IMPROVED CHARACTERIZATION AND MODELING OF TIGHT OIL FORMATIONS FOR CO_2 ENHANCED OIL RECOVERY POTENTIAL AND STORAGE CAPACITY ESTIMATION

DE-FE0024454

Mastering the Subsurface Through Technology Innovation & Collaboration: Carbon Storage & Oil & Natural Gas Technologies Review Meeting

August 17, 2016

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Critical Challenges. Practical Solutions.

ACKNOWLEDGMENT OF PARTNERS

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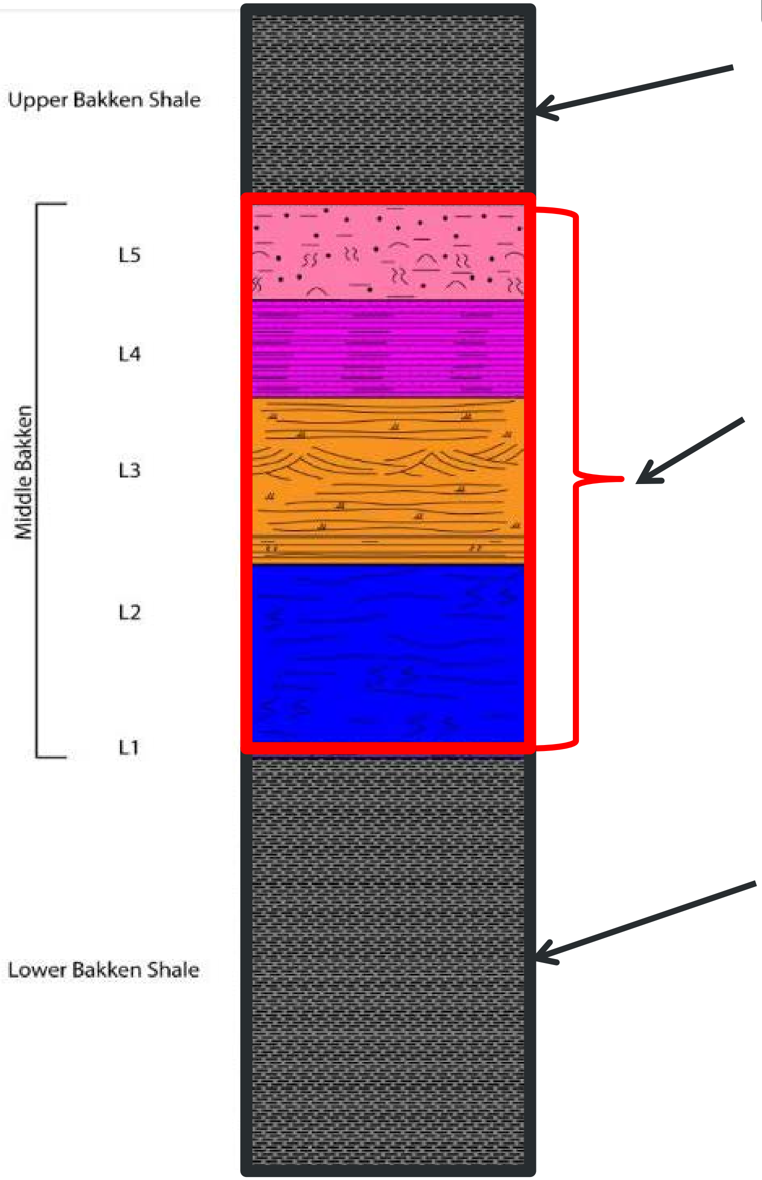
PRESENTATION OUTLINE

- Background
- Project Overview
- Key Lessons Learned
- Future Directions

BAKKEN FORMATION LITHOLOGY



Upper Bakken Shale: Brown to black, organic-rich

- **Bakken source rock**
- **1% to 4% porosity**
- **0.0001 to 0.1 mD permeability**

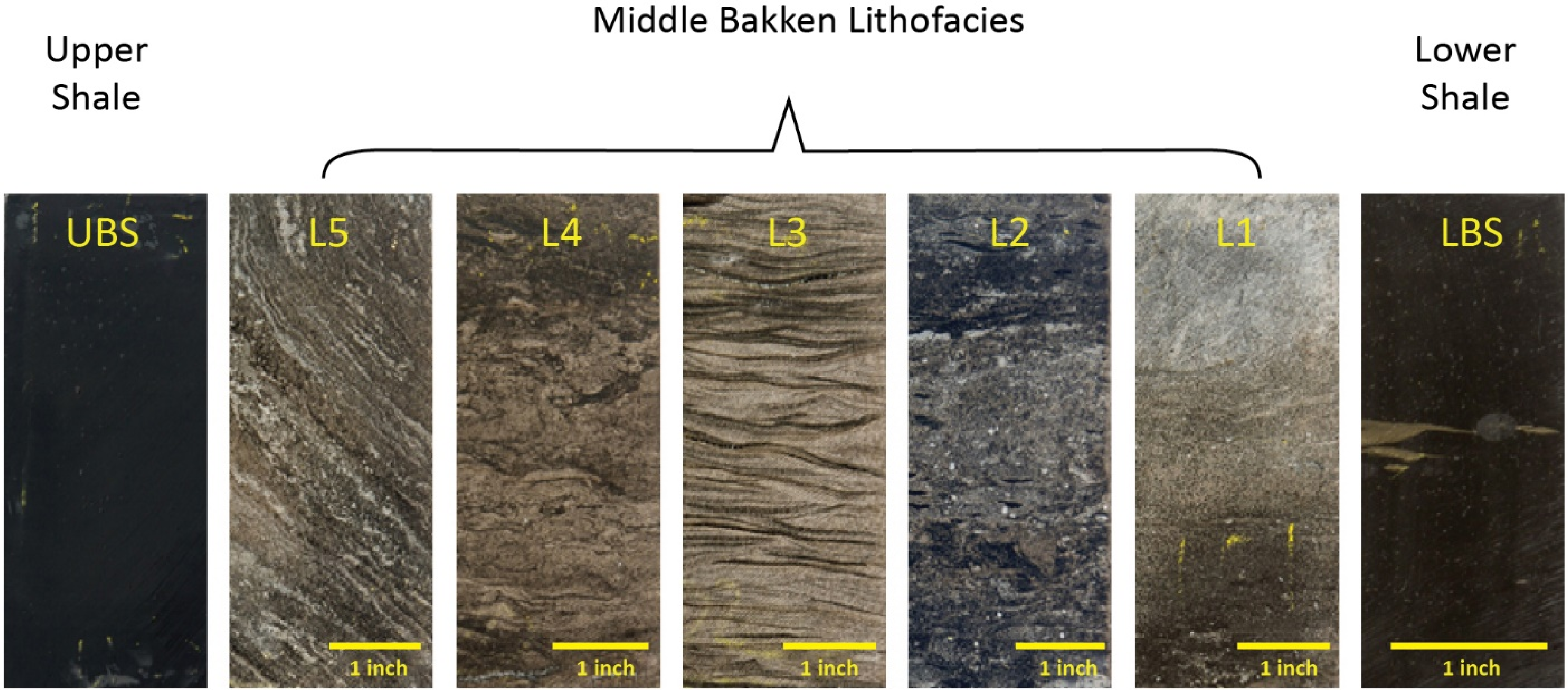
Middle Bakken: Variable lithology (up to nine lithofacies), ranging from silty sands to siltstones and tight carbonates

- **Bakken reservoir rock (horizontal drilling target)**
- **5% to 10% porosity**
- **0.0005 to 50 mD permeability**

Lower Bakken Shale: Brown to black, organic-rich

- **Bakken source rock**
- **1% to 4% porosity**
- **0.0001 to 0.1 mD permeability**

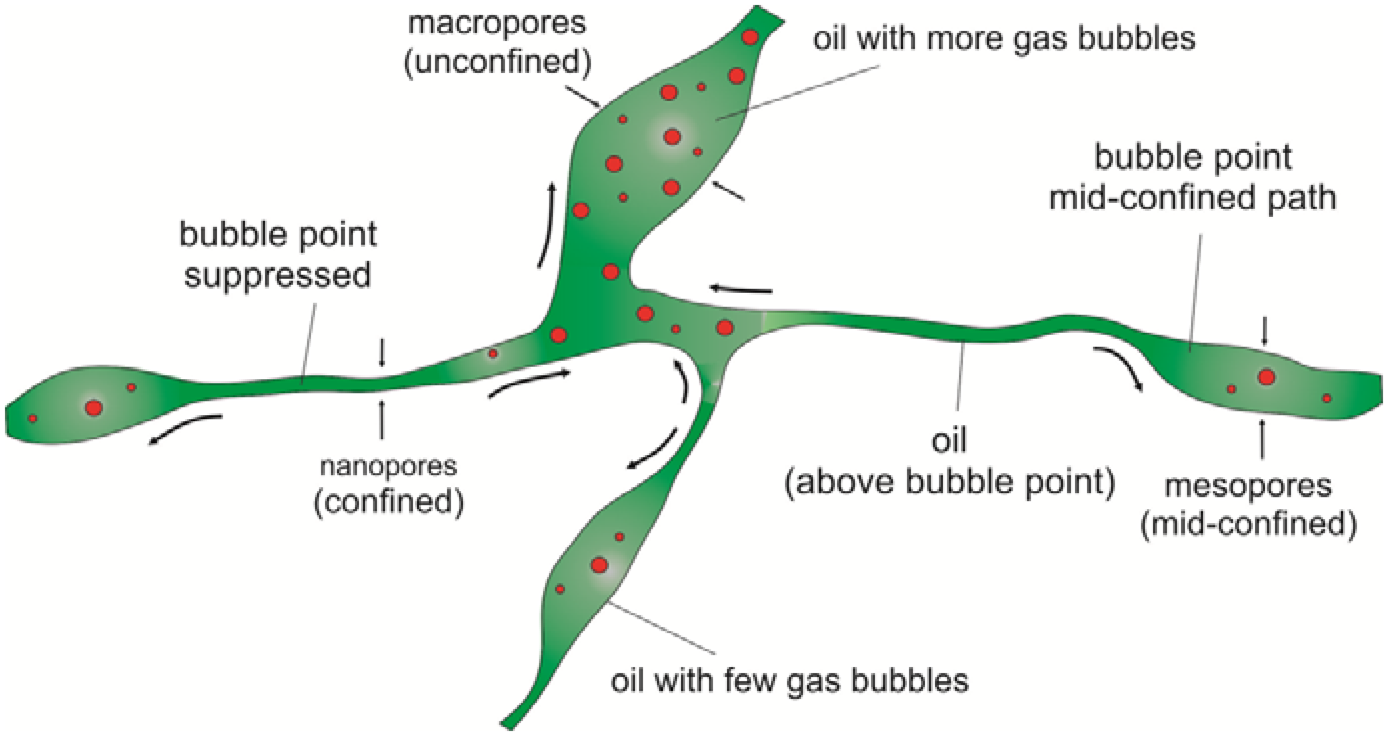
THE ROCKS WITHIN THE SYSTEM ARE COMPLEX



QUESTIONS ADDRESSED BY PROJECT

- Can CO_2 permeate tight rocks and mobilize oil?
- How does the high vertical heterogeneity of the lithofacies affect CO_2 permeation and oil mobility?
- How does the sorptive capacity of the organic carbon materials affect CO_2 mobility, enhanced oil recovery (EOR), and storage?

PORE SIZE AFFECTS FLUID PHASE BEHAVIOR



Conceptual pore network model showing different phase behavior in different pore sizes for a bubblepoint system with phase behavior shift.

Source: Alharthy, N.S., Nguyen, T.N., Teklu, T.W., Kazemi, H., and Graves, R.M., 2013, SPE 166306, Colorado School of Mines, and Computer Modelling Group Ltd.

To predict hydrocarbon phase behavior in the Bakken, we need to understand:

- Size and geometry of the pore throat networks.
- Distribution of those pore throat networks.
- Working fluid/oil interactions at Bakken conditions.
  - Miscibility
  - Hydrocarbon species selectivity

TECHNICAL STATUS

Phase I – November 2014 to April 2016

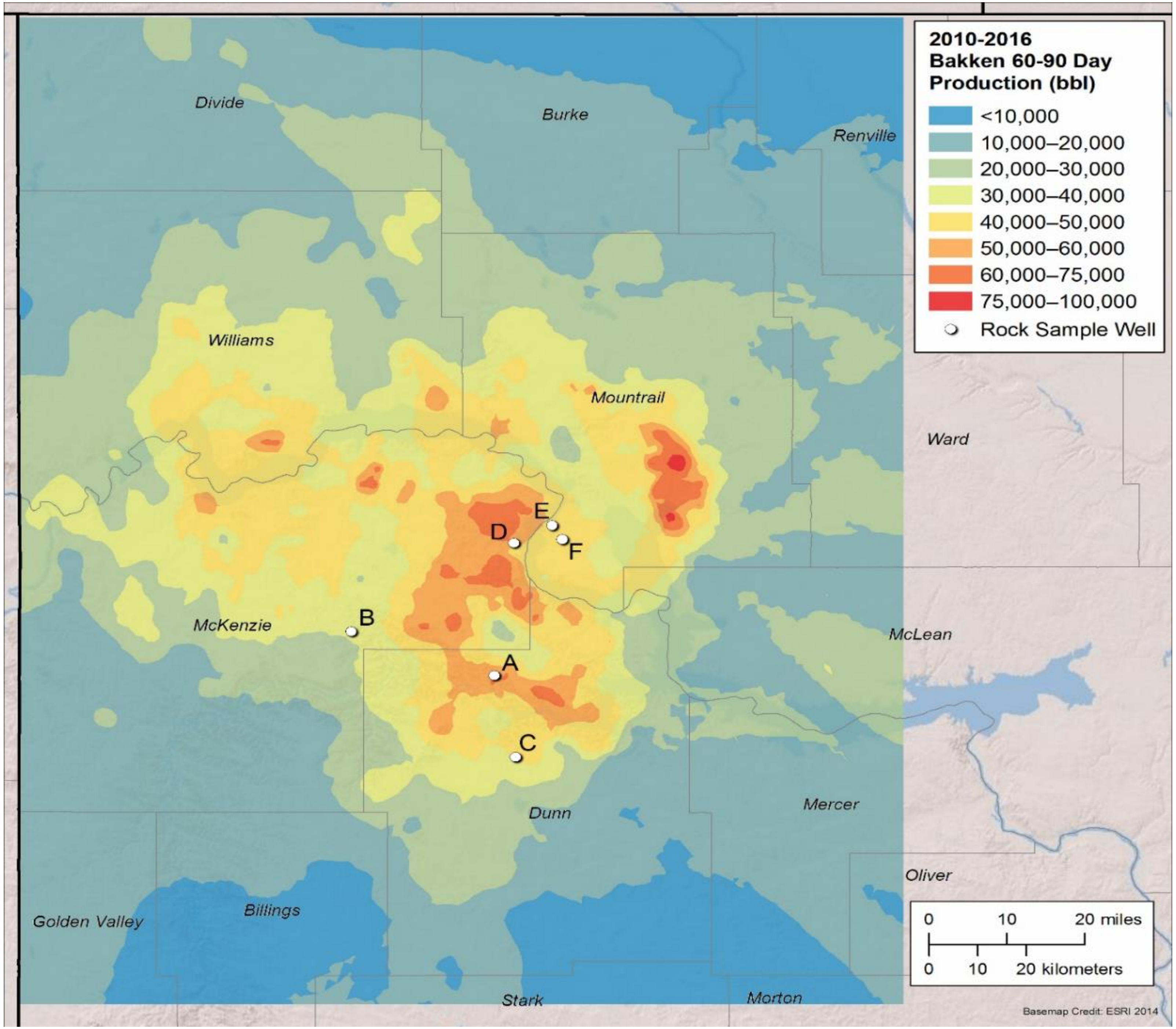
- Sample selection and detailed baseline characterization
- Development of improved methodologies to identify multiscale fracture networks and pore characteristics

