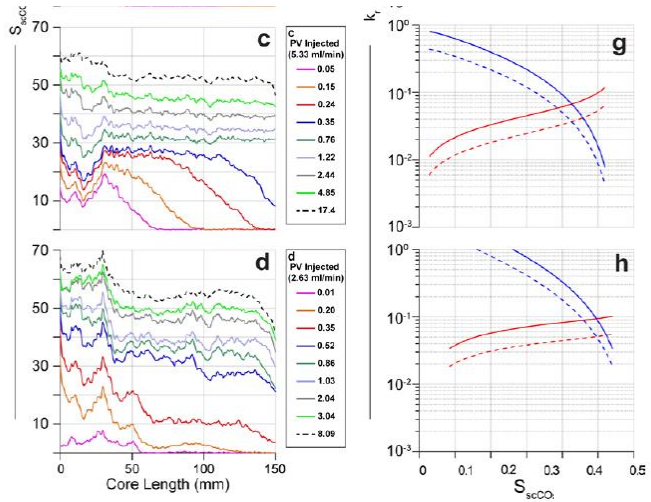
- Numerous models
- Experimental data
  - Unsteady vs steady state
  - Relevance to field operations
  - Fits to models



Rod, K. et al (2019) Relative permeability for water and gas through fractures in cement, PLoS One 14(1): e0210741. https://doi.org/10.1371/journal.pone.0210741

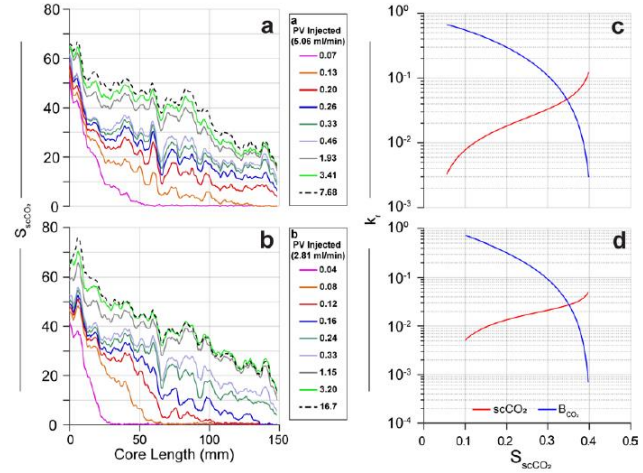
Literature Review Takeaways

- Few studies of high permeability cores at subsea conditions using oil
  - Some decent sand pack studies
  - Very few core studies published from offshore wells
- Data from experiments not readily available
  - Ability to compare techniques and apply different curve fits difficult
- Steady state methods predominant
  - Injection of two fluids simultaneously



Low permeability (24 mD)
Edwards Yellow

Supplemental Figure 3: Saturation and k_r curves for Edwards Yellow. **(a-d)** Saturation curves for flow ml/min (a), 10.73 ml/min (b), 5.33 ml/min (c), and 2.63 ml/min (d). **(e-h)** Representative k_r curves for flo ml/min (e), 10.73 ml/min (f), 5.33 ml/min (g), and 2.63 ml/min (h). Dashed lines in f-h indicate original, u solid lines represent k_r curves after correction.



High permeability (760 mD)
White Rim

Supplemental Figure 11: Saturation and k_r curves for White Rim. **(a-b)** Saturation curves for flow experiments at 5.06 ml/min (a) and 2.81 ml/min (b). **(c-d)** Representative k_r curves for flow experiments at 5.06 ml/min (c) and 2.81 ml/min (d).

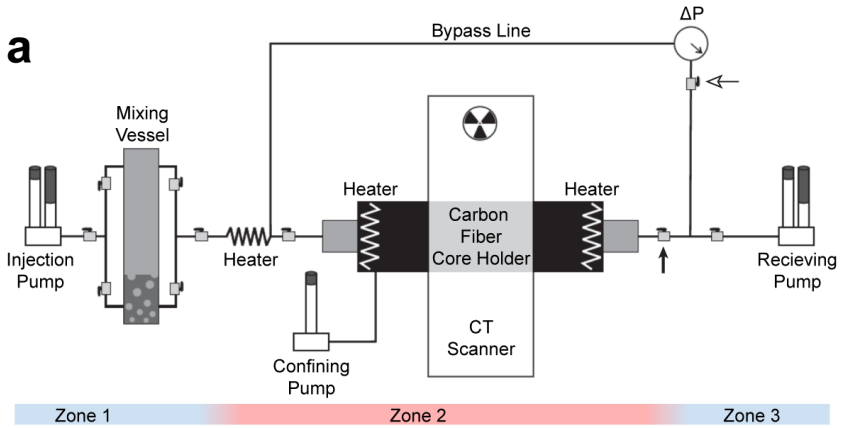
With the few specific studies examining k_r from offshore EOR out there, go/no-go review was passed

