# Bakken $CO_2$ Storage and Enhanced Recovery Program

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Energy & Environmental Research Center

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Transforming Technology through Integration and Collaboration

August 18–20, 2015

# Presentation Outline

- Background – What Is This “Bakken” You’ve Heard So Much About?
- Project Overview
- Key Lessons Learned
- Future Directions

# Bakken $CO_2$ Storage and Enhanced Recovery Program Sponsoring Partners

NETL

North Dakota oil & gas research program

Continental Resources

Marathon Oil

HESS

CMG Computer Modelling Group Ltd.

Baker Hughes

Kinder Morgan Inc.

XTO Energy

Schlumberger

# Other Supporters

NORTH DAKOTA
D
M
R
Department of Mineral Resources

NORTH DAKOTA GEOLOGICAL SURVEY
1895

NORTH DAKOTA
OIL AND GAS DIVISION

NORTH DAKOTA
PETROLEUM
COUNCIL

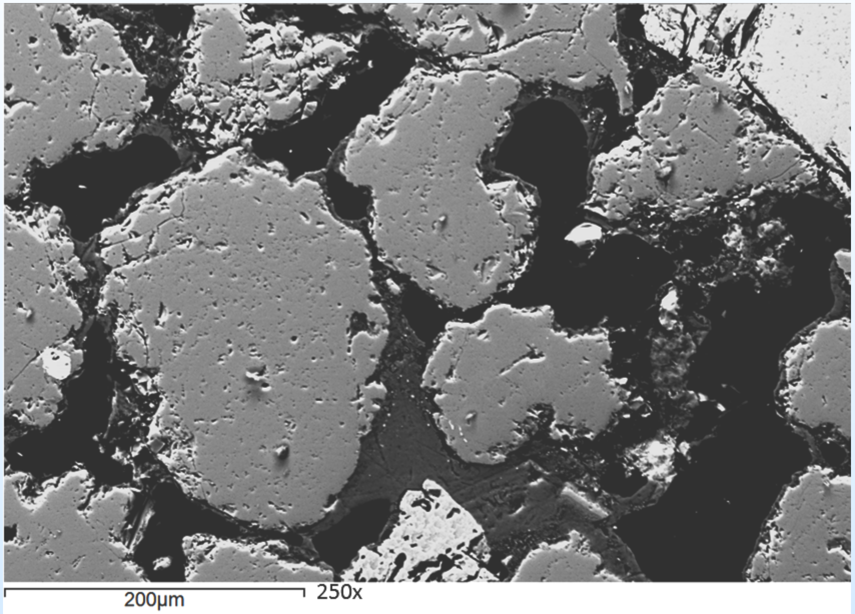
# What Is Tight Oil?

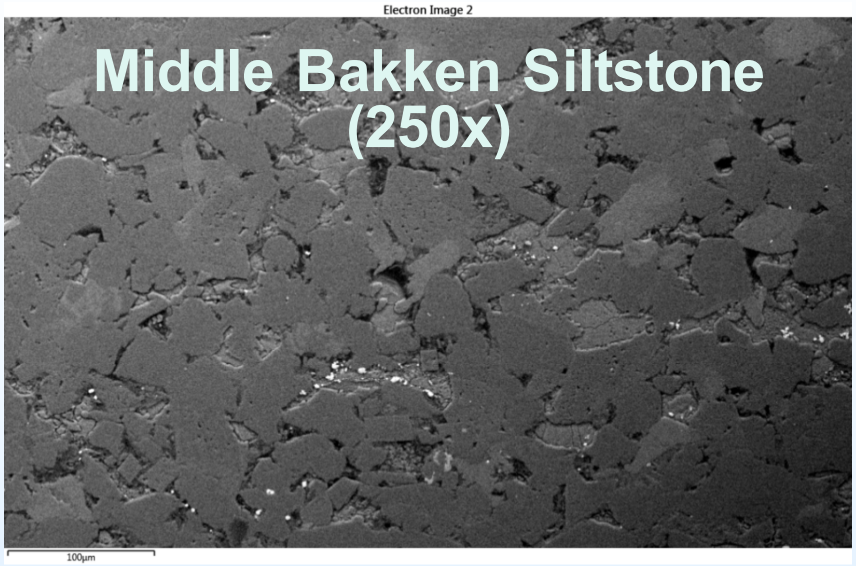
- Extremely low permeability (<0.1 mD) reservoir rock, which impedes the ability of the oil in the formation to flow freely.
- Tight oil formations are associated with organic-rich shale.
- Some produce directly from shales, but much tight oil production is from low-permeability siltstones, sandstones, and carbonates that are closely associated with oil-rich shale.
- Fluid flow is dominated by natural and artificially induced fractures.