Phase II – May 2016 to October 2017

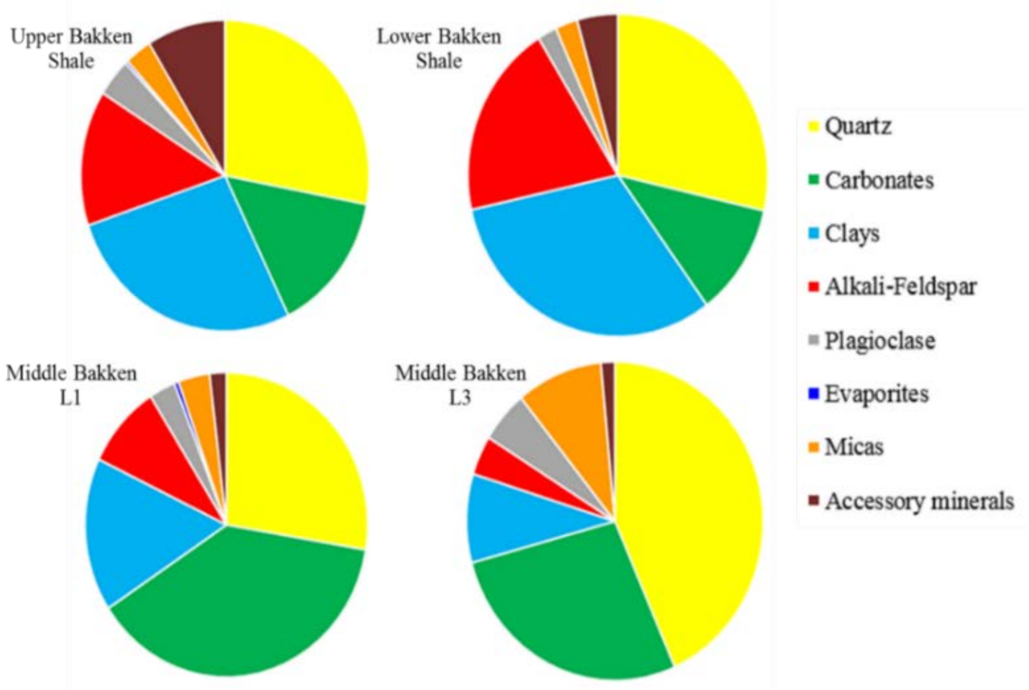
- CO_2 transport, permeation, and oil extraction testing
- Multimineral petrophysical analysis (MMPA)
- Modeling and simulation

ROCK CORE SAMPLE WELL LOCATIONS

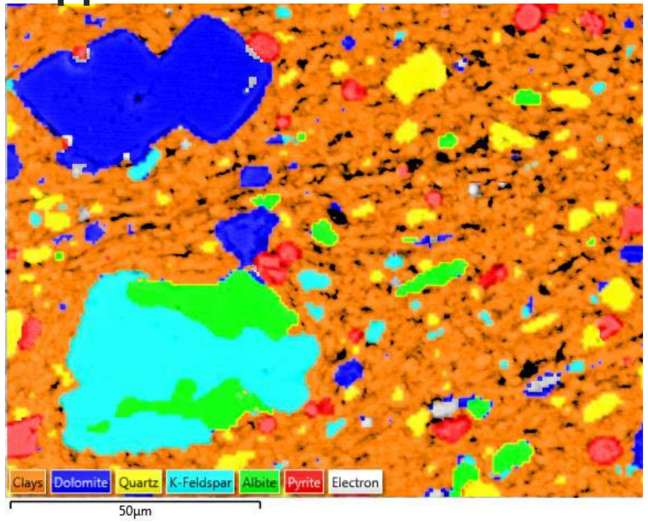
- Cores come from six well locations.
- Samples represent:
  - Middle Bakken reservoir lithofacies.
  - Upper and Lower Bakken shale source rocks.
  - Reservoir–shale interface.
- Samples provided by Marathon and North Dakota Geological Survey.



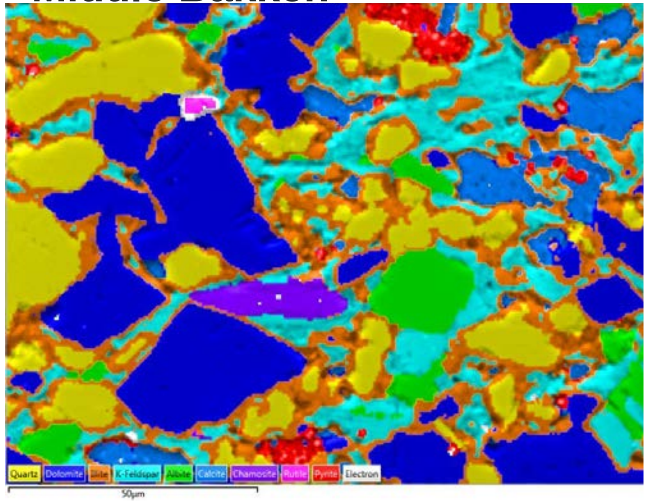
ROCK CHARACTERIZATION

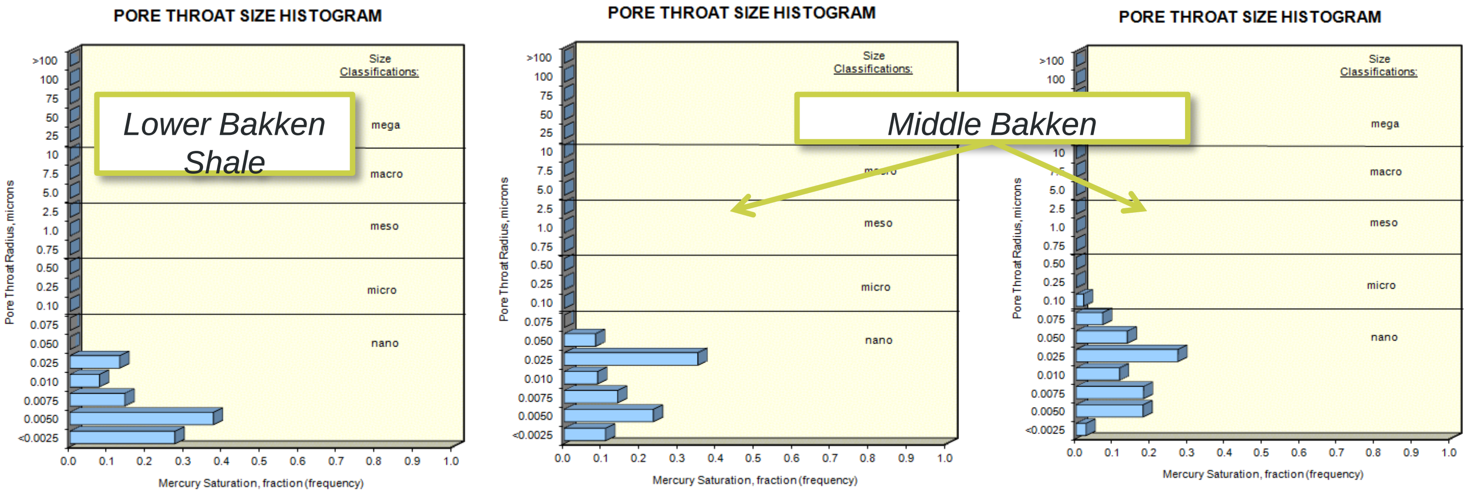


Upper Bakken Shale



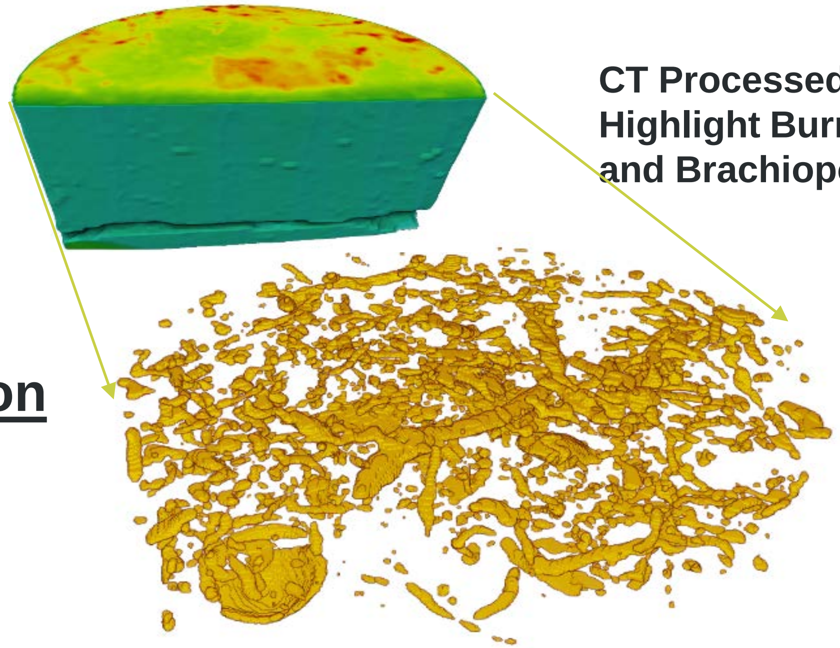
Middle Bakken





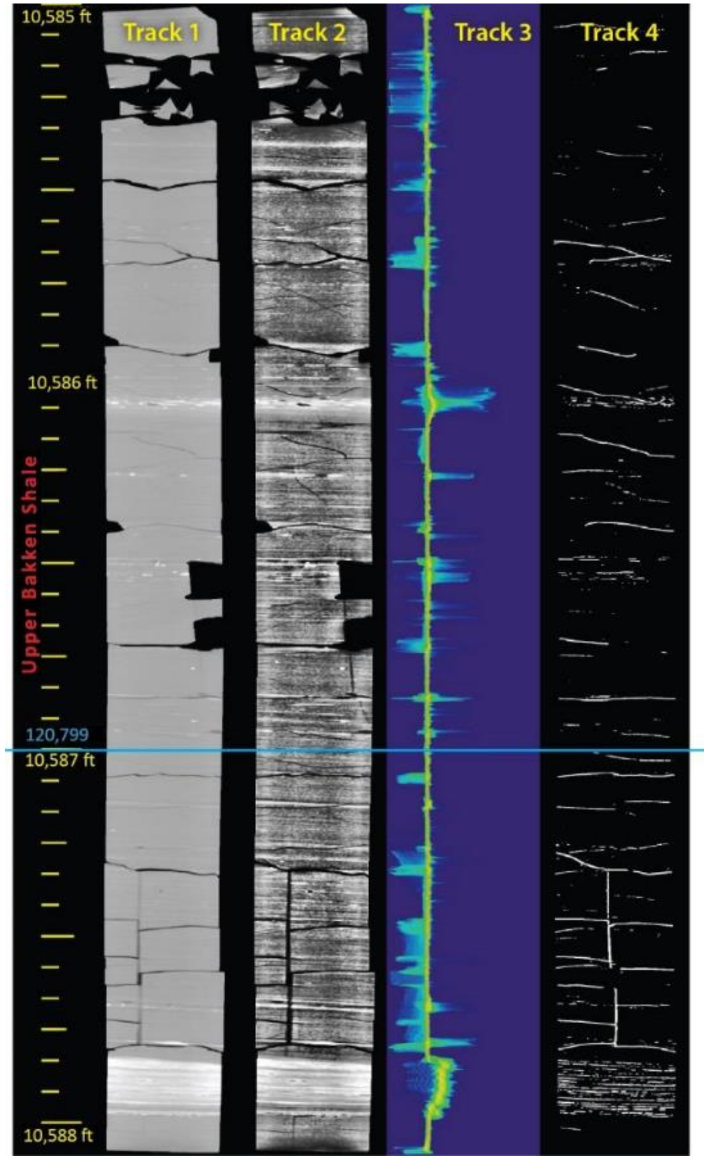
- Mineralogy
- Mineral maps
- Porosity
- Permeability
- Grain density
- Pore throat size distribution

FRACTURE AND PORE ANALYSIS TECHNIQUES



CT Processed to Highlight Burrows and Brachiopod

CT Scan of Middle Bakken whole core

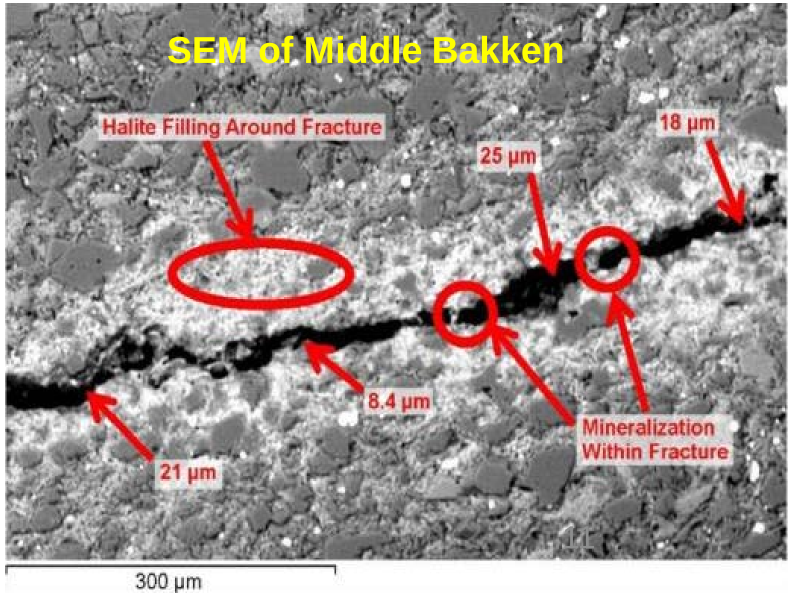


Macro- to Micro-Fracture Characterization

– Whole-core and thin-section analysis.

