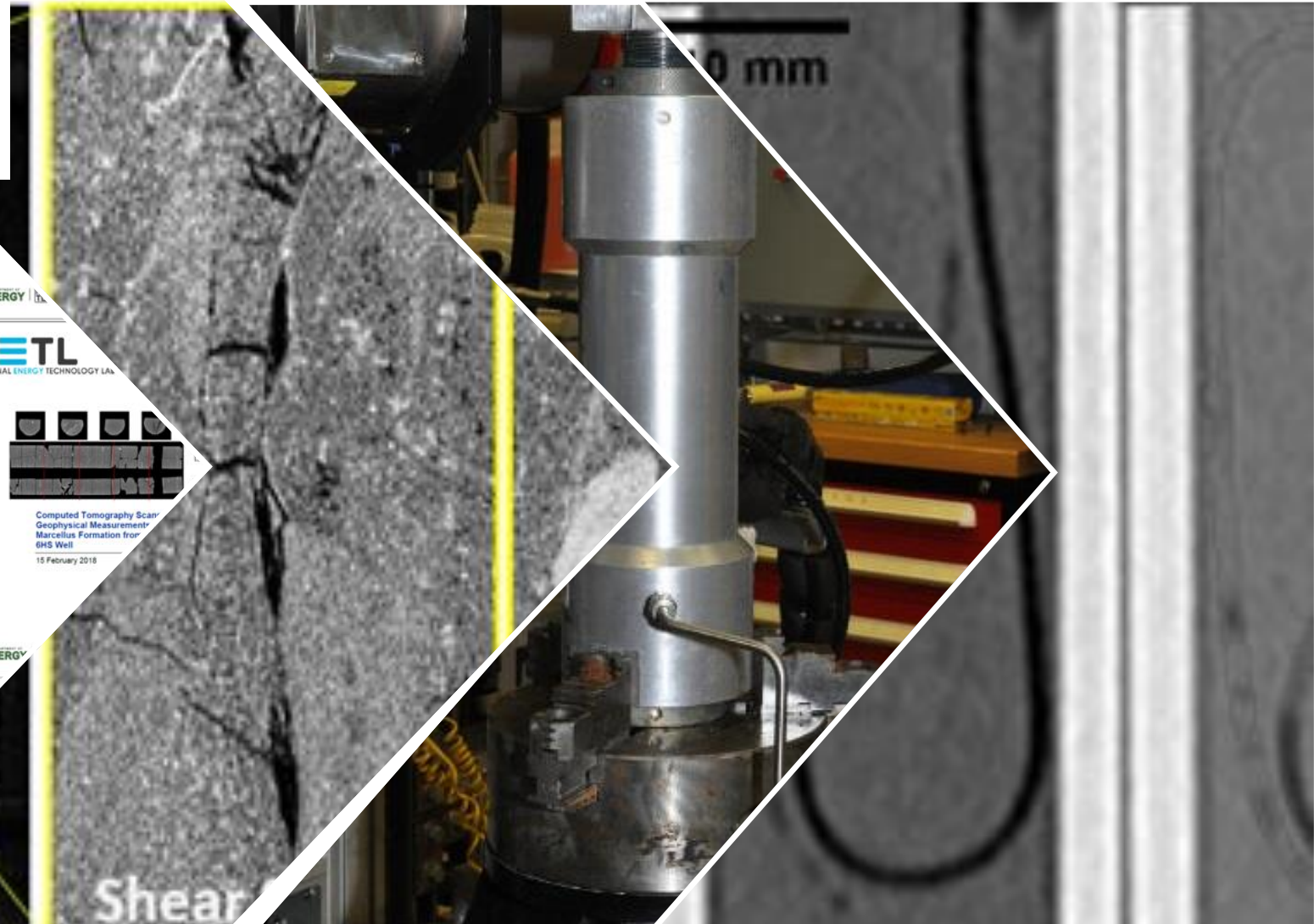


Relative Permeability for Offshore HPHT Reservoirs

NETL Offshore FWP – Task 7

Johnathan Moore

Leidos Research Support Team

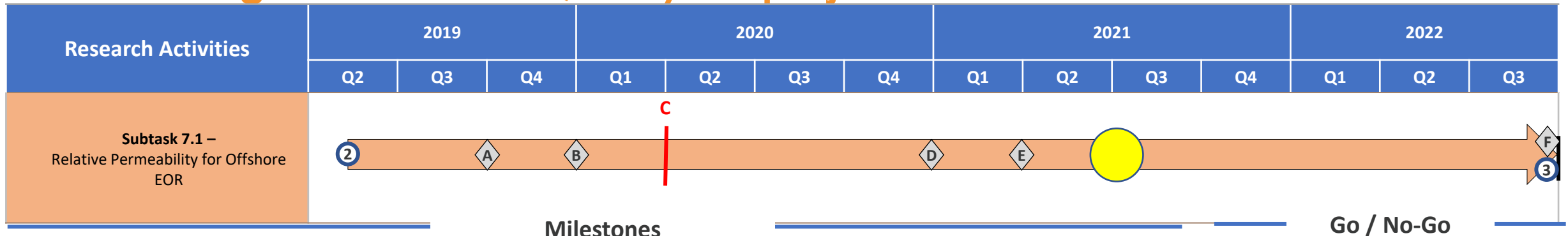


Project Description and Objectives

- 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.
- ~3-year project to (2019-2022)
 - ~~1. Determine if this poor literature description is true for offshore environments.~~
 2. Collect data on the generation of relevant k_r curves for describing fluid flow in these environments: e.g. carbon storage and wellbore.
 3. Distribute this collected data, methodology and resultant curves via easily accessible platform.