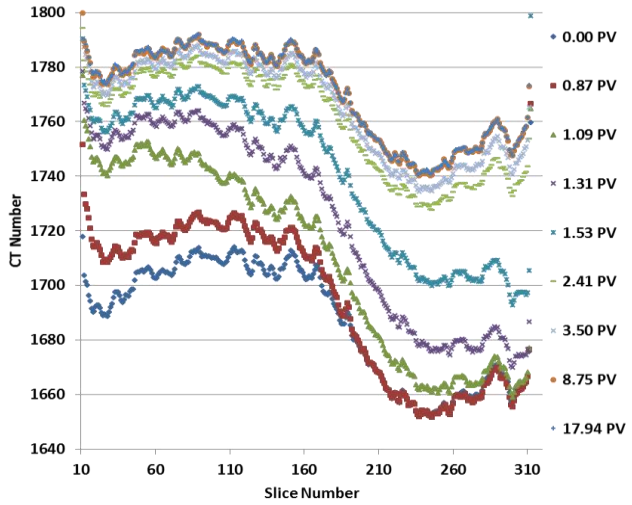
Experimental Process

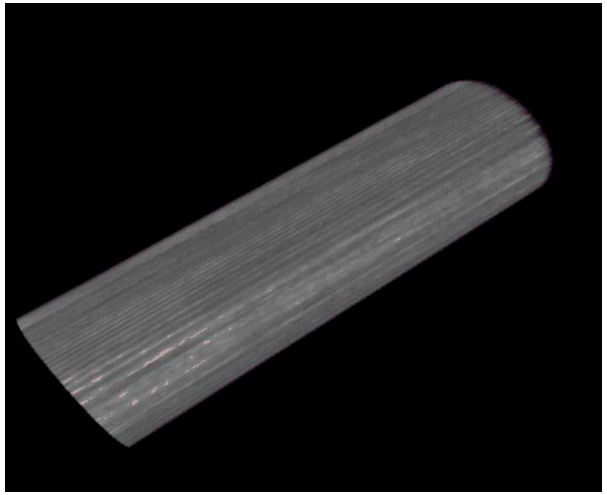
- Controlled injection of one fluid (N_2, H_2O, or CO_2) at elevated temperature and pressure conditions into core initially saturated with oil

  Unsteady state method

- Computed tomography used to determine saturation over time and differential pressure measured