– CT scans.

– Conventional SEM methods.

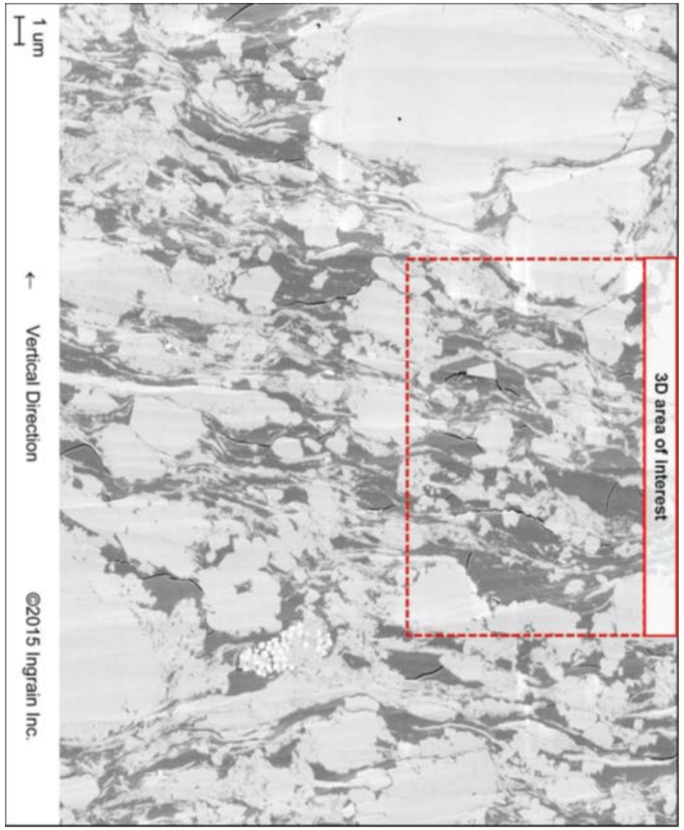


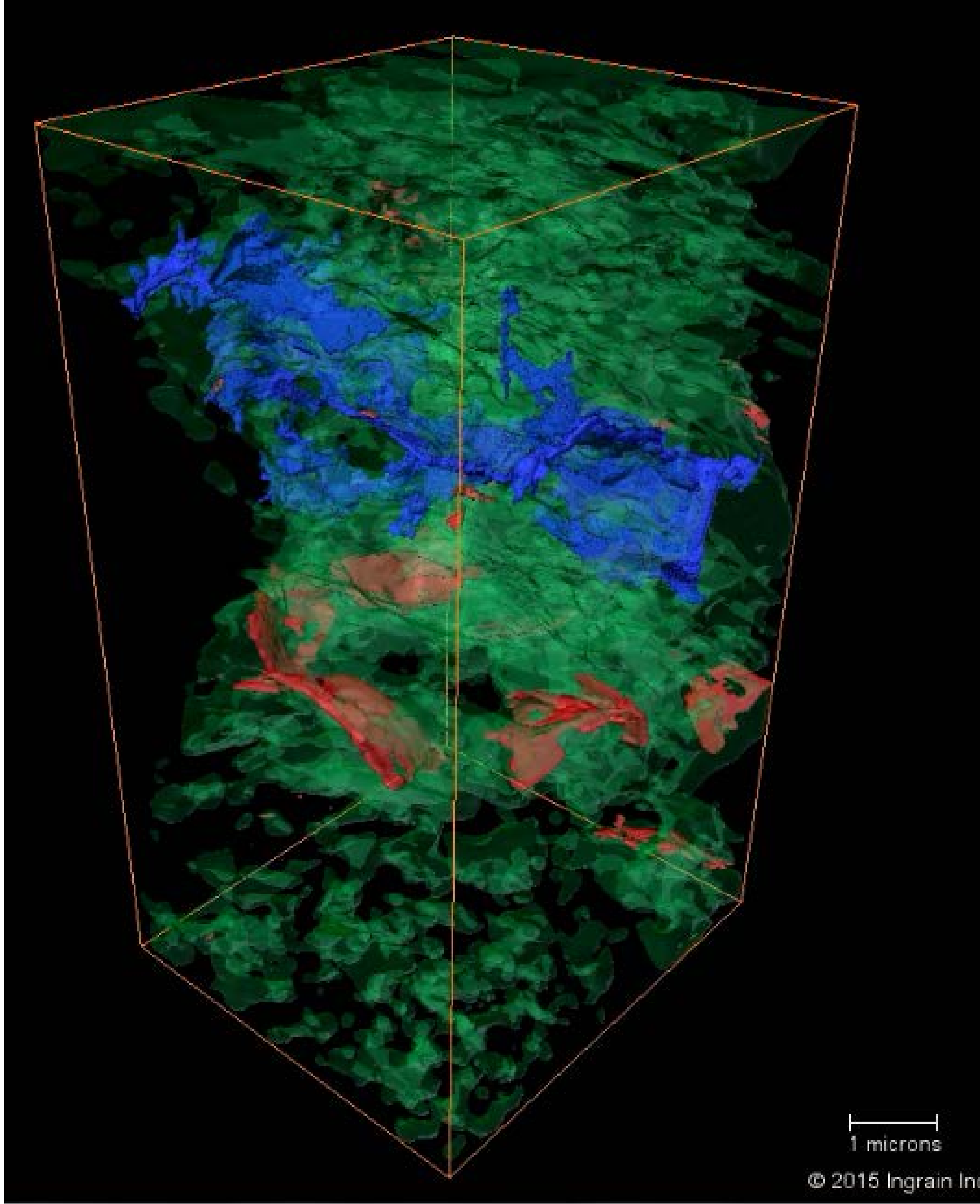
UPPER BAKKEN SHALE

MICRO- AND NANOSCALE FESEM AND FIB–SEM

Green = organics
Red = unconnected Φ
Blue = connected Φ

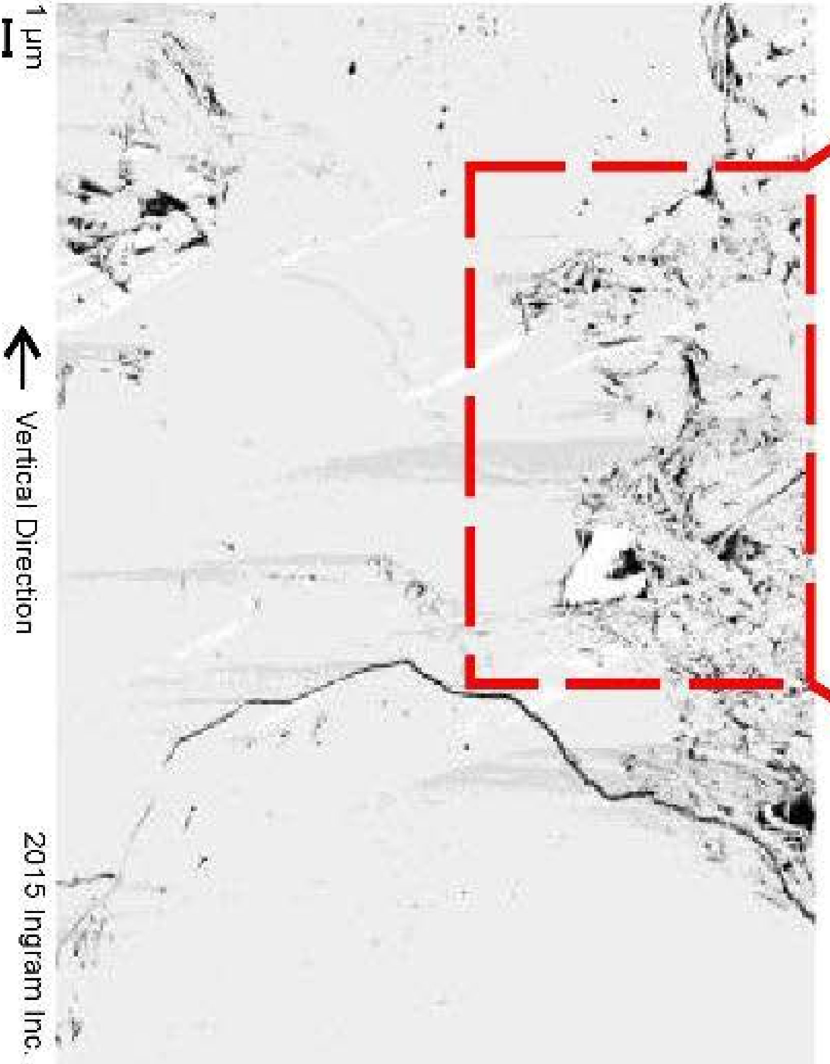
The amount of connected and unconnected pore space is roughly equal.

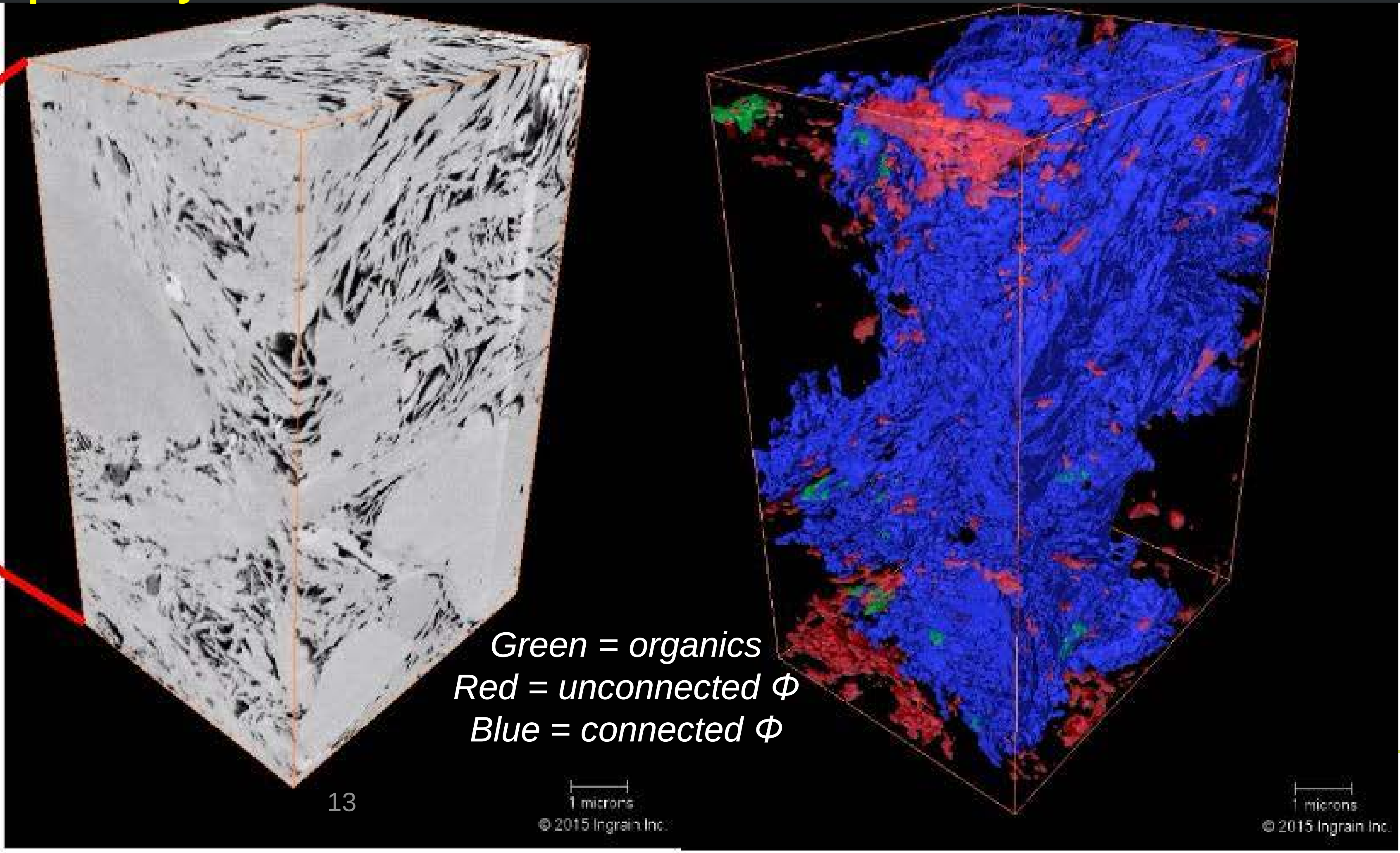




FESEM AND FIB–SEM OF MIDDLE BAKKEN (LAMINATED)