Project Timeline Update

Due to budget constrictions, 3.5-year project



Milestones

Go / No-Go

- ~~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 projects. (Sept '22)~~

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

- 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 cores representative of offshore environments at subsurface temperature and pressure.

Value Delivered

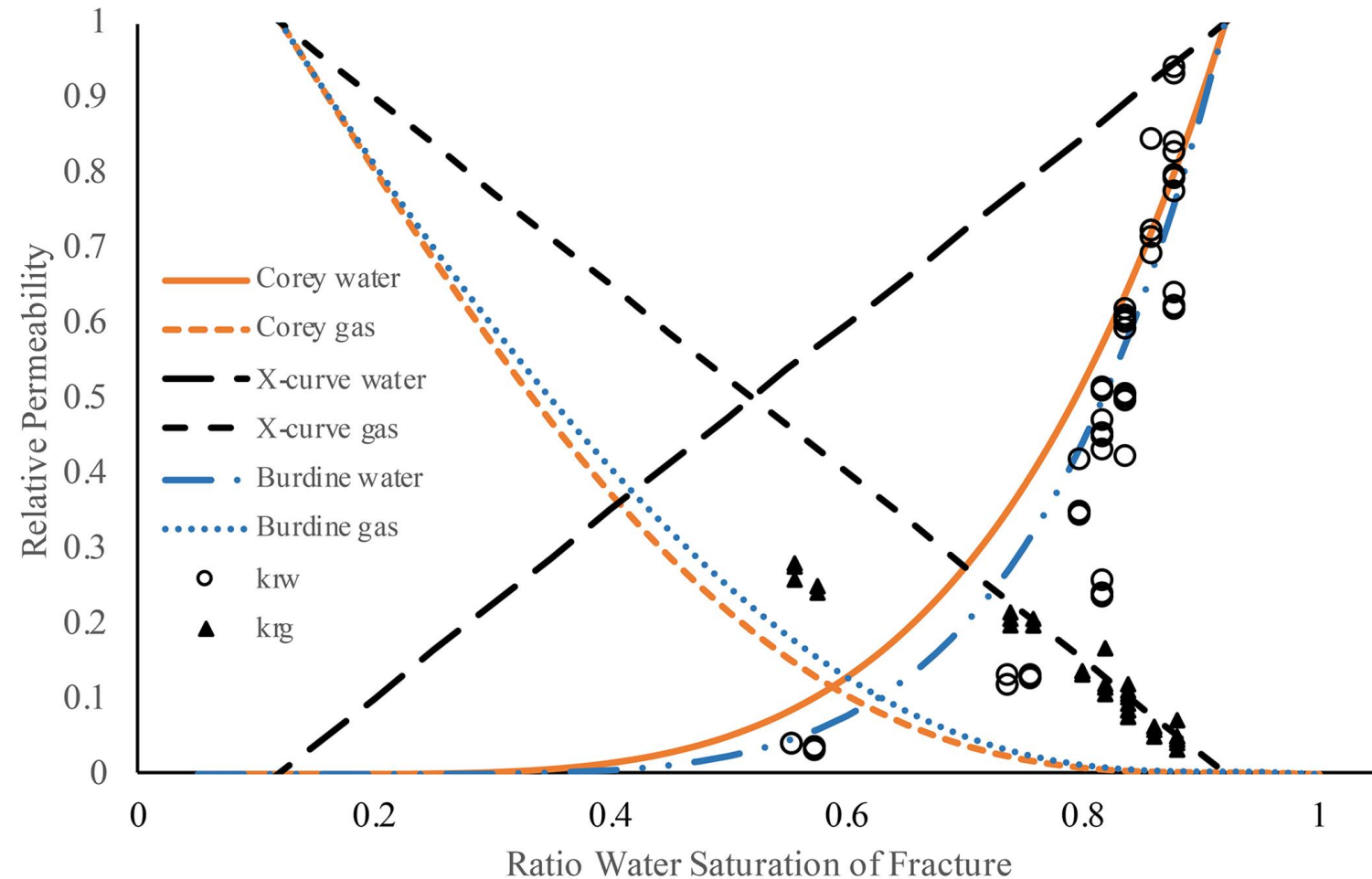
- The product of this work is to deliver a database with measurements of relative permeability, residual saturation, and wettability for offshore storage and resource extraction simulations, and accessible tools for reservoir modelers to access this data and reduce uncertainty in their estimates.