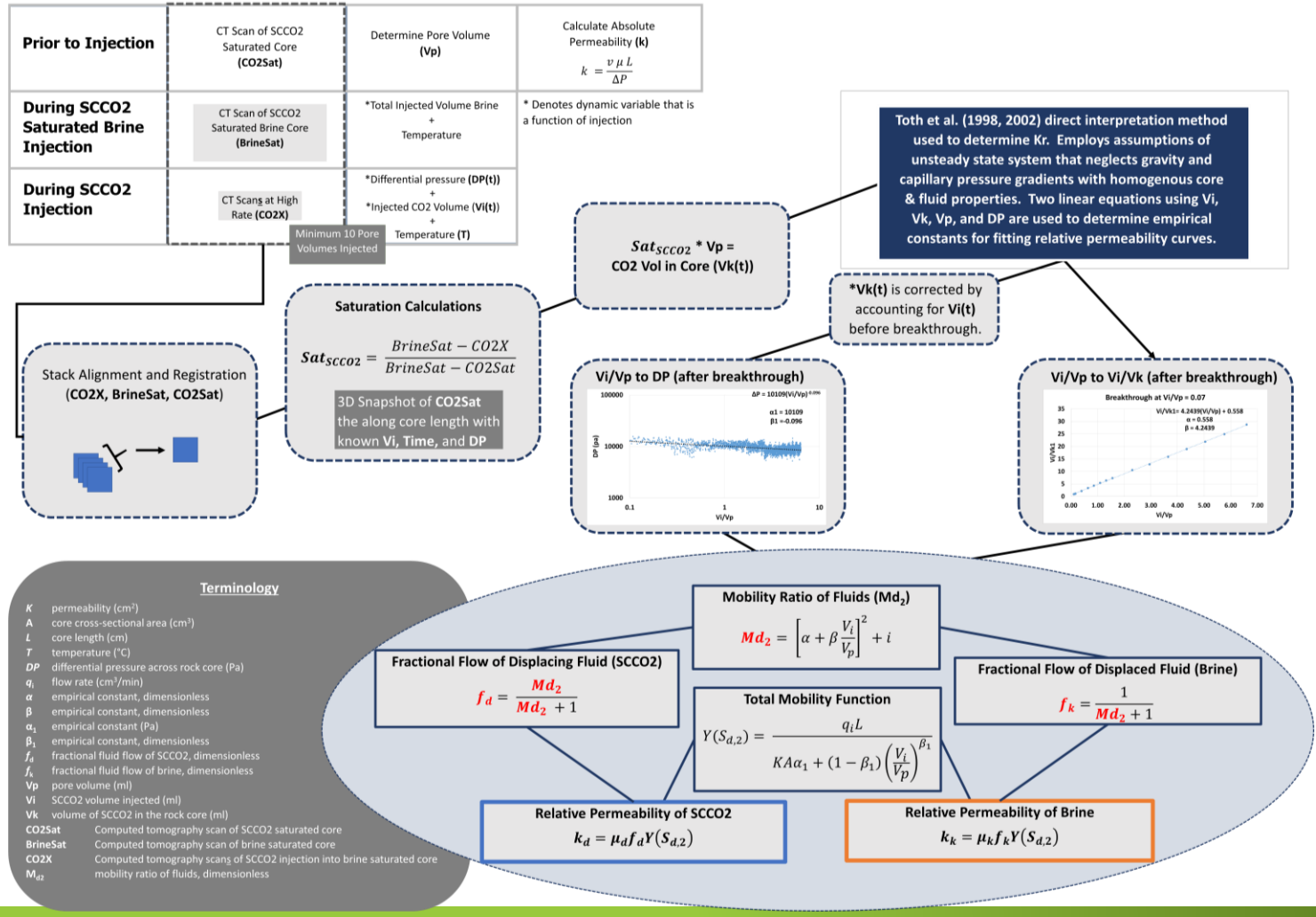


Moore, J. et al (submitted) Raid determination of supercritical CO_2 and brine relative permeability using an unsteady-state flow method, Adv Water Res.

Calculation Method

Toth et al (2002) Convenient formulae for determination of relative permeability from unsteady-state fluid displacements in core plugs. *J Petrol Sci & Eng*, 36(1–2), 33–44.

- Collect data
  - Pre, setup and during flood
- Calculate saturation of fluids from CT scanning via image processing
- Calculate mobility ratios of the fluids from the Toth et al (2002) method
- From the mobility ratios, plot the k_r(saturation)



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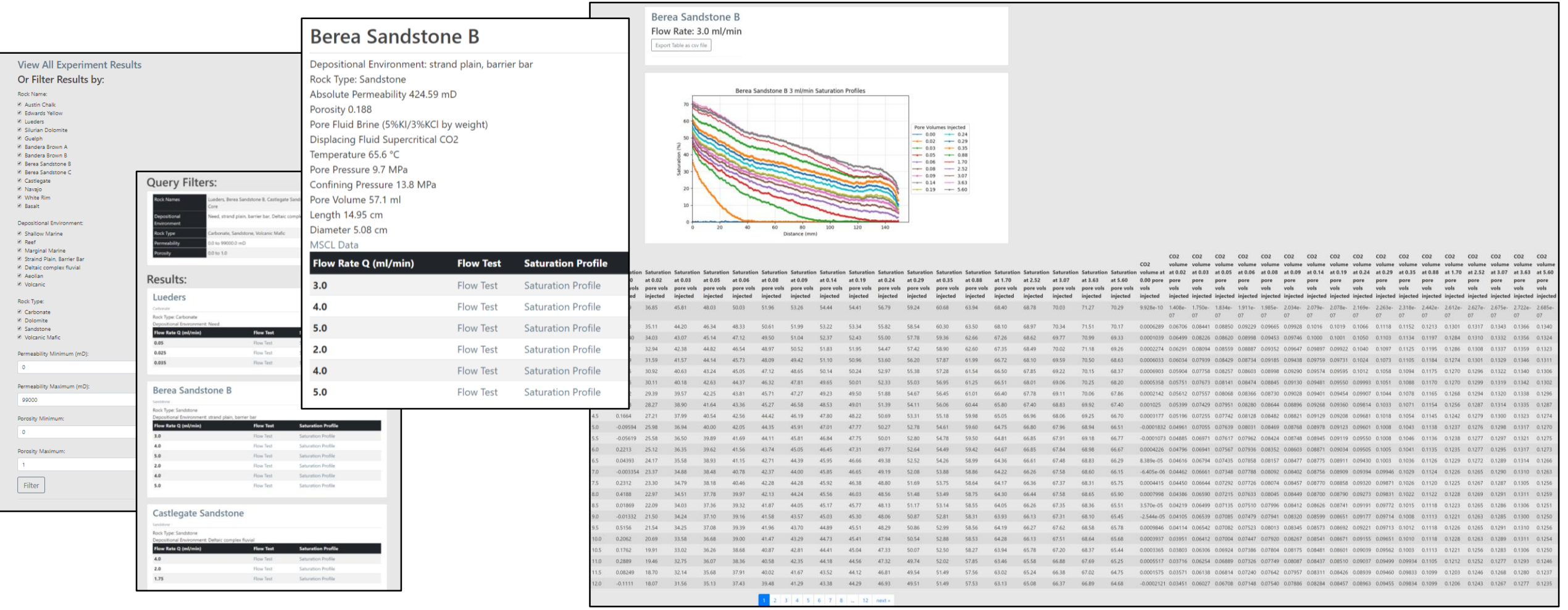
Distribution Platform