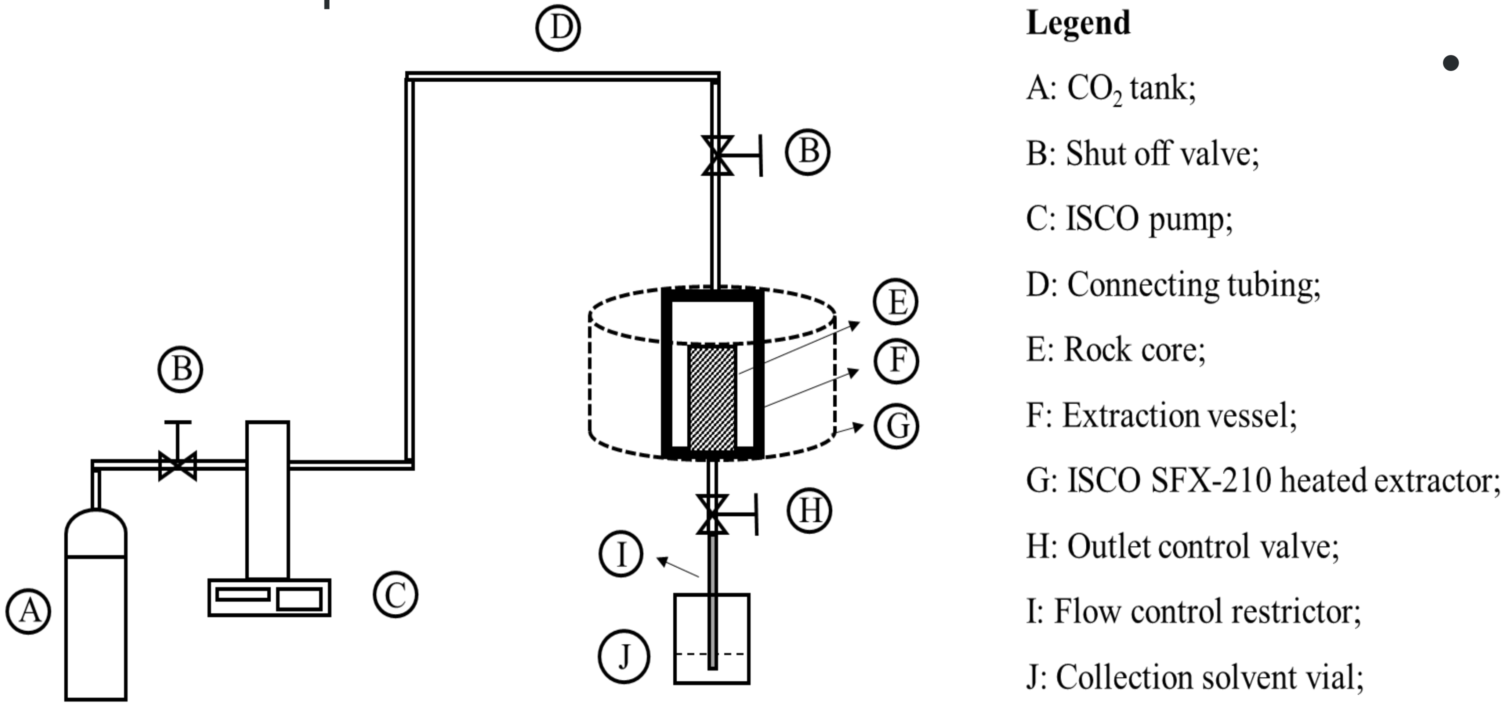
Clay-filled microfractures appear to have highly connected porosity.



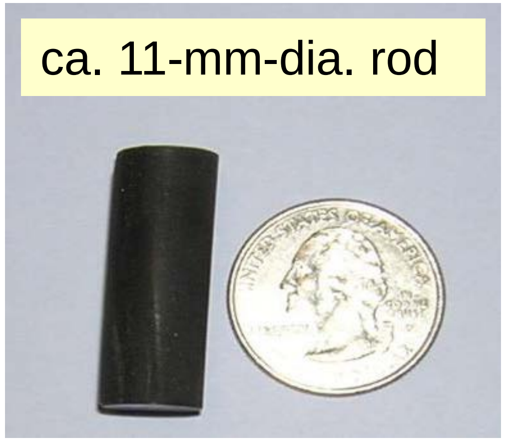


OIL EXTRACTION FROM BAKKEN ROCKS IN THE LAB

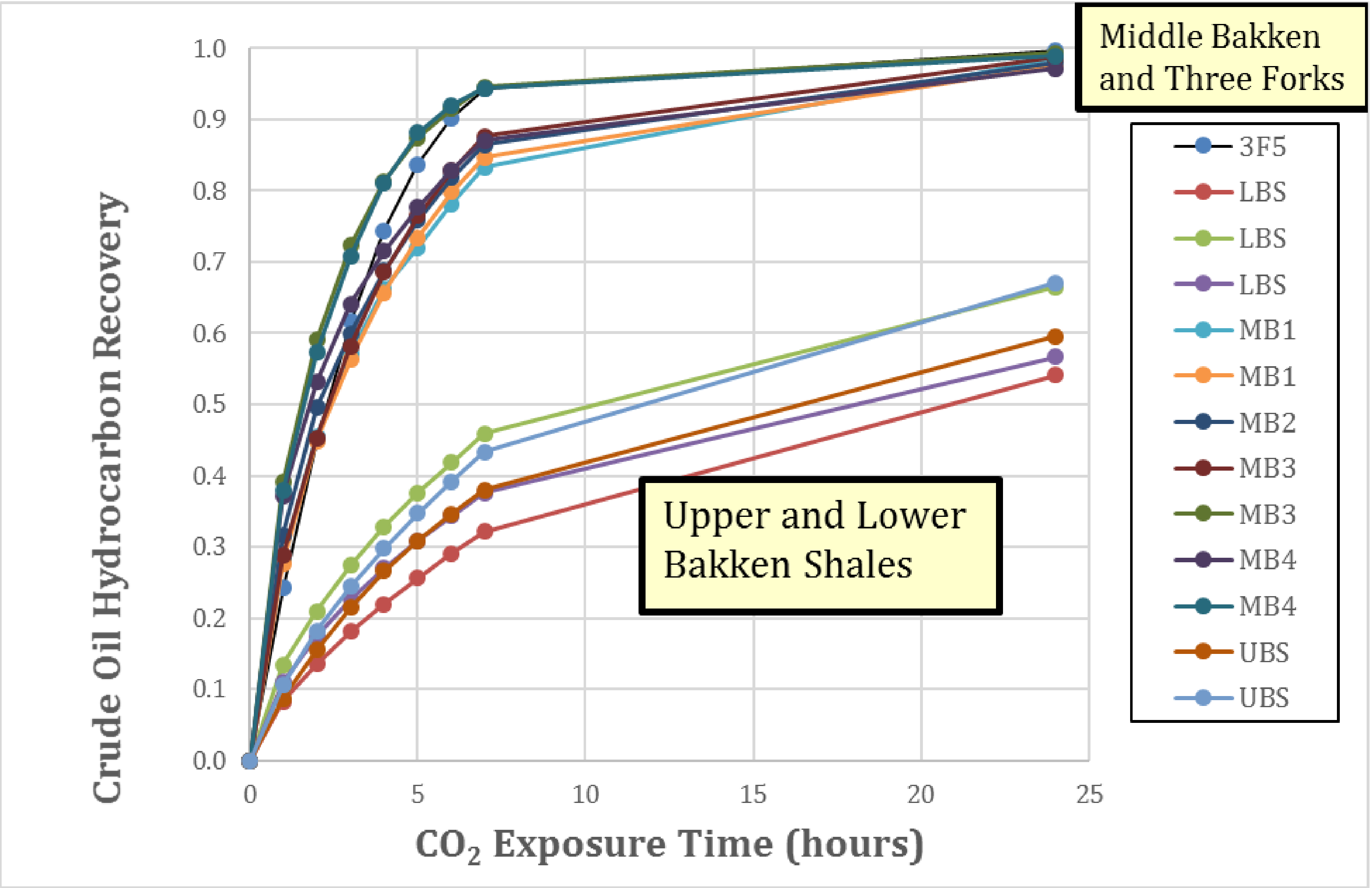
- 46 core plugs from 6 wells representing three Middle Bakken lithofacies and both Upper and Lower Bakken shales were selected to investigate the EOR effects of CO_2.
- 24-hour oil extraction was conducted for the rock samples.
- All experiments were carried out under reservoir conditions (5000 psi, 230°F).



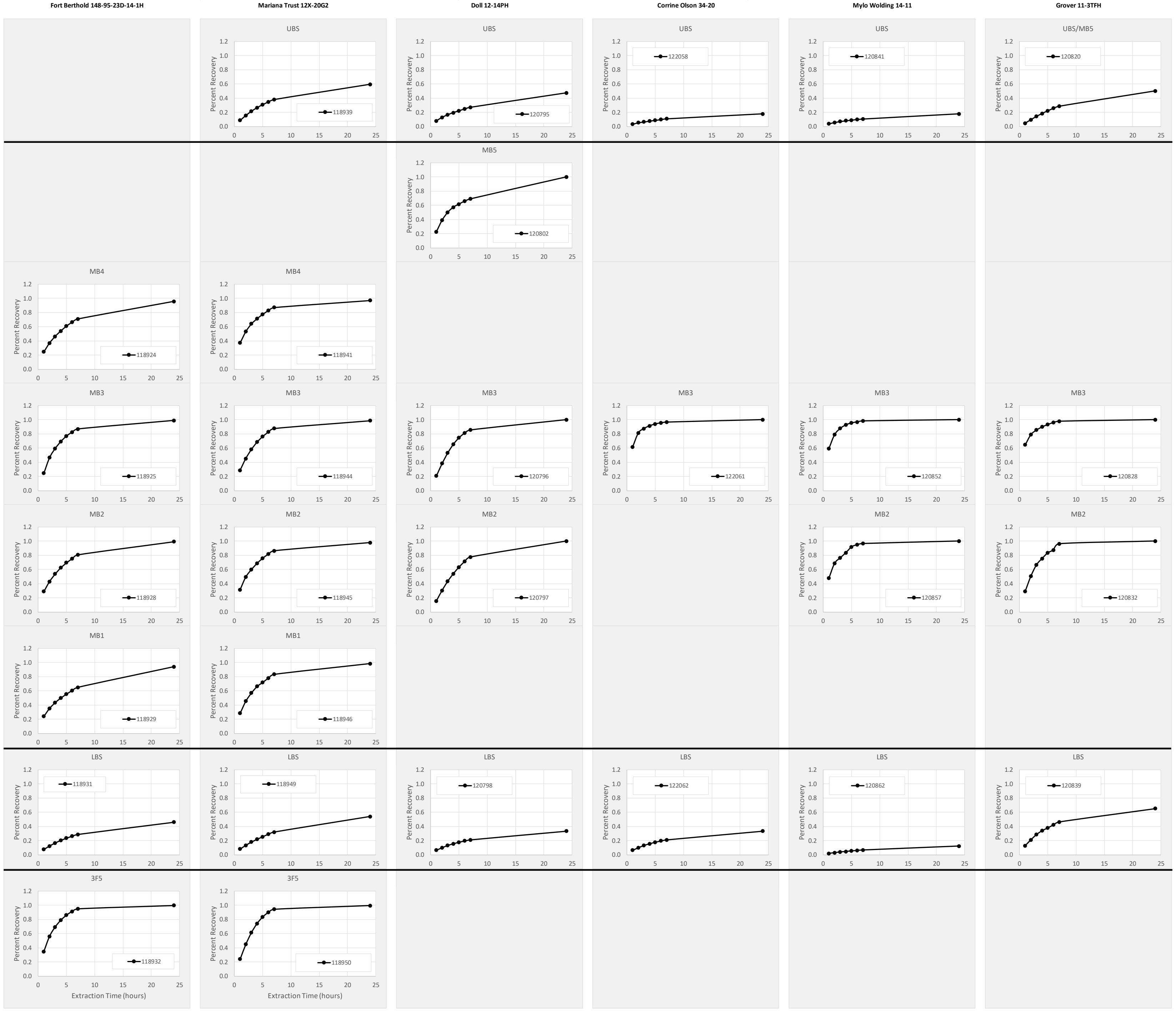
- Rock is “bathed” in gases, not swept with gases as would be the case in confined flow-through tests.

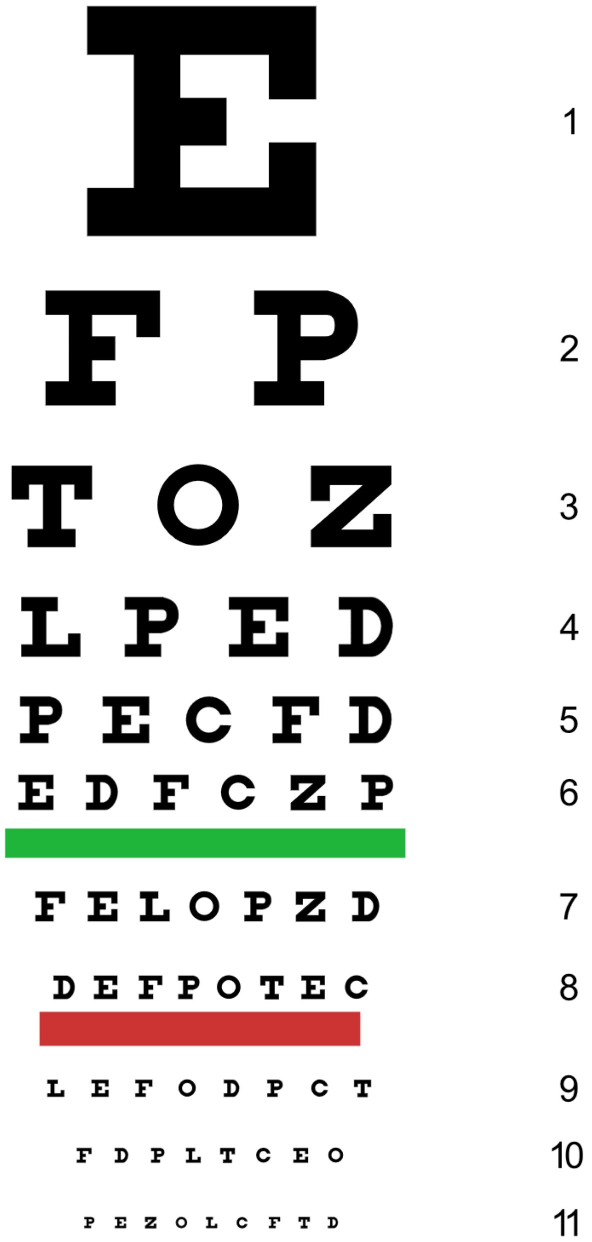


Laboratory CO_2 oil recovery from six Bakken lithofacies from a McKenzie County well (24 hours).