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

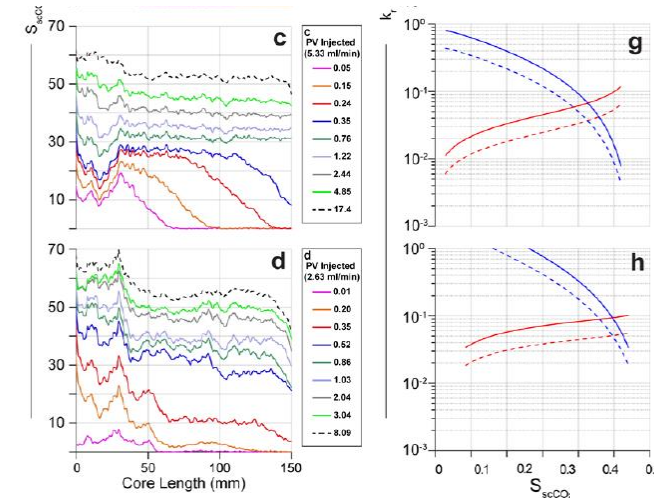
$$k_{rx} = k_x(sat) / k$$

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



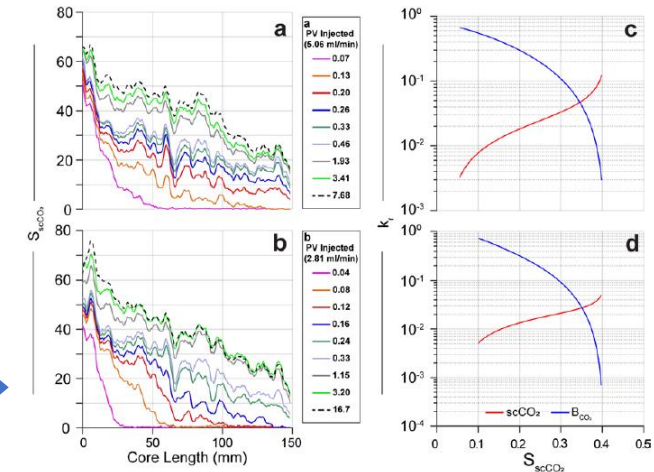
Recap Literature Review

- **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 rates of 10.73 ml/min (a), 5.33 ml/min (b), and 2.63 ml/min (d). (e-h) Representative k_r curves for flow rates of 10.73 ml/min (e), 5.33 ml/min (g), and 2.63 ml/min (h). Dashed lines in f-h indicate original, and 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 and 2.81 ml/min. (c-d) Representative k_r curves for flow experiments at 5.06 ml/min and 2.81 ml/min.

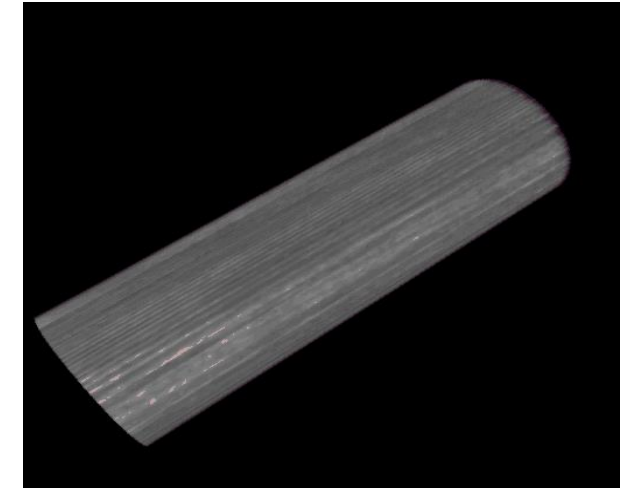
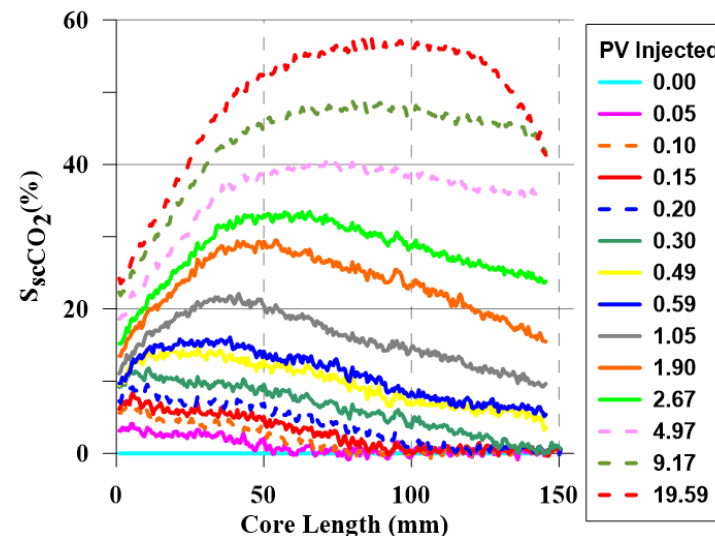
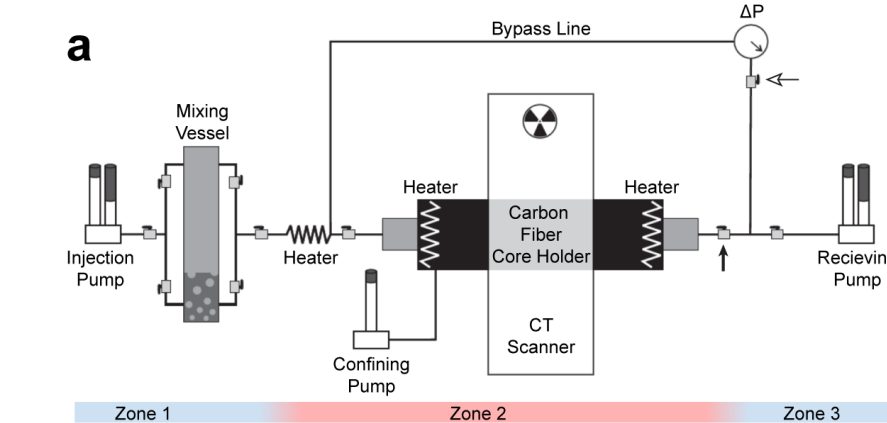
With the few specific studies examining k_r from offshore EOR out there, go/no-go review was passed