CO_2-Brine Relative Permeability Database

- https://edx.netl.doe.gov/hosting/co2bra



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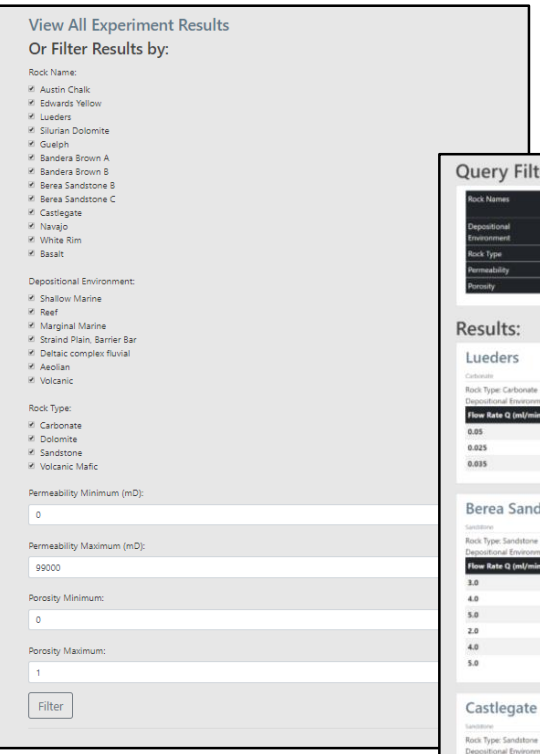
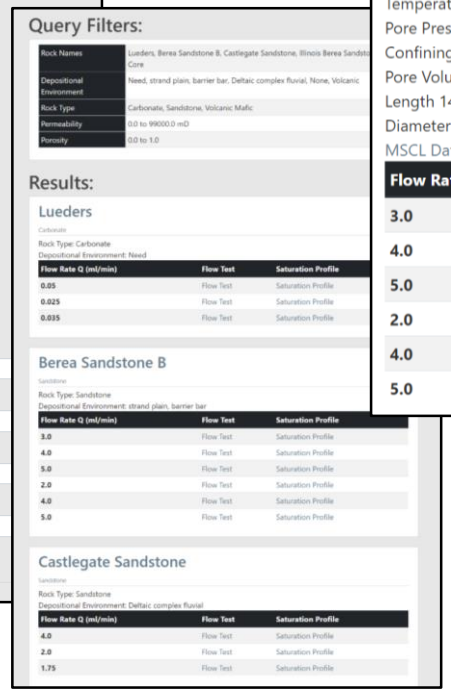
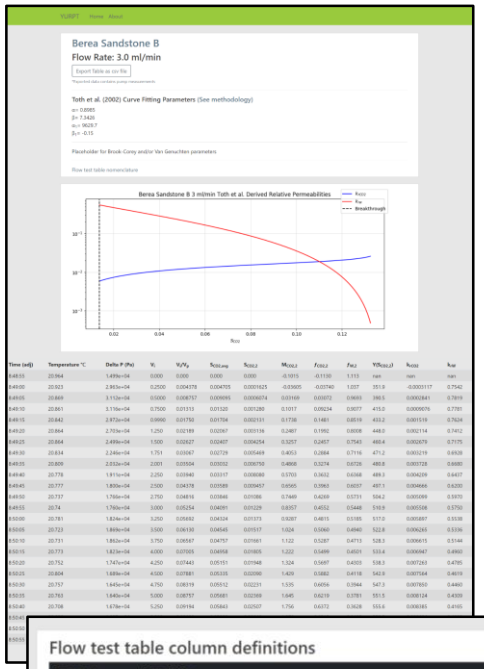




Berea Sandstone B

Depositional Environment: strand plain, barrier bar
Rock Type: Sandstone
Absolute Permeability 424.59 mD
Porosity 0.188
Pore Fluid Brine (5%KI/3%KCl by weight)
Displacing Fluid Supercritical CO2
Temperature 65.6 °C
Pore Pressure 9.7 MPa
Confining Pressure 13.8 MPa
Pore Volume 57.1 ml
Length 14.95 cm
Diameter 5.08 cm
MSCL Data