EXTRACTION RESULTS





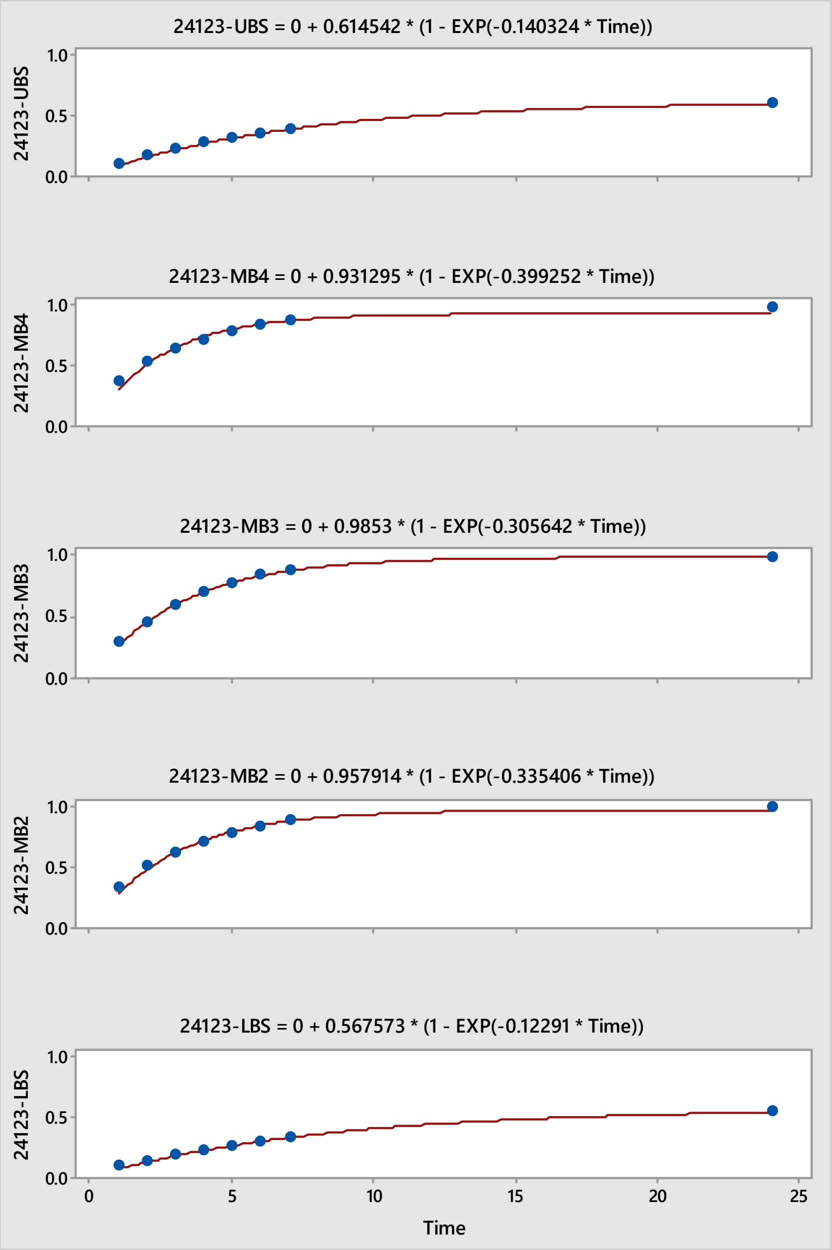
CO_2 EXTRACTION DATA ANALYSIS - WHAT FACTORS CONTROL CO_2 PERMEATION & OIL EXTRACTION

- Evaluated a data set of 46 Bakken samples (rods), which include CO_2 extraction at 1, 2, 3, 4, 5, 6, 7, and 24 hours.
- Compared hydrocarbon recoveries to petrophysical properties:
  - Thermal maturity indicators
    - ♦ TOC, S1, S2, S3 CO_2, S3 CO, T_{max}, HI, OI, PI, and OSI
  - Pore throat size
    - ♦ HPMI-MIPC R35, mean-throat, and Max-Sb-Pc
  - Mineralogy
    - ♦ Quartz, alkali-feldspar, plagioclase, clays, carbonates, and accessory-mineral

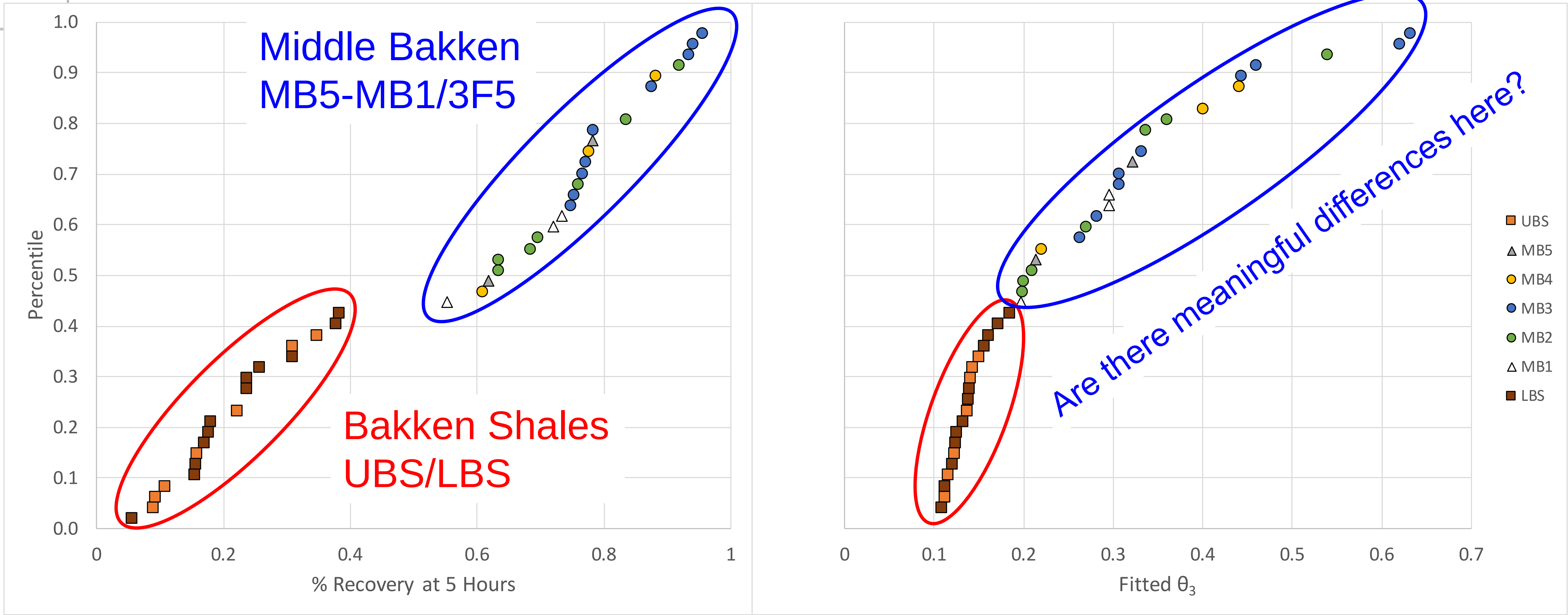
WHY FIT PARAMETERS?

% Recovery = $\theta_1 + \theta_2 * (1 - EXP(-\theta_3 * Time))$

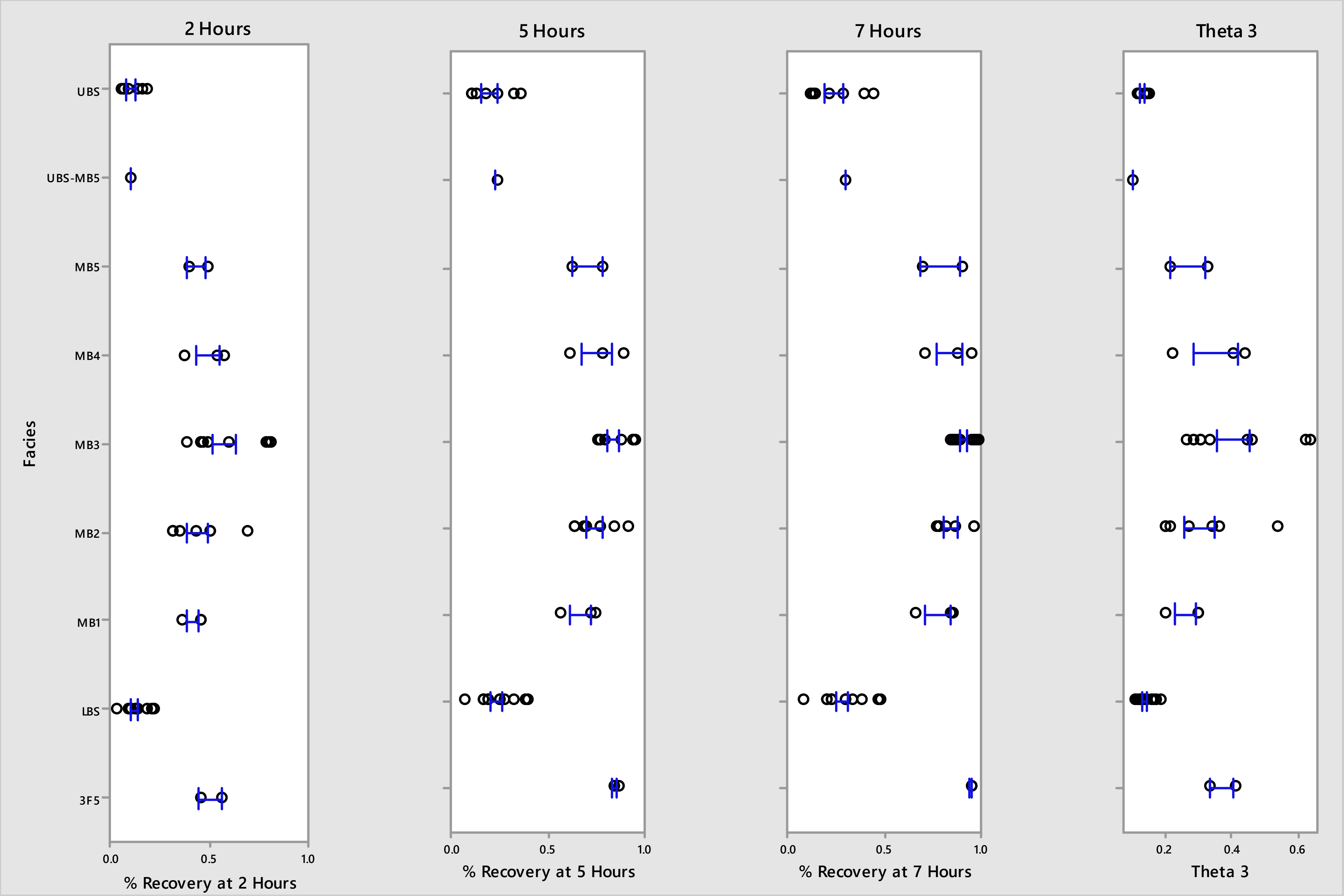
- One model parameter (θ_3) tells us information about the recovery rate.
- Higher θ_3 = faster rate.
- Lower θ_3 = slower rate.
- **Takes a curve and turns it into a point.**



SIMILAR INFORMATION VALUE FOR %RECOVERY AND Θ_3



% RECOVERY TRENDS WITH DEPTH



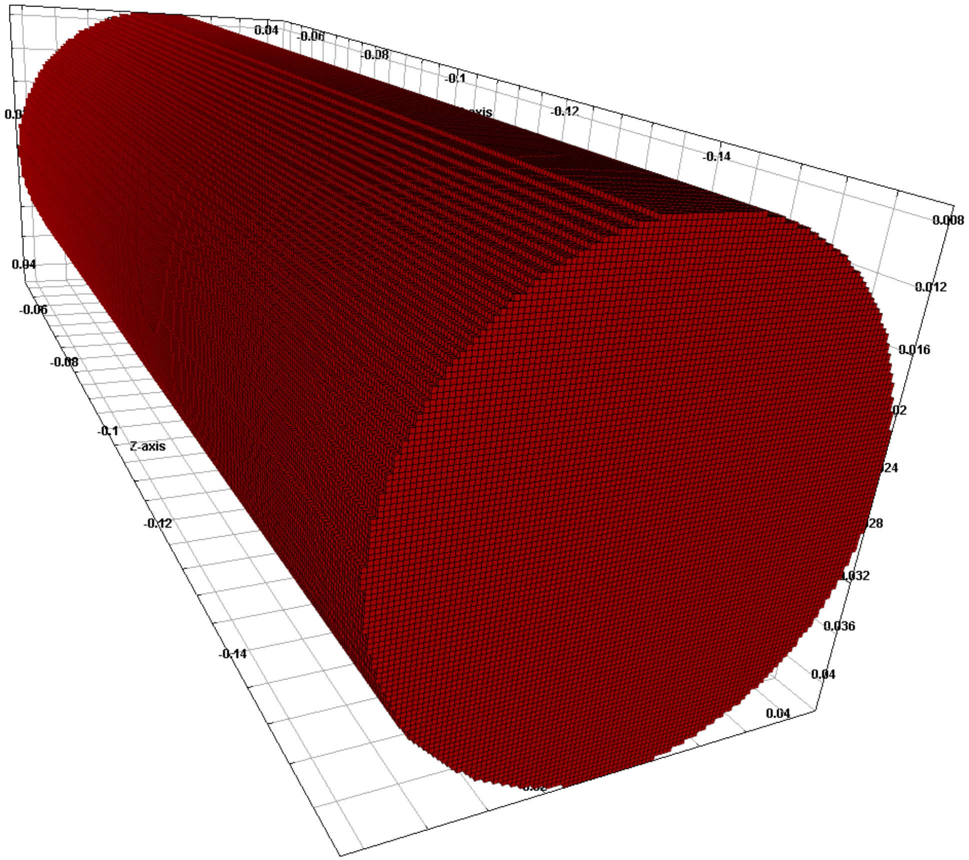
MB DIFFERENCES ARE NOT "STATISTICALLY SIGNIFICANT"