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

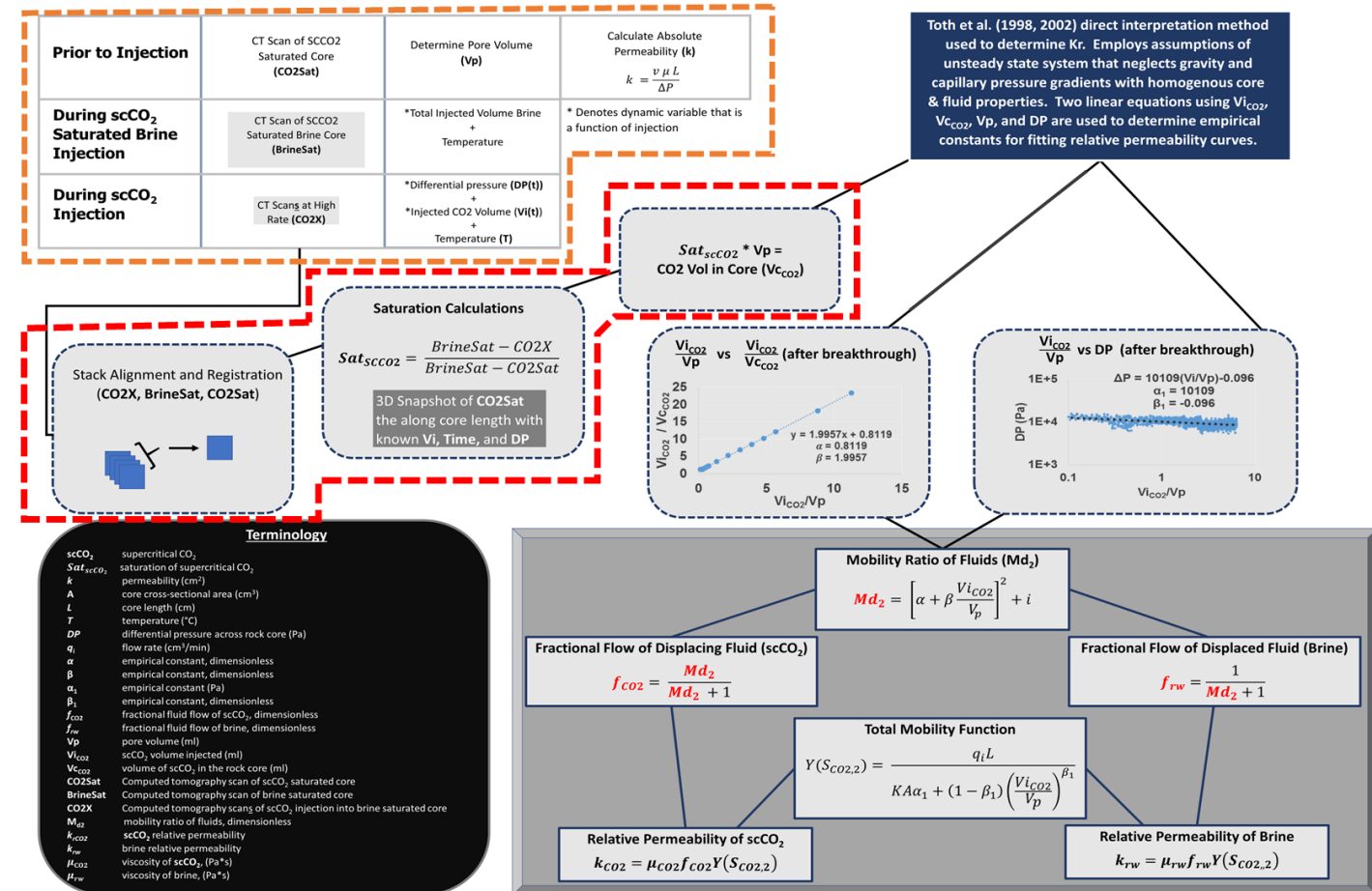


Calculation Method

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.

Moore et al. (2021) Rapid determination of supercritical CO₂ and brine relative permeability using an unsteady-state flow method. *Adv. In Water Res.*, 153.

- **Collect raw 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)



Distribution Platform

CO₂-Brine Relative Permeability Accessible database

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

View All Experiment Results

Or Filter Results by:

Rock Name

- ☒ Austin Chalk
- ☒ Edwards Yellow
- ☒ Lueders
- ☒ Silurian Dolomite
- ☒ Guelph
- ☒ Bandera Brown A
- ☒ Bandera Brown B
- ☒ Berea Sandstone
- ☒ Castlegate
- ☒ Crude Oil Test Alpha - Berea Sandstone
- ☒ Crude Oil Test Beta - Berea Sandstone
- ☒ Navajo Sandstone
- ☒ White Rim
- ☒ Basalt

Depositional Environment

- ☒ Shallow Marine
- ☒ Reef
- ☒ Marginal Marine
- ☒ Straind Plain, Barrier Bar
- ☒ Deltaic complex fluvial
- ☒ Aeolian
- ☒ Volcanic

Rock Type

- ☒ Carbonate
- ☒ Dolomite
- ☒ Sandstone
- ☒ Volcanic Mafic

Crude Oil Test Beta - Berea Sandstone

Depositional Environment: Straind Plain, Barrier Bar
Rock Type: Sandstone
Absolute Permeability 737.45 mD
Porosity 0.194
Pore Fluid Brine (5%KI/3%KCl by weight) /Bakken Crude
Displacing Fluid Supercritical CO₂
Temperature 65.6 °C
Pore Pressure 9.7 MPa
Confining Pressure 13.8 MPa
Pore Volume 59.6 ml
Length 15.15 cm
Diameter 5.08 cm
Notes: First injection is scCO₂ into oil saturated core. Second injection is scCO₂ into brine filled core.
MSCL Data