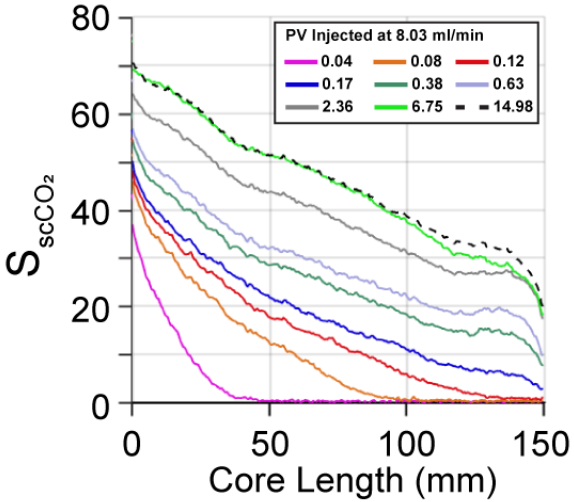
Flow Rate Q (ml/min)	Flow Test	Saturation Profile
3.0	Flow Test	Saturation Profile
4.0	Flow Test	Saturation Profile
5.0	Flow Test	Saturation Profile
2.0	Flow Test	Saturation Profile
4.0	Flow Test	Saturation Profile
5.0	Flow Test	Saturation Profile

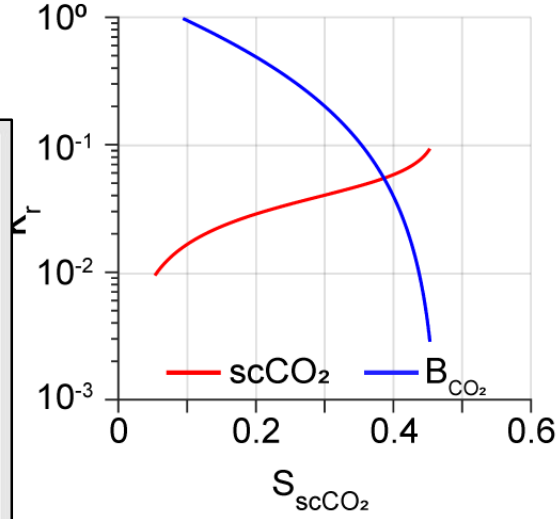


Flow test table column definitions

Property	Description
Time (adj)	Time of measurement adjusted to sync instruments.
Temperature °C	Temperature in degrees C.
Delta P (Pa)	Pressure differential from inlet to outlet of core in Pascals.
V_i	Volume of CO_2 injected in milliliters.
V_i/V_p	Volume of CO_2 injected as a fraction of total pore volume.
$S_{CO2,avg}$	Average CO_2 saturation of the core plug. (See equation 29)[1]
$S_{CO2,2}$	Outlet face CO_2 saturation. (See equation 30)[1]
$M_{CO2,2}$	Mobility ratio of CO_2 at the outlet face. (See equation 26)[1]
$f_{CO2,2}$	Dimensionless fractional fluid flow for CO_2 at outlet. (See equation 24)[1]
$f_{W,2}$	Dimensionless fractional fluid flow for brine at outlet. (See equation 25)[1]
$Y(S_{CO2,2})$	Total Mobility Function. (See equation 39)[1]
k_{rCO2}	Relative permeability of CO_2. (See equation 27)[1]
k_{rW}	Relative permeability of brine. (See equation 28)[1]

[1] J. Toth, T. Bodi, P. Szucs, F. Civan, Convenient formulae for determination of relative permeability from unsteady-state fluid displacements in core plugs. *Journal of Petroleum Science and Engineering*. 36, 33-44 (2002). https://doi.org/10.1016/S0920-4105(02)00249-8