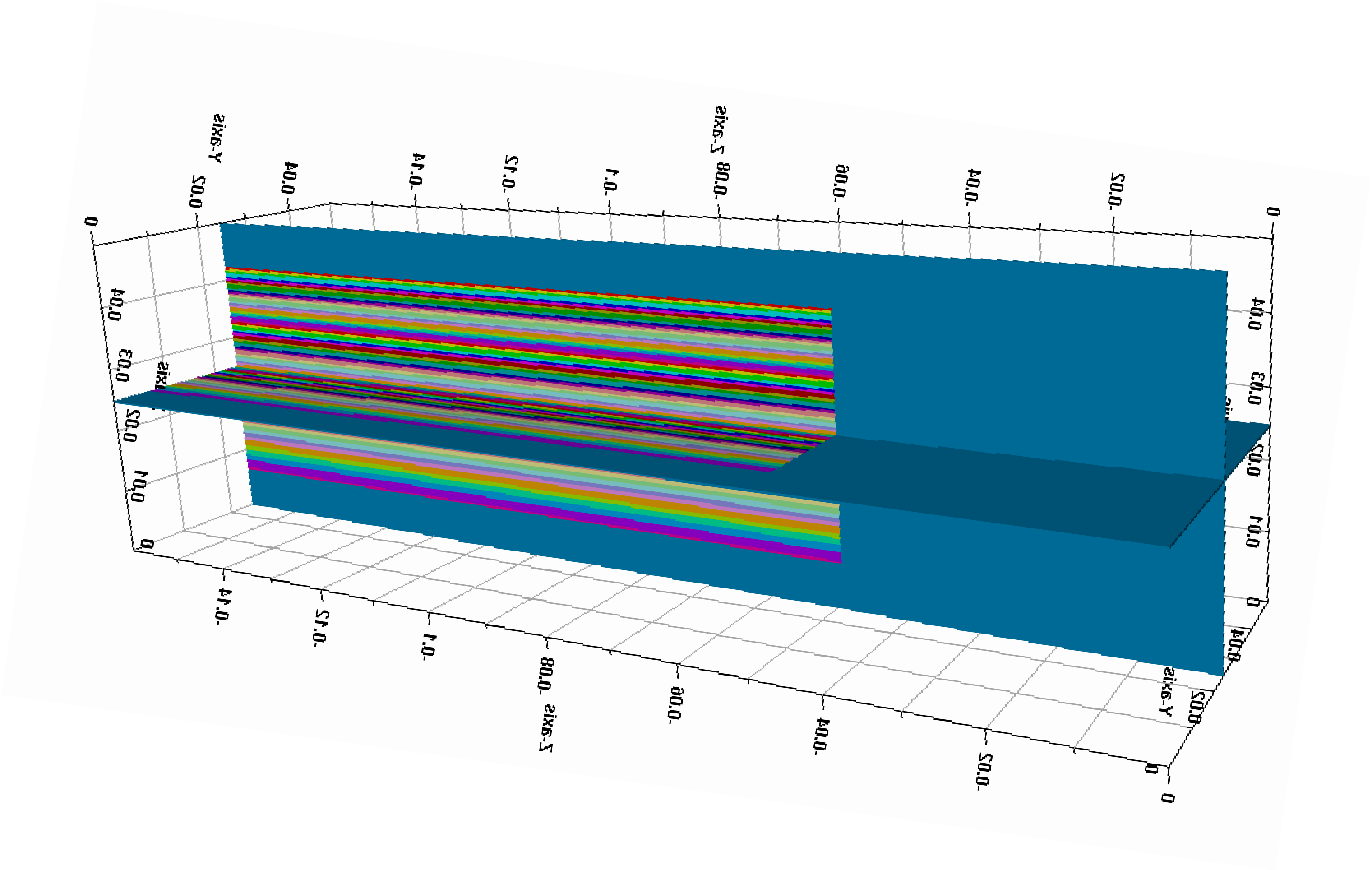
Facies	N	$Median_{2\text{-hr}}$	$Median_{5\text{-hr}}$	$Median_{7\text{-hr}}$	$Median_{\theta 3}$
MB5	3	0.436	0.700	0.792	0.268
MB4	7	0.531	0.776	0.871	0.399
MB3	9	0.489	0.783	0.885	0.331
MB2	3	0.320	0.695	0.808	0.269
MB1	2	0.449	0.720	0.833	0.296
p-value		0.363	0.129	0.159	0.282

Small sample sizes for different facies makes it challenging to assess "statistical significance."

Facies	N	$Median_{2\text{-hr}}$	$Median_{5\text{-hr}}$	$Median_{7\text{-hr}}$	$Median_{\theta 3}$
MB5/1	5	0.449	0.720	0.833	0.296
MB4/3/2	19	0.489	0.770	0.871	0.331
p-value		0.271	0.070	0.082	0.126

PLUG-SCALE MODELING AND SIMULATION



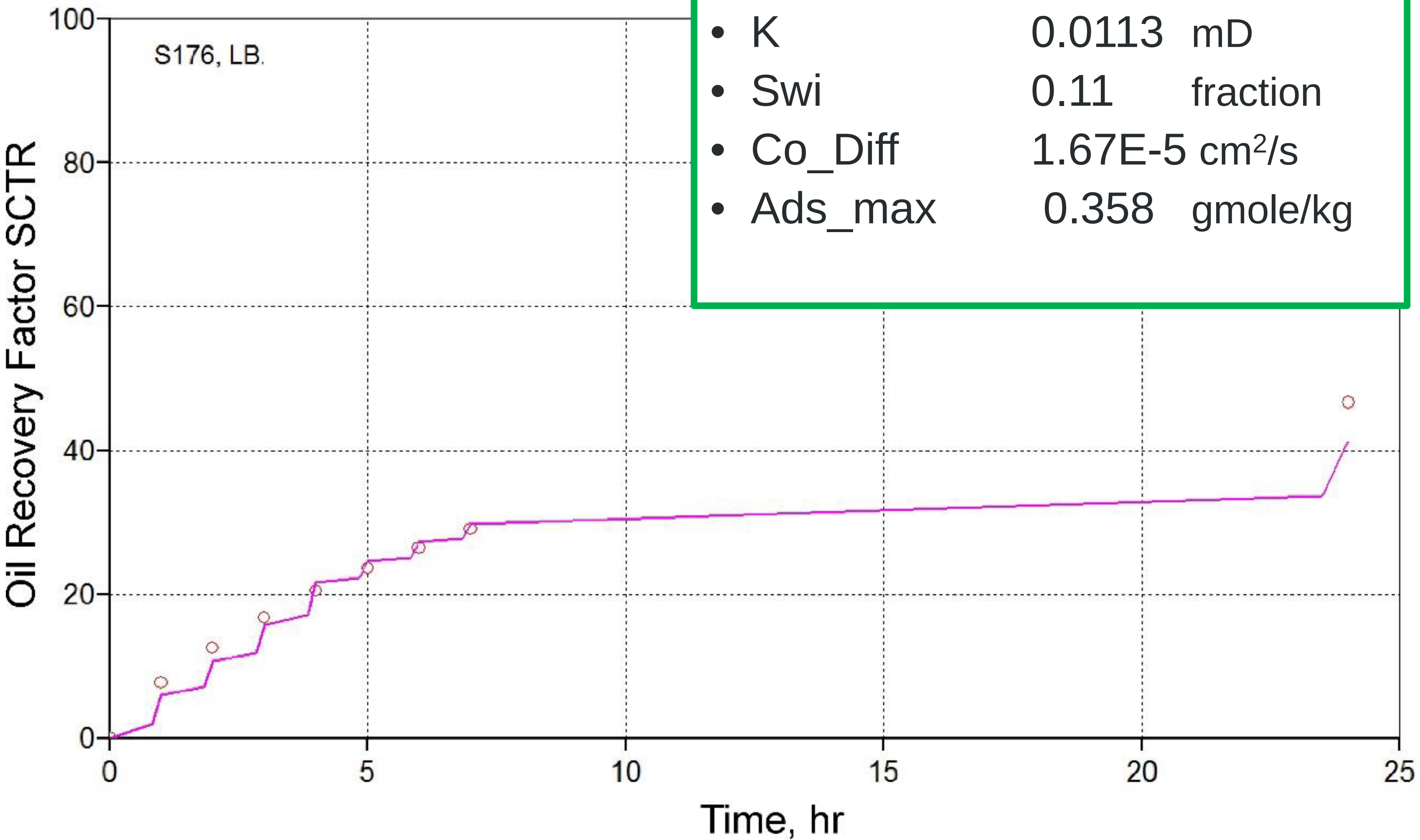


PLUG-SCALE MODELING OF OIL EXTRACTION IN LOWER BAKKEN SHALE

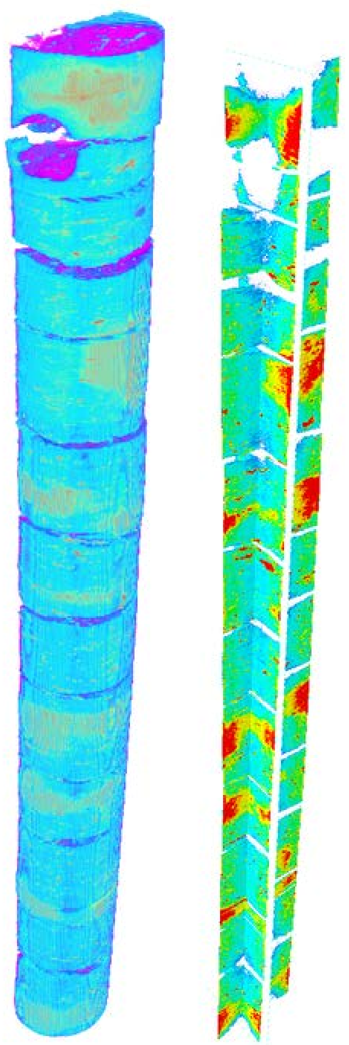
Parameter	LB	Unit
• BHP	34.44	MPa
• ϕ	0.0611	fraction
• K	0.0113	mD
• Swi	0.11	fraction
• Co_Diff	1.67E-5	cm^2/s
• Ads_max	0.358	gmole/kg

Modeling appears to underpredict both rate of oil extraction and total amount of oil recovered:

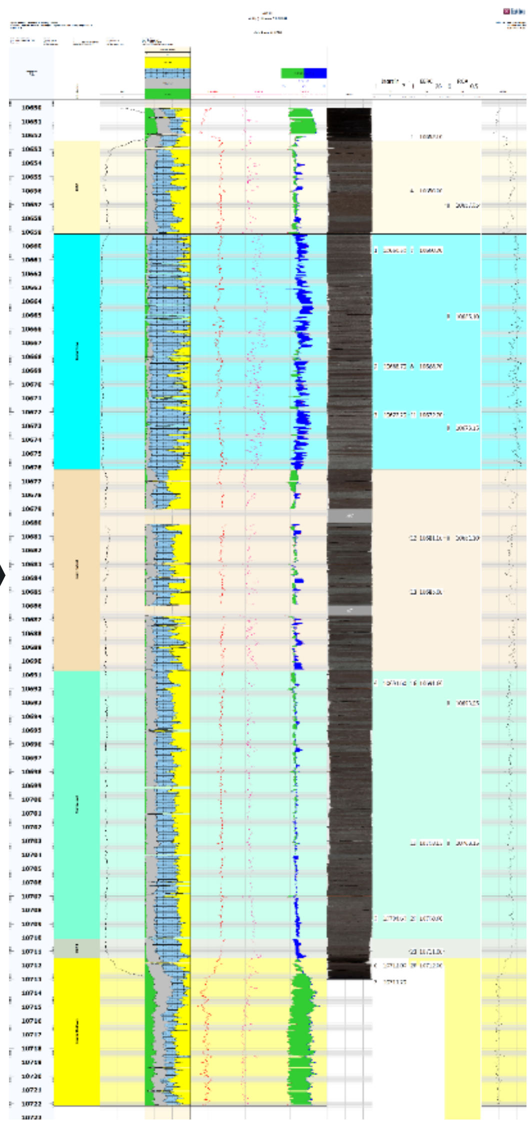
- Model may not account for the connected nature of the porosity, as observed in FIB–SEM.
- While porosity is low, the relatively high connectivity of that porosity may account for the higher CO_2 permeation and oil mobility observed in the lab.