Flow Rate Q (ml/min)	Flow Test	Saturation Profile	Pore Volume Correction
8.022	Flow Test	Saturation Profile	Pore Volume Correction
8.022	Flow Test	Saturation Profile	Pore Volume Correction

Query Filters:

Rock Name

Lueders, Berea Sandstone B, Castlegate

Depositional Environment

Need, strand plain, Barrier bar

Rock Type

Carbonate, Sandstone, Volcanic

Permeability

0.0 to 99000.0 mD

Porosity

0.0 to 1.0

Results:

Lueders

Carbonate

Rock Type: Carbonate

Depositional Environment: Need

Flow Rate Q (ml/min)	Flow Test	Saturation Profile
0.05	Flow Test	Saturation Profile
0.025	Flow Test	Saturation Profile
0.015	Flow Test	Saturation Profile

Berea Sandstone B

Sandstone

Rock Type: Sandstone

Depositional Environment: strand plain, barrier bar

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

Castlegate Sandstone

Sandstone

Rock Type: Sandstone

Depositional Environment: Deltaic complex fluvial

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

Flow test table column definitions

Property	Description
Time (s)	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 28) ¹
S _{CO2,o}	Outlet face CO ₂ saturation. (See equation 30) ¹
M _{CO2}	Mobility ratio of CO ₂ at the outlet face. (See equation 26) ¹
f _{CO2}	Dimensionless fractional fluid flow for CO ₂ at outlet. (See equation 24) ¹
f _{CO2,b}	Dimensionless fractional fluid flow for brine at outlet. (See equation 25) ¹
Y _{CO2}	Total Mobility Function. (See equation 39) ¹
K _{rel,CO2}	Relative permeability of CO ₂ . (See equation 27) ¹
K _{rel}	Relative permeability of brine. (See equation 28) ¹

¹ Toth, T. Book, P. Sores, F. Given, Convenient Formulas 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\(02\)00049-8](https://doi.org/10.1016/S0920-4105(02)00049-8)

Crude Oil Test Beta - Berea Sandstone

Flow Rate: 8.022 ml/min

Export Table as csv file

*Exported data contains pump measurements

Toth et al. (2002) Curve Fitting Parameters (See methodology)
 $\alpha = 4.7383$
 $\beta = 1.818$
 $\alpha_1 = 16567.0$
 $\beta_1 = -0.133$