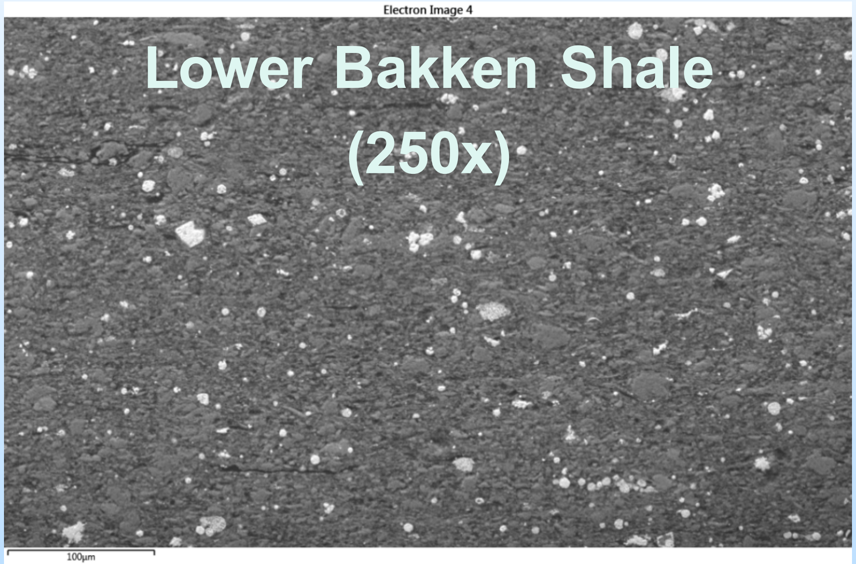

Core from Bakken Middle Member

# Conventional vs. Tight Oil Reservoir

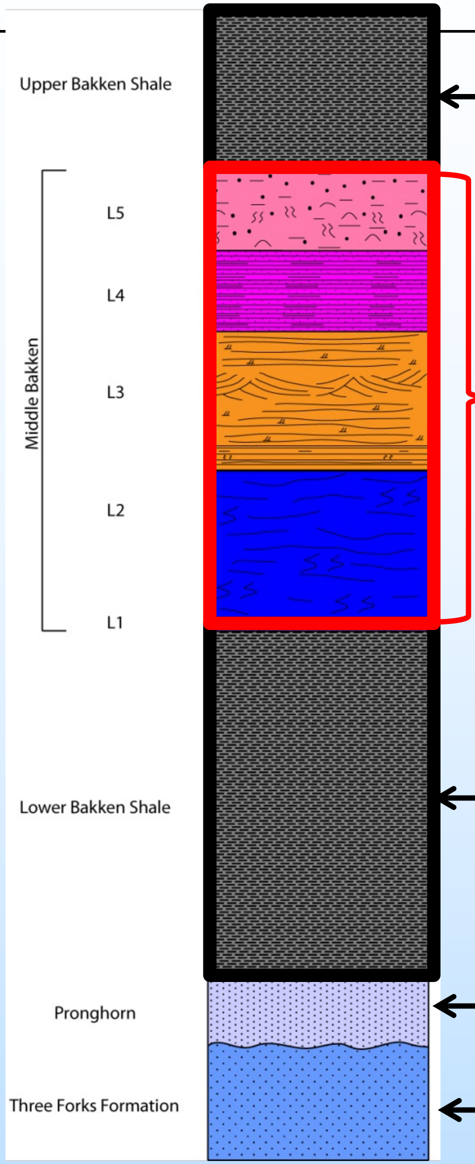
**Muddy Fm Sandstone (Bell Creek) (250x)**