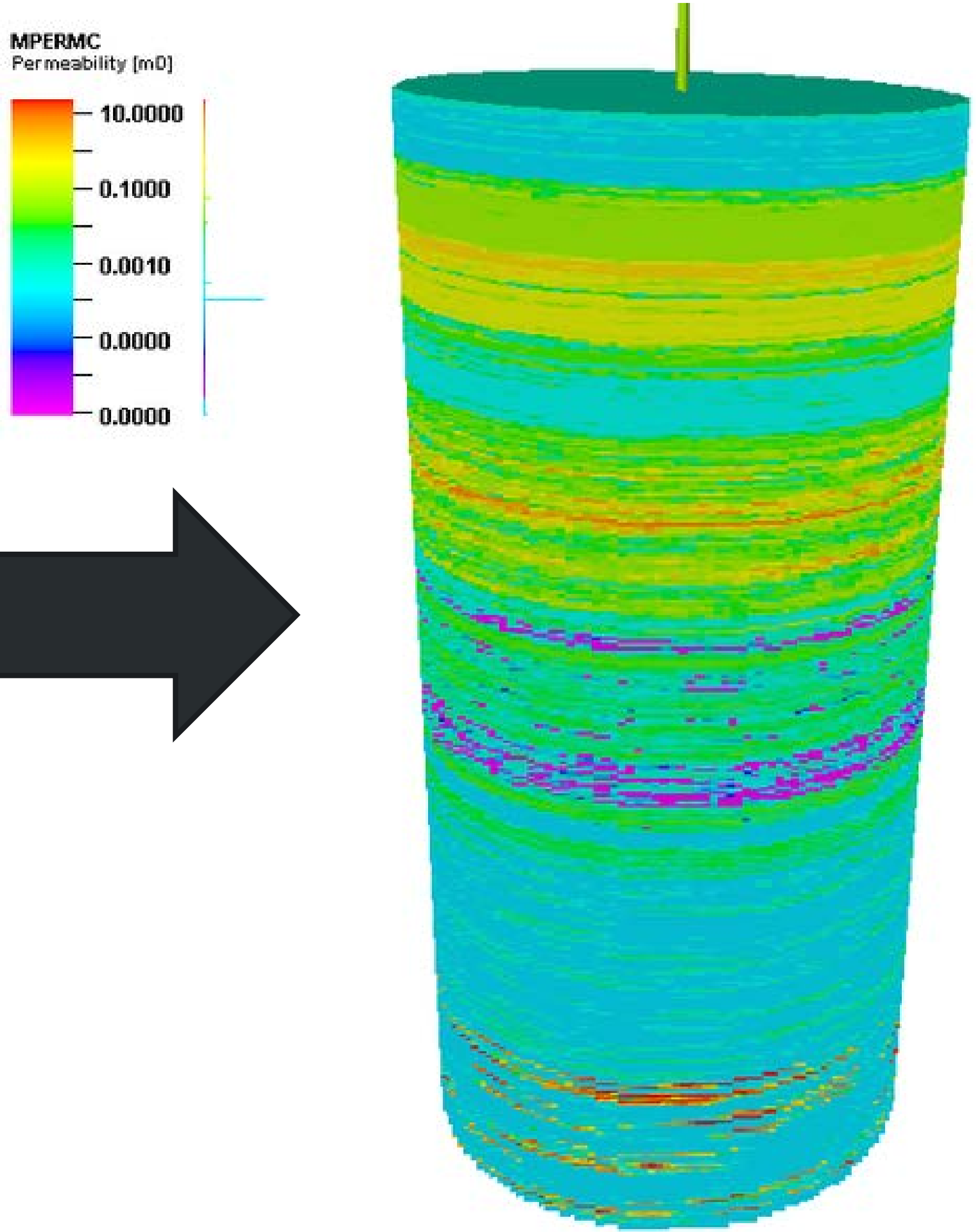
Core CT Processed for Porosity–Permeability



Log Data and MMPA

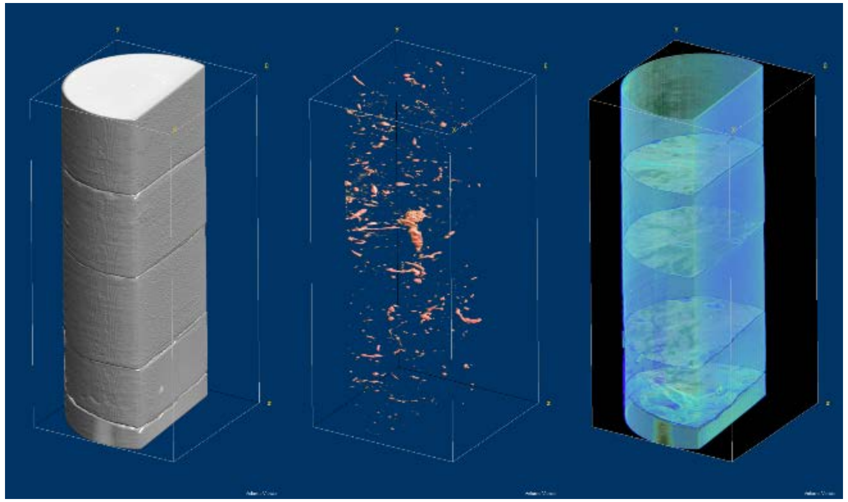


Near-Wellbore Perm. Model

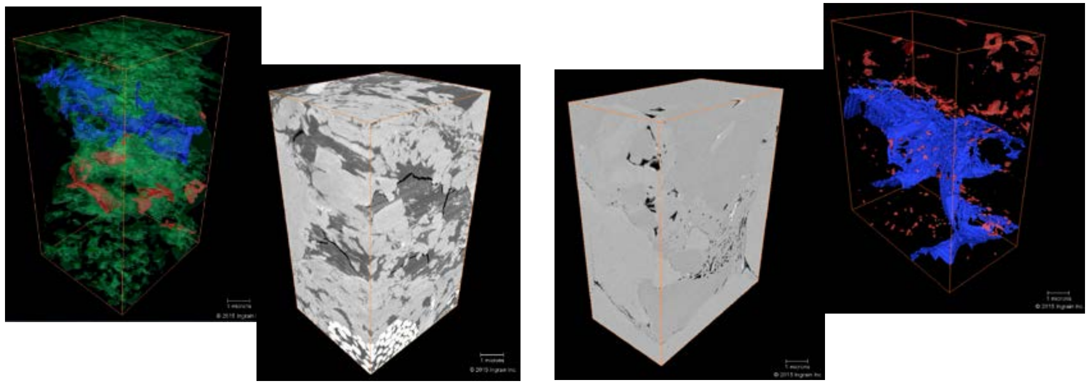


ACCOMPLISHMENTS TO DATE

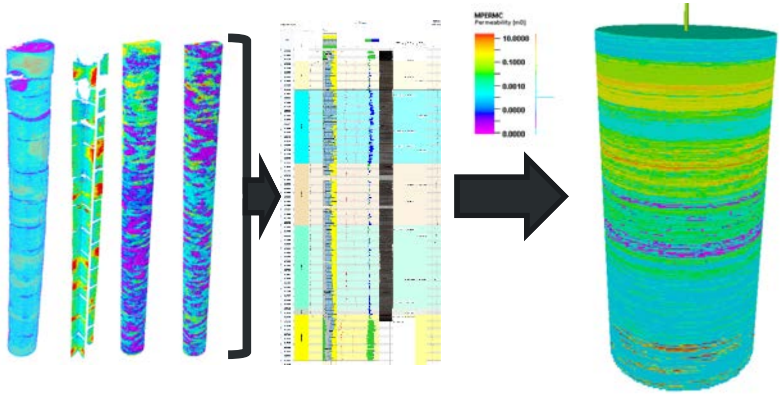
- CT scanning and micro-CT demonstrated to be useful tools for identifying macro- to microscale fractures.



- FIB-SEM and FESEM demonstrated to be useful for identifying micro- to nanoscale fractures and pore networks.

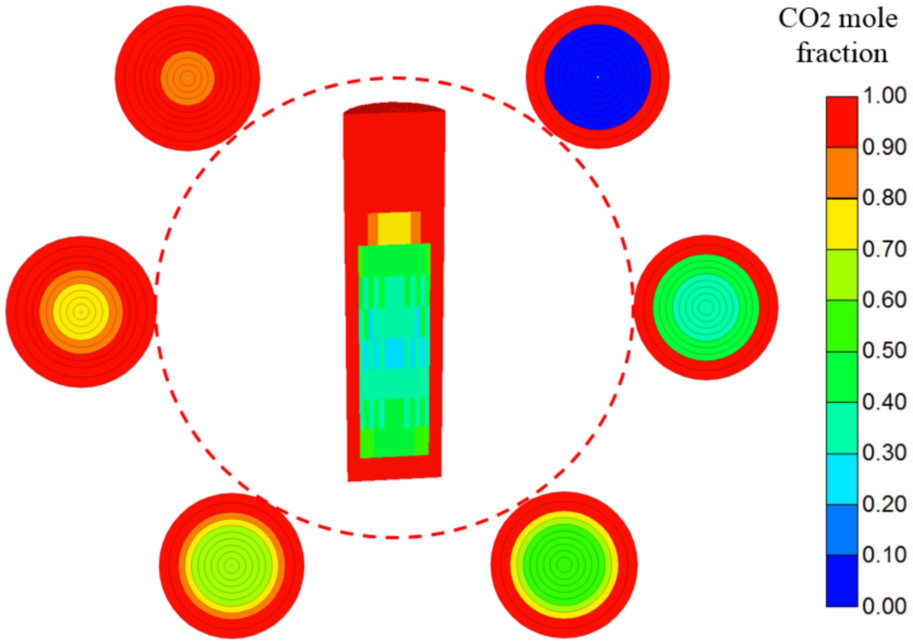


- Techniques for integrating images and data from advanced characterization technologies into geocellular models were developed.



ACCOMPLISHMENTS TO DATE

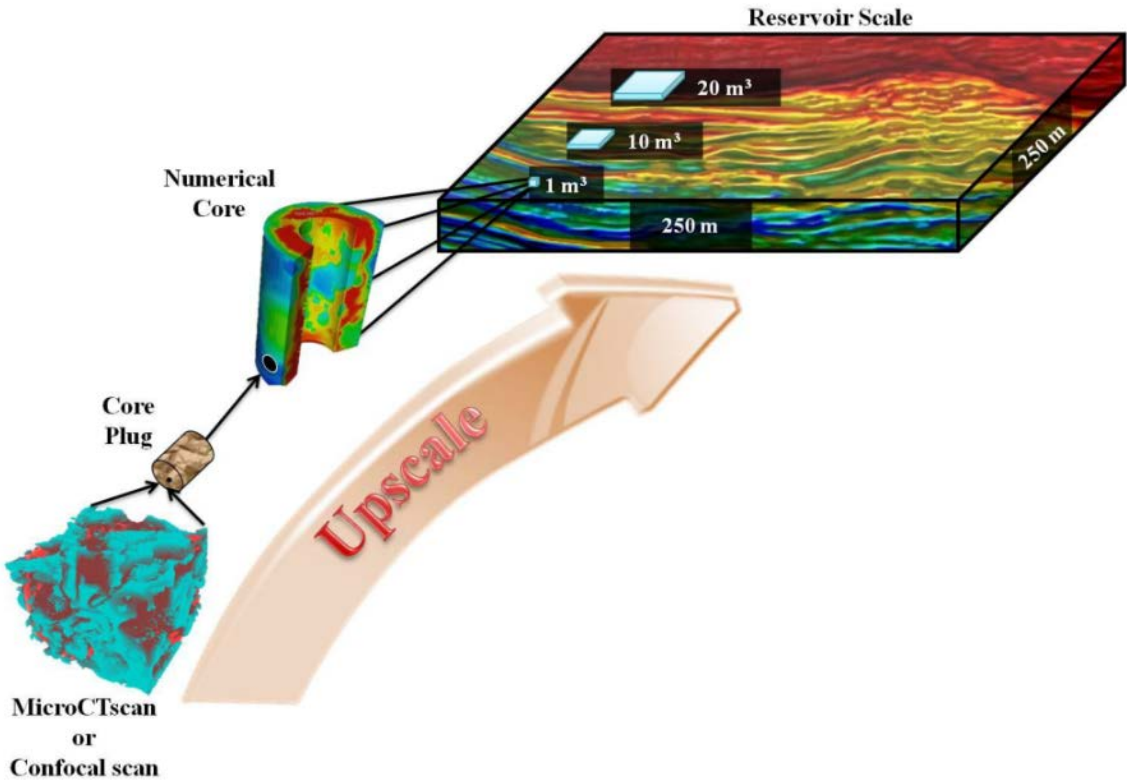
- Ability of CO_2 to permeate and mobilize oil in tight oil formations (shales and nonshales) at the core scale has been demonstrated and quantified.
- Initial statistical analysis indicates organic carbon content, mean pore throat radius, thermal maturity, are primary controlling parameters.
- Geocellular models of Bakken rocks at the core plug, core, near-wellbore, and reservoir scale have been constructed.
- Simulations of CO_2 permeation and hydrocarbon extraction have been conducted.



Core-Scale Model and Simulation

LESSONS LEARNED

- Research gaps/challenges:
  - Upscaling the advanced analytical and laboratory results from plugs to predict fluid behavior at the reservoir scale.



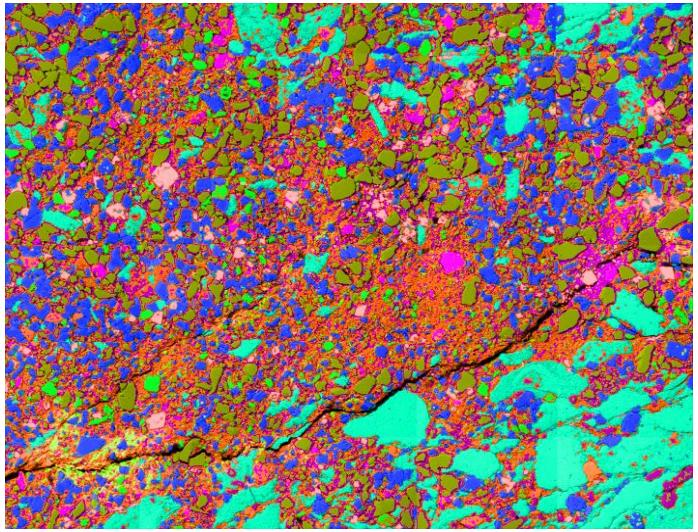
- Unanticipated research difficulties:
  - Limitations to testing methods for thermal maturity and wettability made it difficult to quantitatively address the effects of those parameters and compare results from different samples.

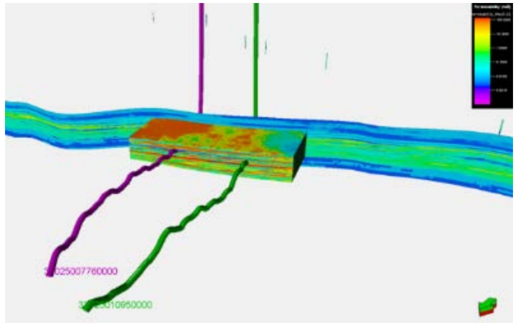
LESSONS LEARNED

- Technical disappointments
  - Even with great cooperation from partners, the number of rock samples is always limited and there is no such thing as a true duplicate when it comes to rocks, so statistical analysis is less robust than one would like.
  - Modeling and simulation are time-intensive, so the number of variables and scenarios that can be evaluated is limited.
- Changes that should be made next time
  - Focus modeling and simulation efforts on a single Middle Bakken lithofacies.