Placeholder for Brook-Corey and/or Van Genuchten parameters

Flow test table nomenclature

Crude Oil Test Beta - Berea Sandstone 8.022 ml/min Saturation Profiles

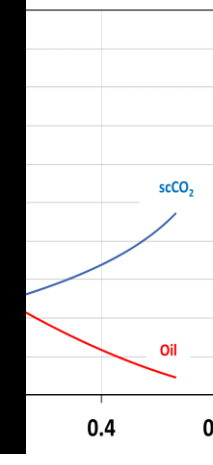
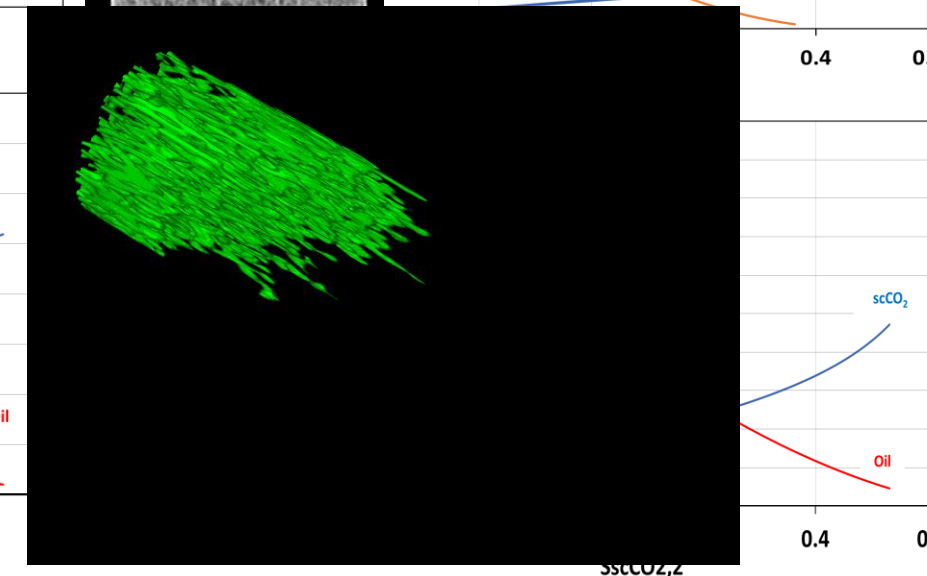
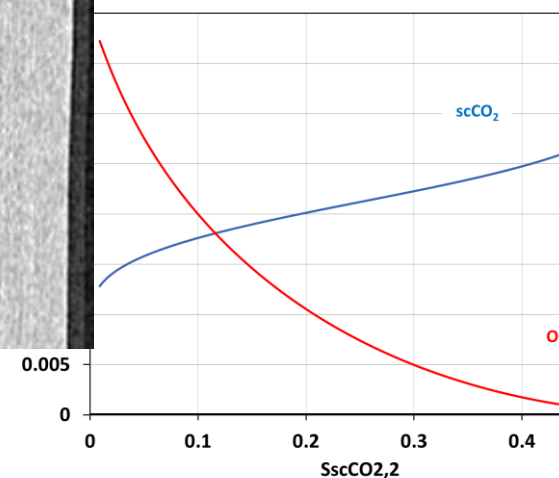
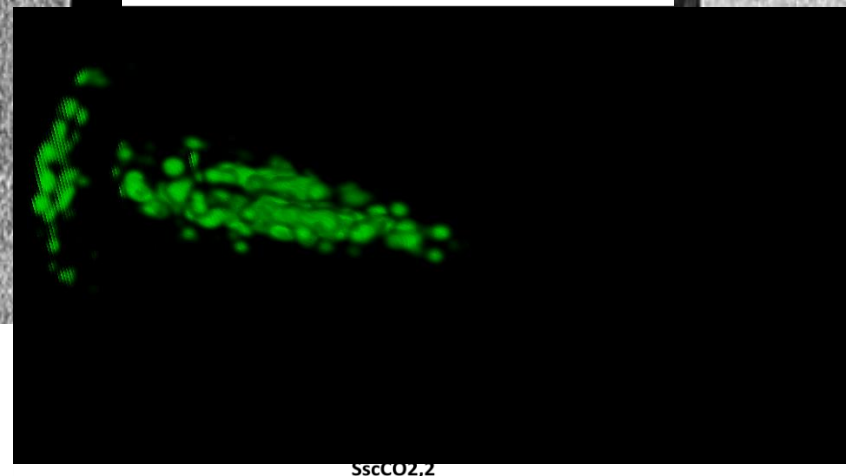
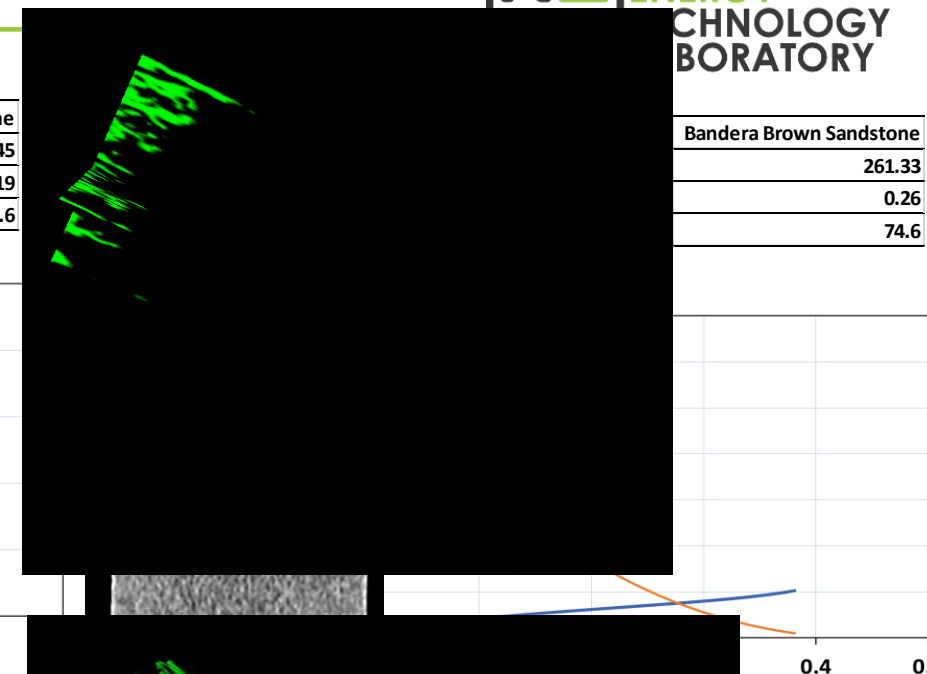
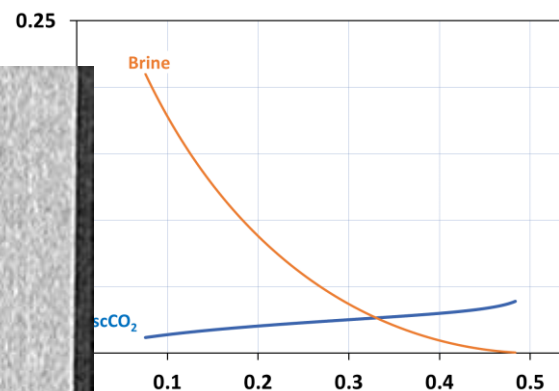
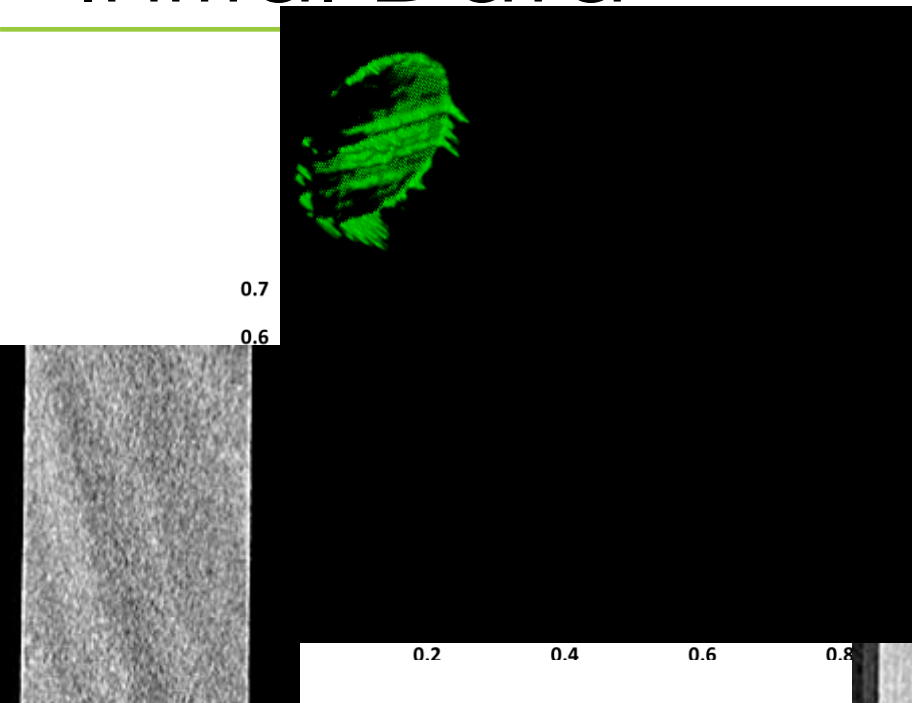
Crude Oil Test Beta - Berea Sandstone 8.022 ml/min Toth et al. Derived Relative Permeability