# Bakken Petroleum System Lithology




**Upper Bakken Shale:** Brown to black, organic-rich.

- **Bakken source rock**

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

- **Bakken tight reservoir rock (horizontal drilling target)**

**Lower Bakken Shale:** Brown to black, organic-rich.

- **Bakken source rock**

**Pronghorn Member:** Mixed sandstone, siltstone, dolomite, and shale.

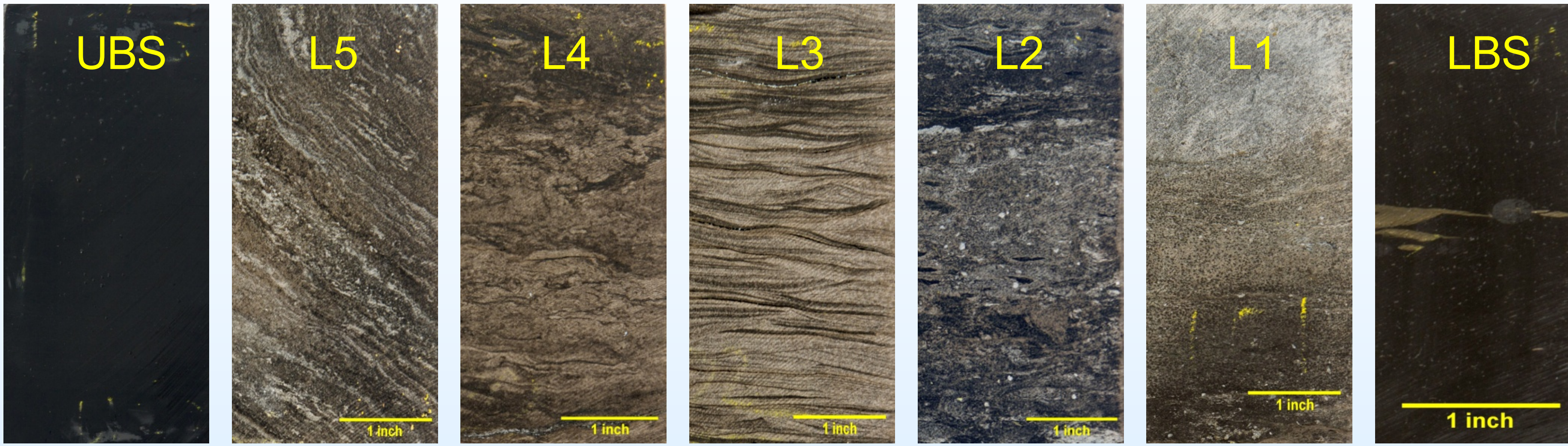
**Three Forks Formation:** Interbedded dolostone/limestone, siltstone/mudstone, shale, and evaporites.