SYNERGY OPPORTUNITIES

- Methods and insights developed by this project can be directly applicable to projects in many North American tight oil formations.
  - Micro- and nanoscale analysis techniques.
  - Novel approaches to rock CO_2 permeation and hydrocarbon extraction studies.
  - Improved modeling workflows and enhancements to existing software packages.
  - Support the development of CO_2 storage estimation methodologies that are specific to organic-rich, oil-saturated shales.





PROJECT SUMMARY

- Key findings
  - Micro- and nanoscale porosity appear to be more highly connected than previously thought.
  - Micro- and nanoscale pore networks may have a greater role in fluid movement and behavior than previously thought.
  - Current modeling and simulation approaches do not adequately incorporate micro- and nanoscale rock characteristics and fluid behavior to accurately predict behavior in the lab.
- Next steps
  - Evaluate results and write final report.

ACKNOWLEDGMENT

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Disclaimer

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THANK YOU!

Critical Challenges. **Practical Solutions.**

APPENDIX

BENEFIT TO THE PROGRAM

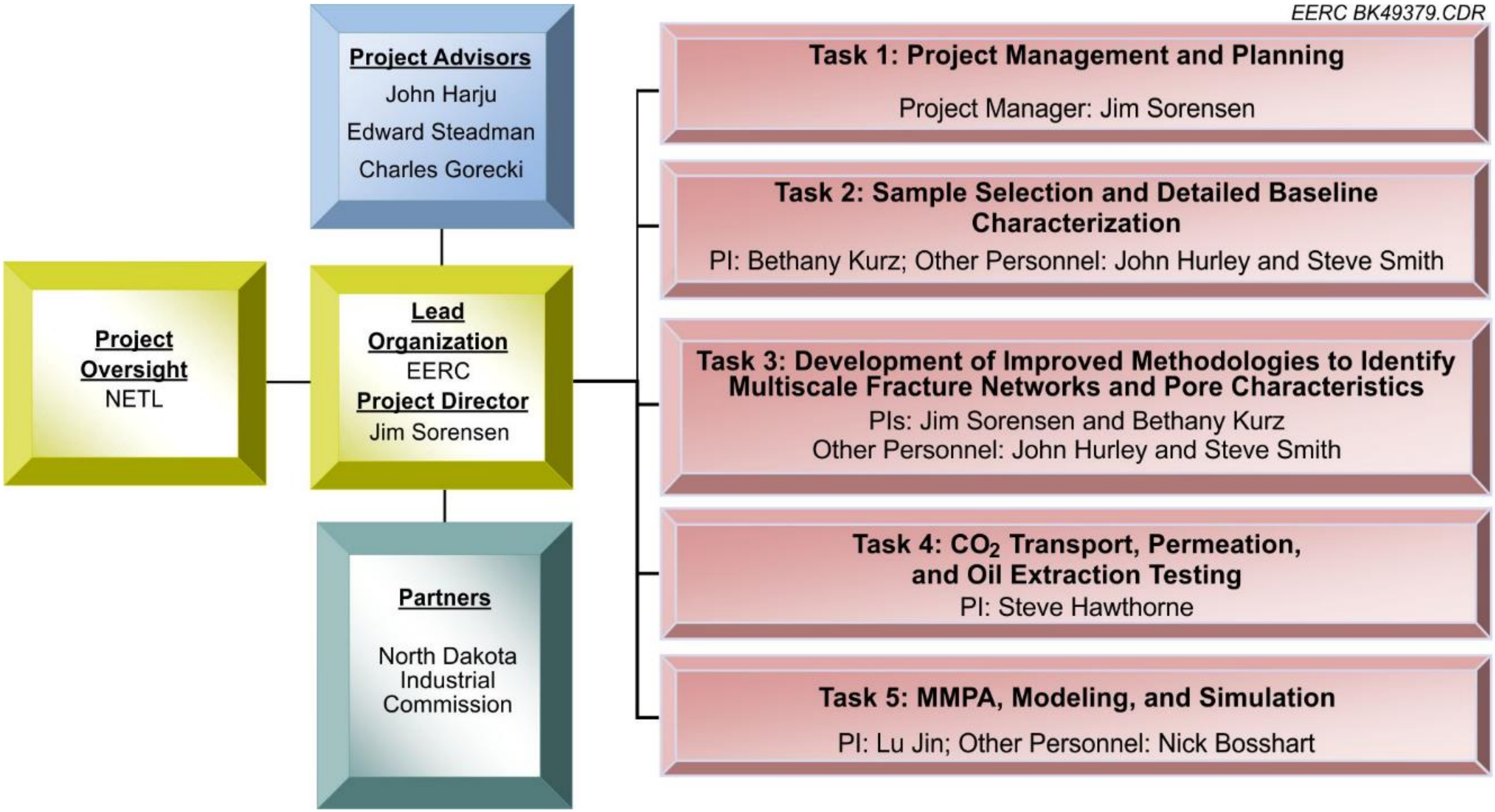
- Program goal being addressed:
  - Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
    - ♦ Characterize geologic settings in the United States that are "non-conventional CO_2-EOR targets that have the potential accept and store CO_2 while producing hydrocarbon resources.

- Project benefits statement:
  - The project is developing data that yields insight regarding mechanisms controlling CO_2 transport and fluid flow in fractured tight oil reservoirs of the Bakken, and the roles that organic rich, oil wet shales may play with respect to CO_2 storage, containment, EOR, or possibly all three. This information will serve as the basis for developing an improved approach to estimating the suitability and storage capacity of unconventional tight oil formations for CO_2 storage and EOR. This effort supports industry's ability to predict CO_2 storage capacity in geologic formations within ±30 percent.

PROJECT OVERVIEW – GOALS AND OBJECTIVES

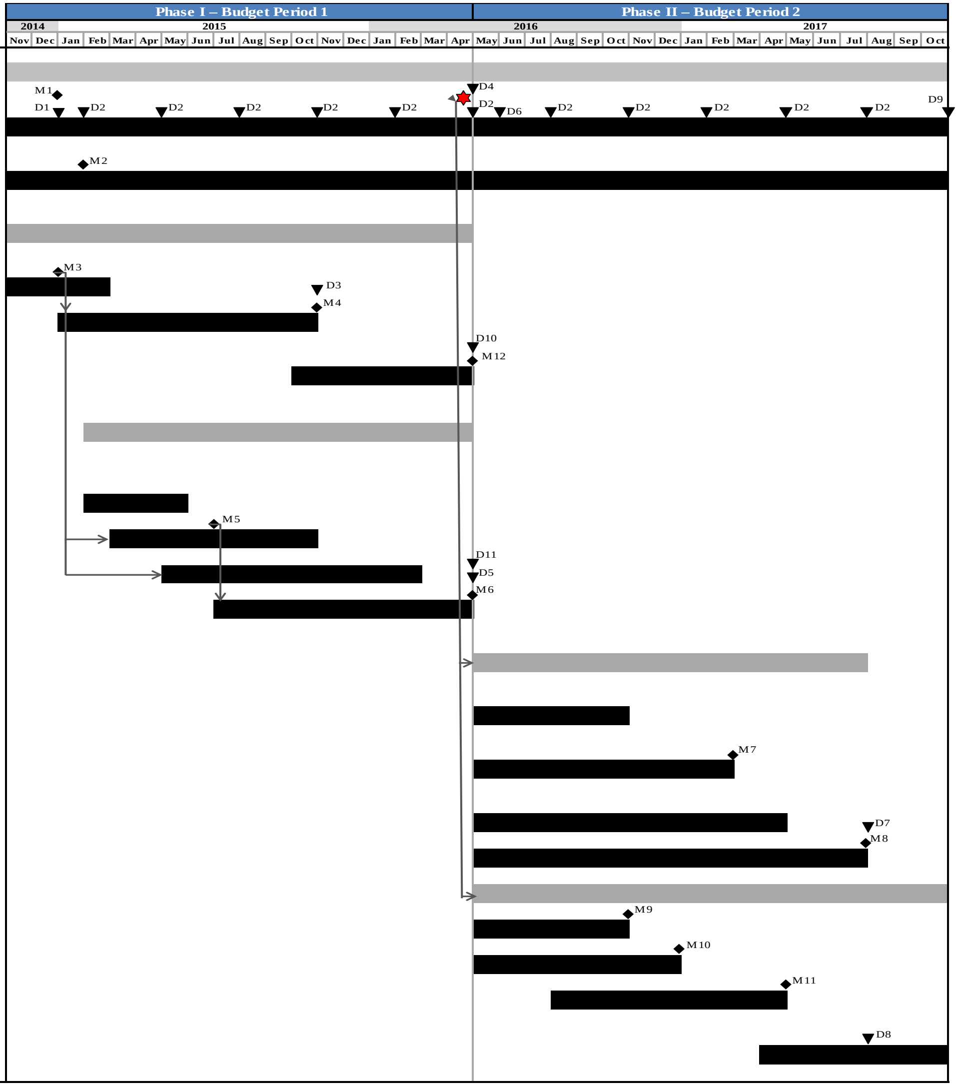
- Goals:
  - Better assess and validate CO_2 transport and fluid flow in fractured tight oil reservoirs of the Bakken.
  - Illuminate the roles that organic rich, oil wet shales may play with respect to CO_2 storage, containment, EOR, or possibly all three.
  - These goals relate to the Program goals in that:
    - ♦ Tight oil and gas plays are found throughout North America.
    - ♦ Methods and insights gained in this project can be applied to many, if not all, of these formations.
    - ♦ Understanding the movement of CO_2 within and/or through these tight formations is critical to understanding their roles in carbon capture and storage (CCS) (sinks or seals?).
    - ♦ Supports industry's ability to predict CO_2 storage capacity in geologic formations within ± 30%.
- Success criteria
  - Collection and analysis of relevant rock samples.
  - Successful identification and characterization of pore and fracture networks at micro- and nanoscales.
  - Measurement of CO_2 permeation rates in Bakken fractured reservoir and shale rocks.
  - Completion of petrophysical analysis using project generated characterization data and existing well logs.
  - Creation of static geocellular models at multiple scales.
  - Completion of dynamic simulations.

ORGANIZATION CHART



GANTT CHART

	Start Date	End Date
Task 1 – Project Management and Planning	**11/1/2014**	**10/31/2017**
1.1 – Reporting Requirements	11/1/2014	10/31/2017
1.2 – Information Dissemination and Input from Stakeholders	11/1/2014	10/31/2017
Task 2 – Sample Selection and Detailed Baseline Characterization	**11/1/2014**	**4/30/2016**
2.1 – Sample Identification and Selection	11/1/2014	2/28/2015
2.2 – Laboratory Determination of Baseline Rock Properties	1/1/2015	10/31/2015
2.3 – Laboratory Evaluation of the Effects of CO_2 on Kerogen and Bitumen in Bakken Shale	10/1/2015	4/30/2016
Task 3 – Development of Improved Methodologies to Identify Multiscale Fracture Networks and Pore Characteristics	**2/1/2015**	**4/30/2016**
3.1 – Core-Scale Fracture Analysis	2/1/2015	5/31/2015
3.2 – Macrofracture Characterization	3/1/2015	10/31/2015
3.3 – Micro- and Nanoscale Fracture and Pore Analysis	5/1/2015	2/29/2016
3.4 – Development of Multiscale Pore and Fracture Models	7/1/2015	4/30/2016
Task 4 – CO_2 Transport, Permeation, and Oil Extraction Testing	**5/1/016**	**7/31/2017**
4.1 – Determination of Permeation Rates in Tight, Fractured Reservoir Rocks	5/1/2016	10/31/2016
4.2 – Determination of CO_2 Permeation Rates in Organic-Rich Shale Rocks	5/1/2016	2/28/2017
4.3 – CO_2-Soluble Tracers	5/1/2016	4/30/2017
4.4 – Hydrocarbon Extraction	5/1/2016	7/31/2017
Task 5 – MMPA, Modeling, and Simulation	**5/1/2016**	**10/31/2017**
5.1 – MMPA Analysis	5/1/2016	10/31/2016
5.2 – Geocellular Modeling	6/1/2016	12/31/2016
5.3 – Dynamic Simulation of Tight Oil Formation Reservoirs and Shales	8/1/2016	4/30/2017
5.4 – Best Practices Manual for CO_2 Storage and EOR Potential Estimation of Tight Oil Formations	4/1/2017	10/31/2017



Summary Task	
Activity Bar	
Milestone (M) ◆	Critical Path
Deliverable (D) ▼	Decision Point

Key for Deliverables (D) ▼	Key for Milestones (M) ◆
D1 – Updated Project Management Plan (PMP)	M1 – Updated Project Management Plan Submitted to DOE
D2 – Quarterly Progress Report	M2 – Project Kickoff Meeting Held
D3 – Sample Characterization Data Sheets	M3 – First Samples Collected for Characterization
D4 – Project Fact Sheet Information	M4 – Completion of Baseline Sample Characterization
D5 – Manuscript – Use of Advanced Analytical Techniques to Identify and Characterize Multiscale Fracture Networks in Tight Oil Formations	M5 – First Macroscale Fracture Data Sets Generated
D6 – Phase I Interim Report	M6 – Completion of Fracture Network Characterization
D7 – Manuscript – Laboratory-Measured CO_2 Permeation and Oil Extraction Rates in Tight Oil Formations	M7 – Completion of CO_2 Permeation Testing
D8 – Best Practices Manual – Estimation of CO_2 Storage Resource of Fractured Reservoirs	M8 – Completion of Hydrocarbon Extraction Testing
D9 – Final Report	M9 – MMPA Analysis Completed
D10 – Manuscript – Effects of Kerogen-bitumen content on CO_2 Storage and EOR in Tight Oil Formations	M10 – Completion of Geocellular Models
D11 – Manuscript – Development and Application of Multiscale Pore and Fracture Models to CO_2 Storage and EOR in Tight Oil Formations	M11 – Completion of Simulations
	M12 – Completion of Kerogen and Bitumen Studies

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