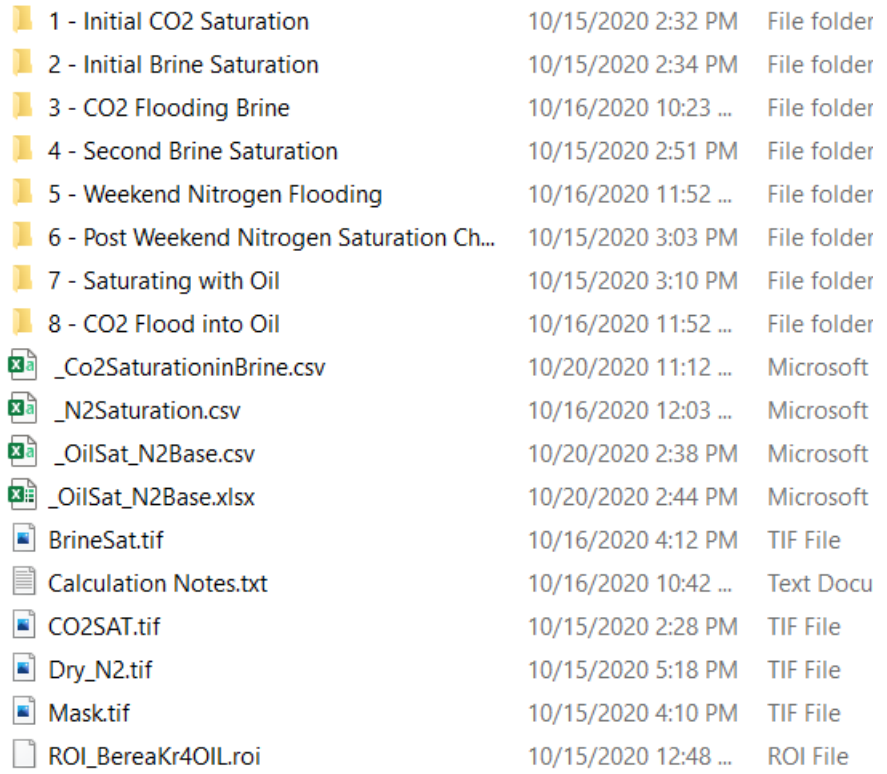




Project Updates

Data collection underway

- There was a slow down on these floods earlier this year due to COVID
  - We'll be back on track by the end of the calendar year.
- Use of previously refined unsteady state methodology for CO_2/brine k_r curve measurements working well
  - High permeability cores means that high resolution differential pressure measurements needed
  - Oil contamination of system, and resulting cleaning, results in slightly longer experiment times. But under control.