# The Rocks Within the System Are Complex

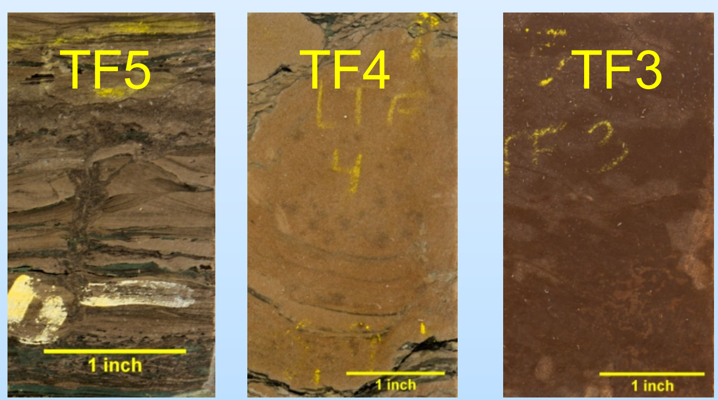
Upper Shale

Middle Bakken Lithofacies

Lower Shale

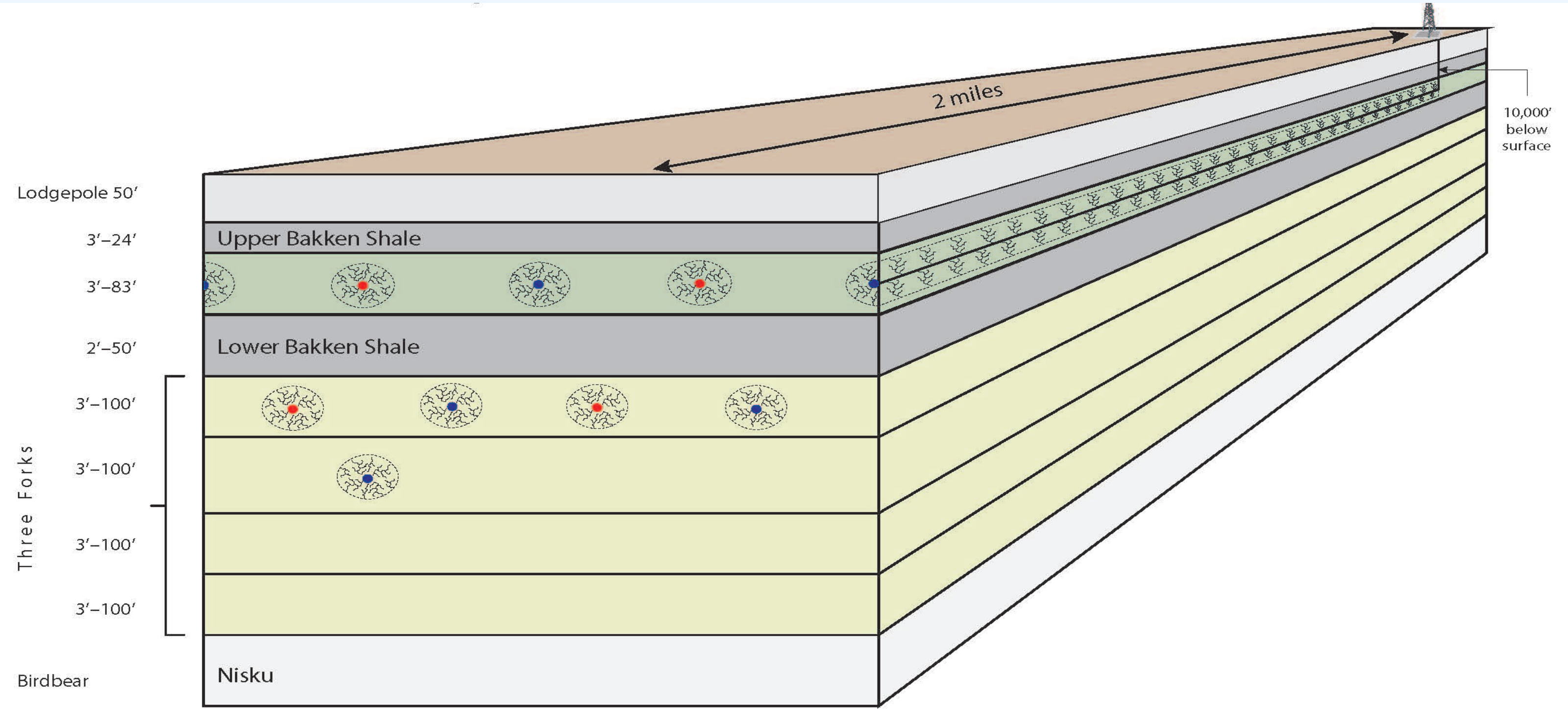



Three Forks Lithofacies



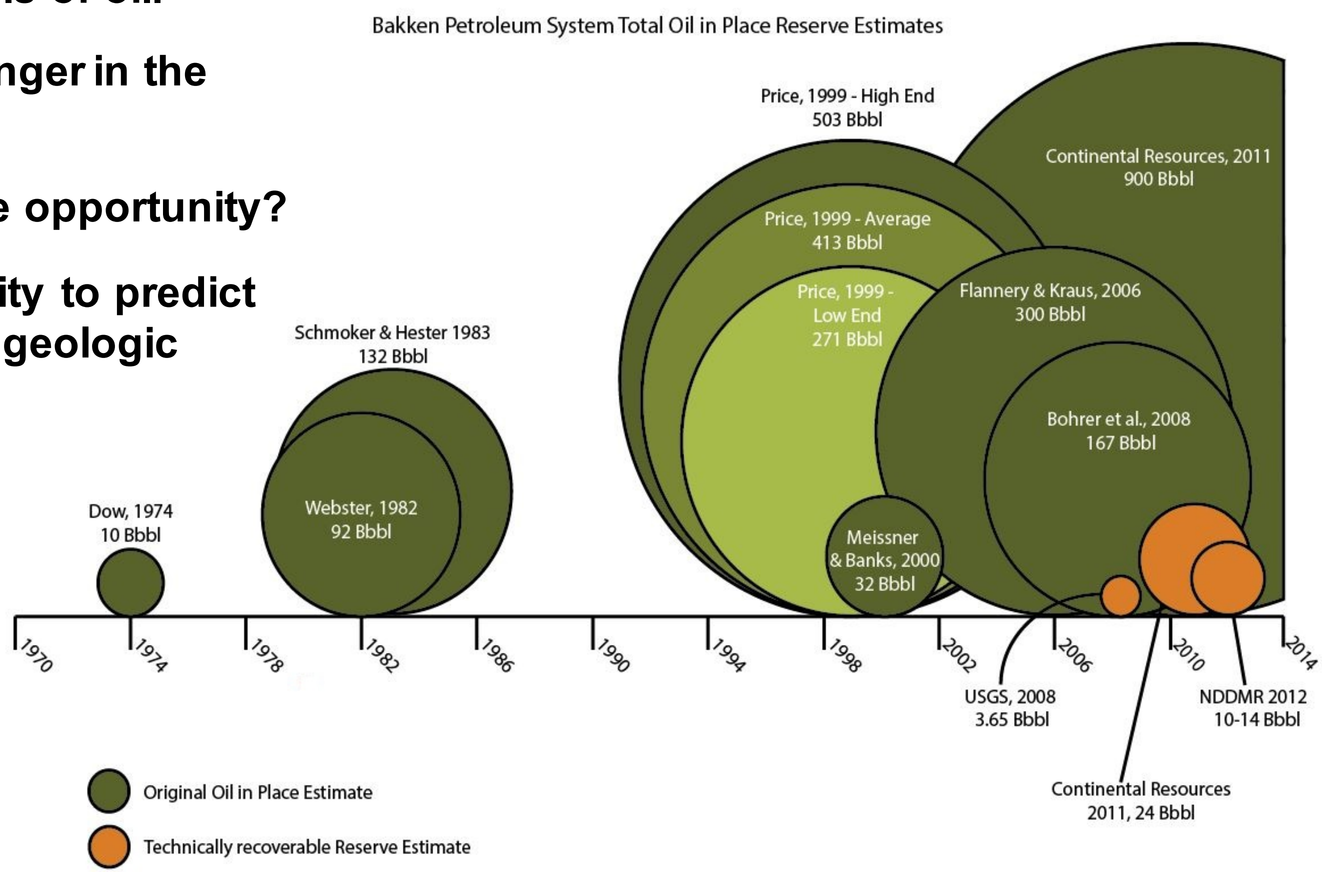
# Bakken and Three Forks Production

- **Production (April 2015)**
  - 9570 wells in North Dakota.
  - Over **1.1 million bbl/day** of oil.
  - Over **1.5 Bcf/day** of gas.
  - Horizontal wells and hydraulic fracturing enable prolific production.



# Benefit to the Program: Size of the Bakken Oil Resource

- **Currently, only a 3%–10% recovery factor.**
- **Small improvements in recovery could yield over a billion barrels of oil.**
- **Can $CO_2$ be a game changer in the Bakken?**
- **If so, what is the storage opportunity?**
- **Supports industry's ability to predict $CO_2$ storage capacity in geologic formations within ±30%.**