Receiving b q ml min	Delivery a p psi	Delivery a vol ml	Delivery a q ml min	Delivery b p psi	Delivery b vol ml	Delivery b q ml min	Diff p high psi	Setra delivery p psi	Setra receive p psi	Diff p low psi	Temperature °C
0.0	1175.6	0.059	0.0	1412.6	1265.4705	8.022	4.534	1452.182	-13.157	8.836	17.33
0.0	1174.6	0.059	0.0	1408.8	1264.802	8.022	4.356	1447.041	-8.016	7.864	17.388
0.0	1173.8	0.059	0.0	1408.6	1264.1335	8.022	3.086	1447.041	-13.157	5.369	17.411

Initial Data

Rock name	Berea Sandstone
Absolute Permeability (k, mD)	737.45
Porosity (ϕ)	0.19
Pore Volume	59.6

Bandera Brown Sandstone	
	261.33
	0.26
	74.6



Project Updates

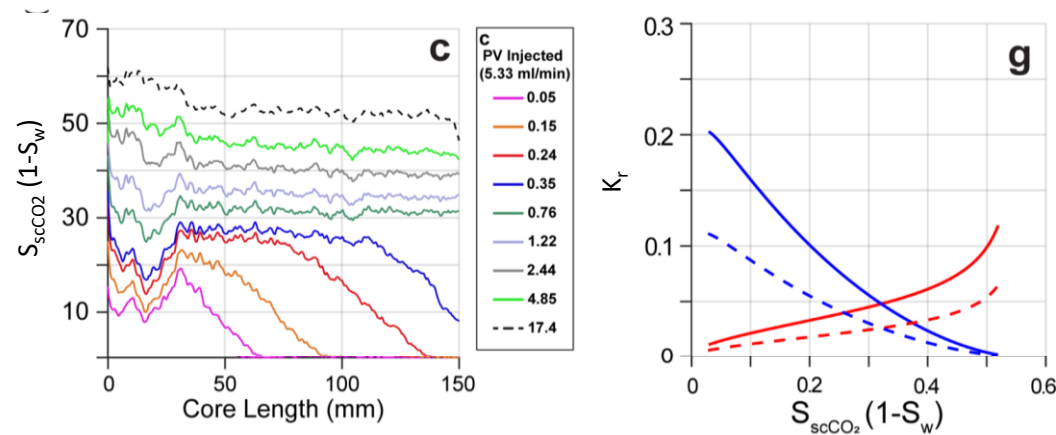
Data collection underway

- There was a slow down on these floods earlier last year due to COVID but we have recovered
 - Currently have completed 6 experiments, with 3 viable results
 - Working on completing #7
 - 3 of the cores were not fully analyzed due to equipment failures resulting in lost tests
- Use of previously refined unsteady state methodology for CO₂/brine k_r curve measurements still working well
 - Oil contamination of system, and resulting cleaning, results in slightly longer experiment times. We now have a fully developed methodology for QA/QC of equipment to mitigate this issue.
 - Oil attenuation is harder to differentiate from CO₂ than brine. We have had to modify our image analysis protocol