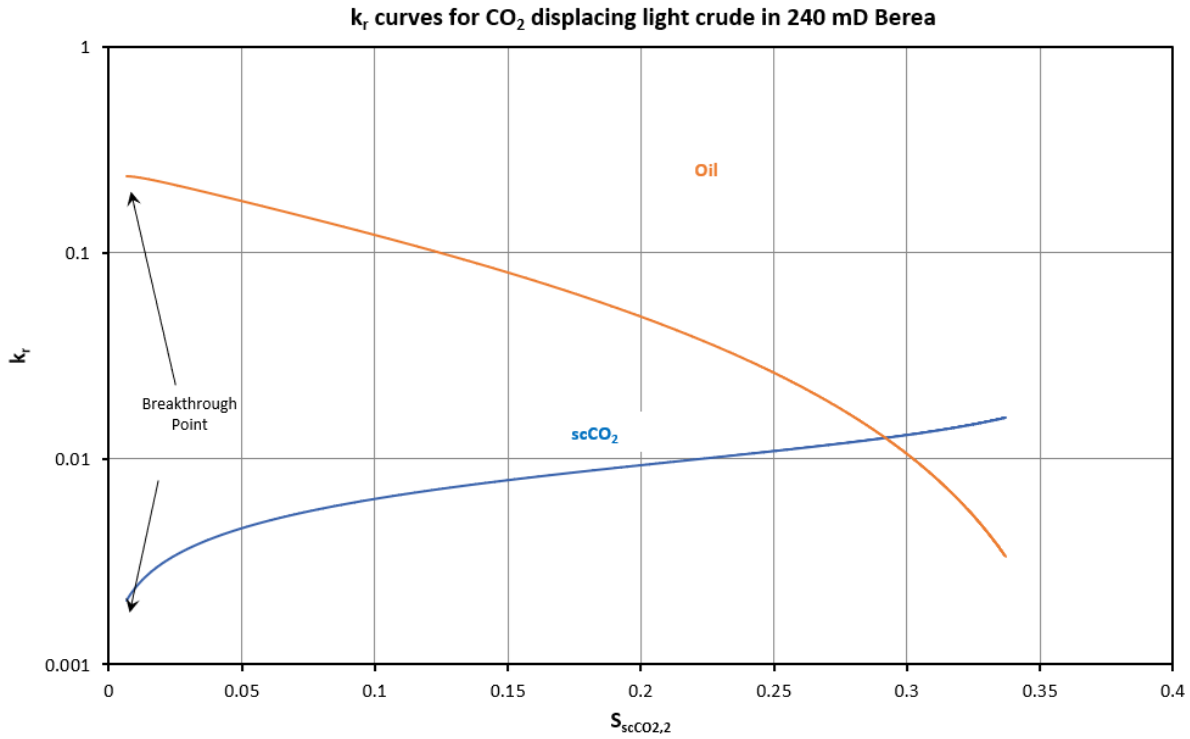


1 - Initial CO2 Saturation	10/15/2020 2:32 PM	File folder
2 - Initial Brine Saturation	10/15/2020 2:34 PM	File folder
3 - CO2 Flooding Brine	10/16/2020 10:23 ...	File folder
4 - Second Brine Saturation	10/15/2020 2:51 PM	File folder
5 - Weekend Nitrogen Flooding	10/16/2020 11:52 ...	File folder
6 - Post Weekend Nitrogen Saturation Ch...	10/15/2020 3:03 PM	File folder
7 - Saturating with Oil	10/15/2020 3:10 PM	File folder
8 - CO2 Flood into Oil	10/16/2020 11:52 ...	File folder
_Co2SaturationinBrine.csv	10/20/2020 11:12 ...	Microsoft
_N2Saturation.csv	10/16/2020 12:03 ...	Microsoft
_OilSat_N2Base.csv	10/20/2020 2:38 PM	Microsoft
_OilSat_N2Base.xlsx	10/20/2020 2:44 PM	Microsoft
BrineSat.tif	10/16/2020 4:12 PM	TIF File
Calculation Notes.txt	10/16/2020 10:42 ...	Text Docu
CO2SAT.tif	10/15/2020 2:28 PM	TIF File
Dry_N2.tif	10/15/2020 5:18 PM	TIF File
Mask.tif	10/15/2020 4:10 PM	TIF File
ROI_BereaKr4OIL.roi	10/15/2020 12:48 ...	ROI File

Project Updates

Data collection underway

- Next months we'll be performing another 3 experiments, and the associated analysis to develop curves
  - Cores, fluids, and equipment on hand
  - Ordering some tubing for backup, but not holding us up in the least