# Estimation of Bakken $CO_2$ Storage Capacity and EOR Potential

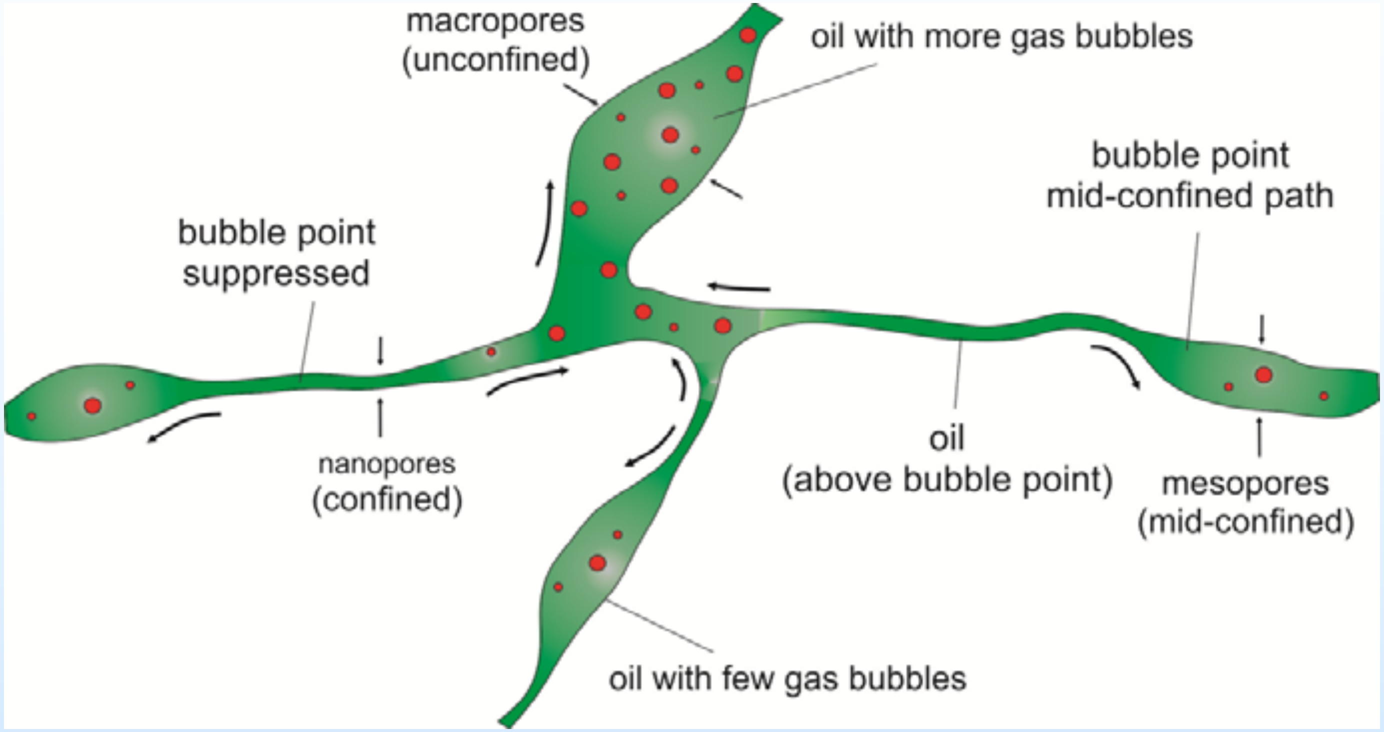
The U.S. Department of Energy (DOE) methodology for estimating $CO_2$ enhanced oil recovery (EOR) and storage capacity (2007) was applied to the Bakken in North Dakota:

- The approach that uses cumulative production/estimated recovery factor to calculate original oil in place (OOIP) yields a storage capacity ranging from **121 to 194 million tons of $CO_2$**.
  - This could yield **420 to 670 million barrels** of incremental oil.
- The reservoir properties approach to calculate OOIP yields a storage capacity ranging from **1.9 to 3.2 billion tons of $CO_2$**.
  - This could yield **4 to 7 billion barrels** of incremental oil.

# Challenges of EOR in Tight Oil Formations

- Mobility and effectiveness of fluids through fractures relative to very low matrix permeability.
- How will clays react to $CO_2$?
- The role of wettability (oil-wet and mixed-wet) with respect to $CO_2$ in tight oil reservoirs is not well understood.
- High vertical heterogeneity of the lithofacies complicates our understanding of flow regimes (fractures and matrix).
- Multiphase fluid flow behavior varies substantially depending on the size of the pore throats.
- Fluid viscosity and density are much different in nanoscale pores than in macroscale pores.
- How does the sorptive capacity of the organic carbon materials affect $CO_2$ mobility, 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.