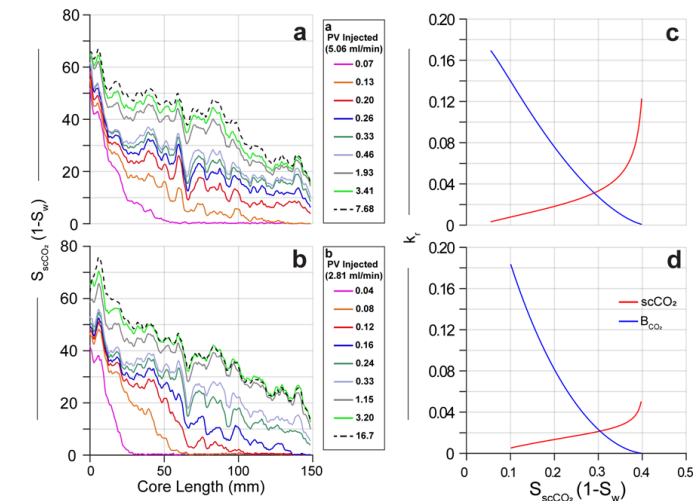
Project Next Steps

Continue measurements

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



Low permeability (24 mD) Edwards Yellow



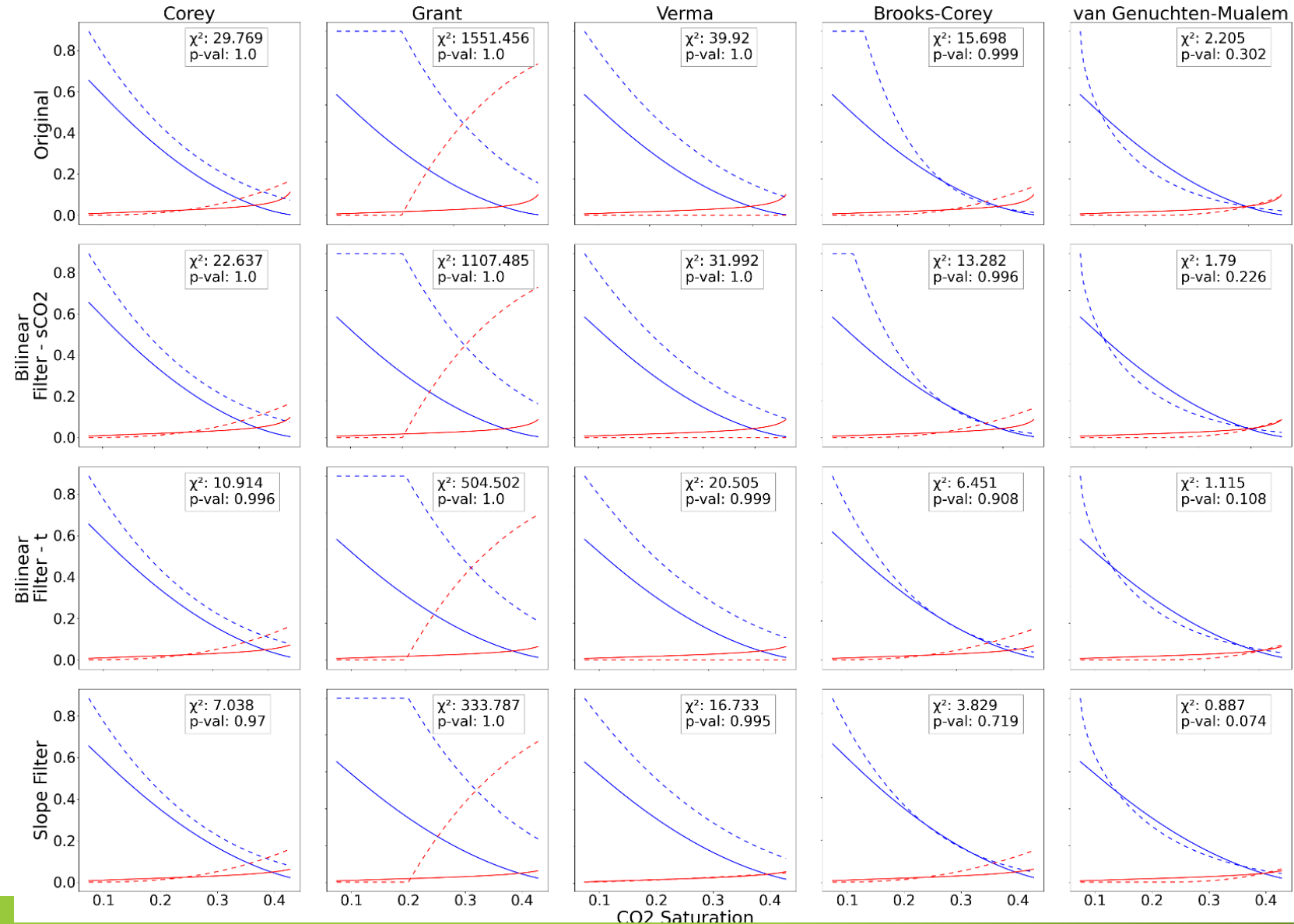
High permeability (760 mD) White Rim

Technology-to-Market Path

- Continue adding data to the CO2BRA platform in 2021/2022
- Added value via data that can be used to model fluid behavior in offshore environment for applications in carbon storage, wellbore-reservoir flow issues (blowout) and EOR.

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**



Concluding Remarks

- At the conclusion of this project, we will have an open platform with fluid relative permeability curves, data used to collect those curves, and explanations of the process. These curves will be generated for conditions relevant to the Offshore environment, with the benefits of:
 - Providing additional improved modeling parameters for
 - CO₂ storage in petroleum plays
 - Wellbore blowout and near wellbore flow
 - Providing open access to relative permeability data for oil/water/CO₂ systems
- The next 3 quarters will primarily be in finishing the data collection/analysis phase, with some preparation of the open online platform.
 - **Strong push to obtain offshore cores. Currently have discussions ongoing with government agencies, academia and industry.**

Thank you

Big thanks to Dustin Crandall, Kelly Rose, Paul Holcomb, Scott Workman, Jeong Choi, Seth King and all the others who have made this work possible.

Thank you for your interest today!

Moore, J., Holcomb, P., Crandall, D., King, S., Choi, J., Brown, S., & Workman, S. (2021). Rapid determination of supercritical CO₂ and brine relative permeability using an unsteady-state flow method. *Advances in water resources*, 153, .
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