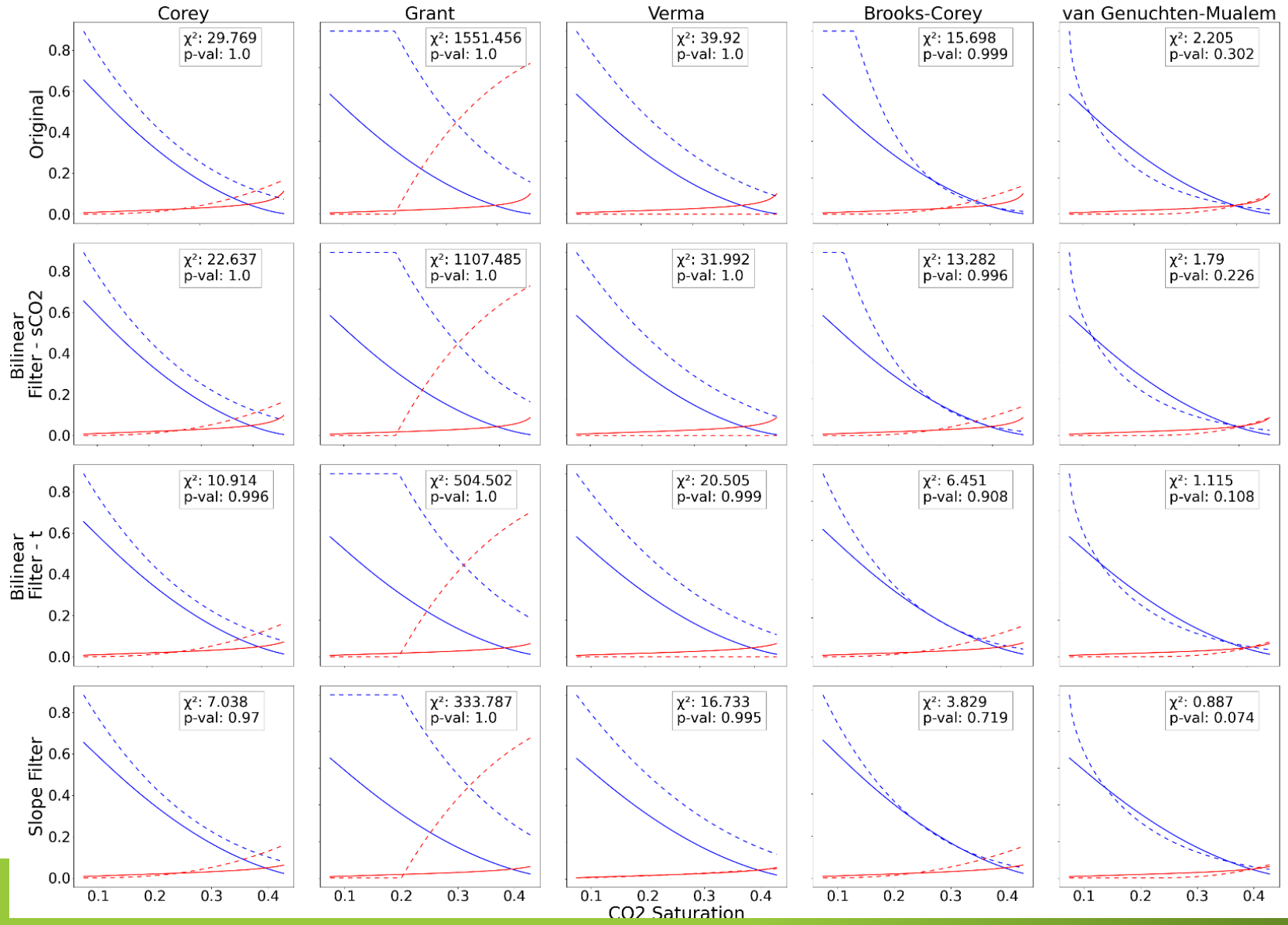


Project Next Steps

Leverage ML and SMART to improve curve fits

- Enhanced data filters
- Multiple curve parameter simultaneous fits

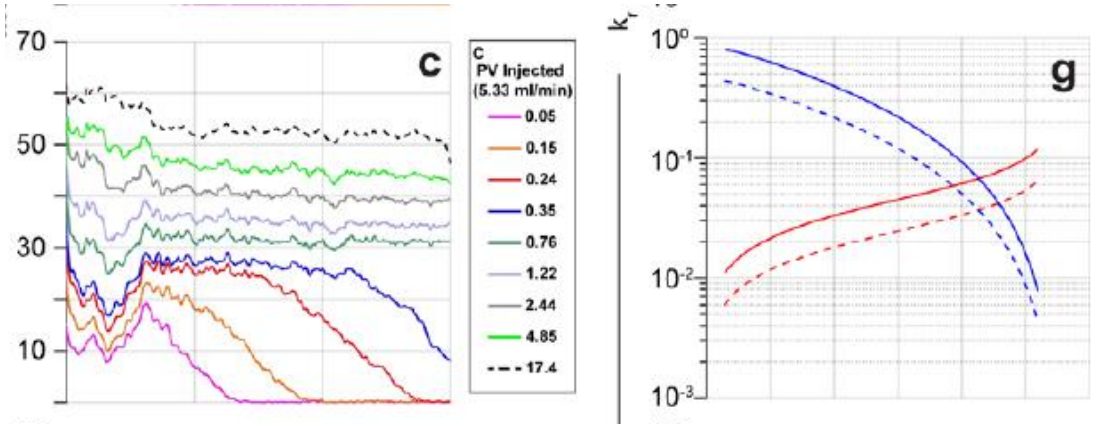
These improvements have led to research questions about appropriate k_r curve behavior after high pore volume injection, versus primary drainage behavior



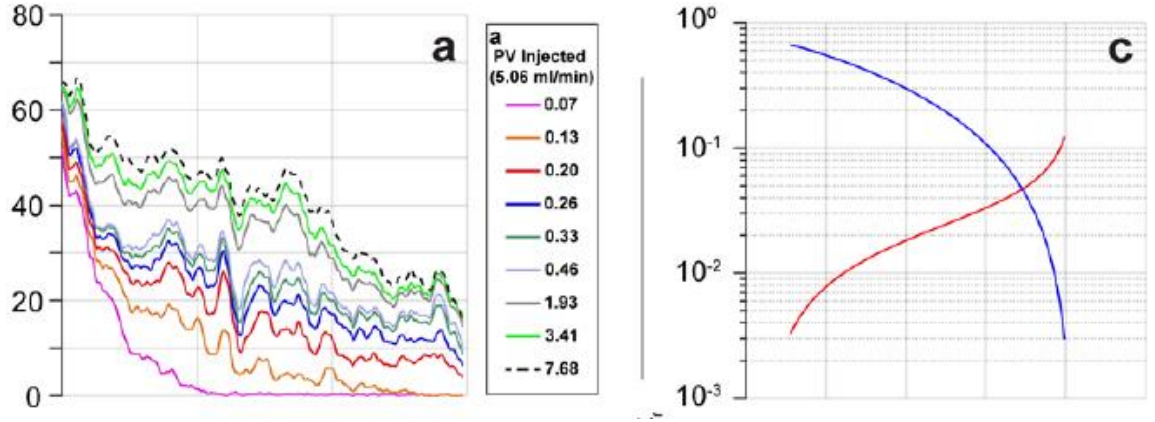
Project Next Steps

Continue measurements

- Close attention to the impact of high permeability/high connectivity porous structures



Low permeability (24 mD) Edwards Yellow



High permeability (760 mD) White Rim

Technology-to-Market Path

- Expand CO2BRA platform in 2021 to include data from this project

Concluding Remarks

Relative Permeability for Offshore EOR

- At the conclusion of this project, we will have an open platform with oil/fluid relative permeability curves, data used to collect those curves, and explanations of the process. These curves will be generated for conditions relevant to Offshore EOR, with the benefits of:
    - Providing improved modeling parameters for enhanced offshore recovery to improve production strategies

- The next year will primarily be in the data collection/analysis phase, with some preparation of the open online platform.
    - Seeing some early indications that fundamental examinations of long-term desiccation/stripping behavior may impact late term k_r curves

Thank you

Big thanks to Johnathan Moore, Paul Holcomb, Scott Workman, Jeong Choi, Seth King and all the others who have made this work possible.

Thank you for your interest today!