# Elements of the Program

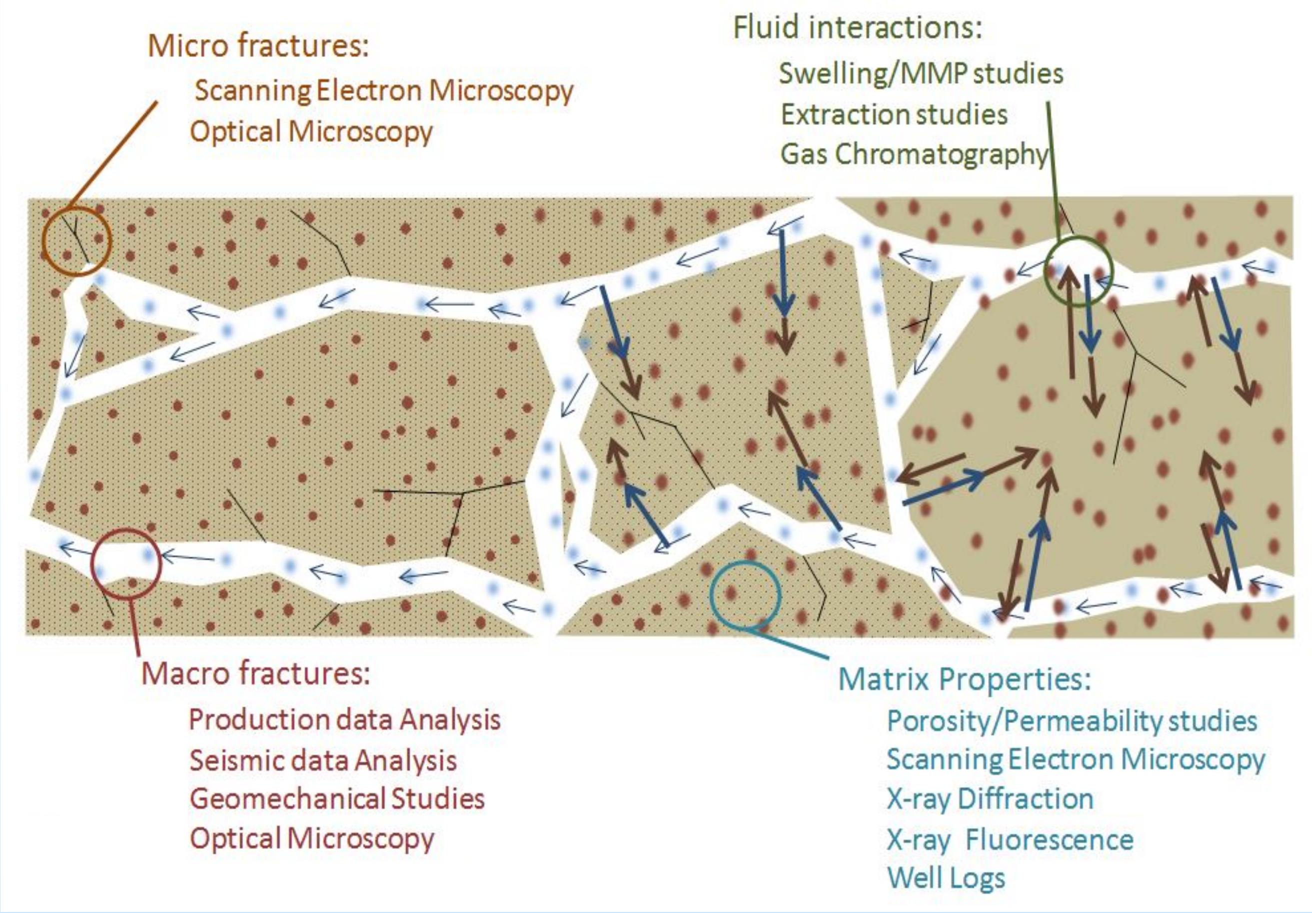
**Laboratory work to evaluate:**

- **Rock matrix.**
- **Nature of fractures.**
- **Effects of $CO_2$ on oil.**
- **Ability of $CO_2$ to remove oil from rock.**

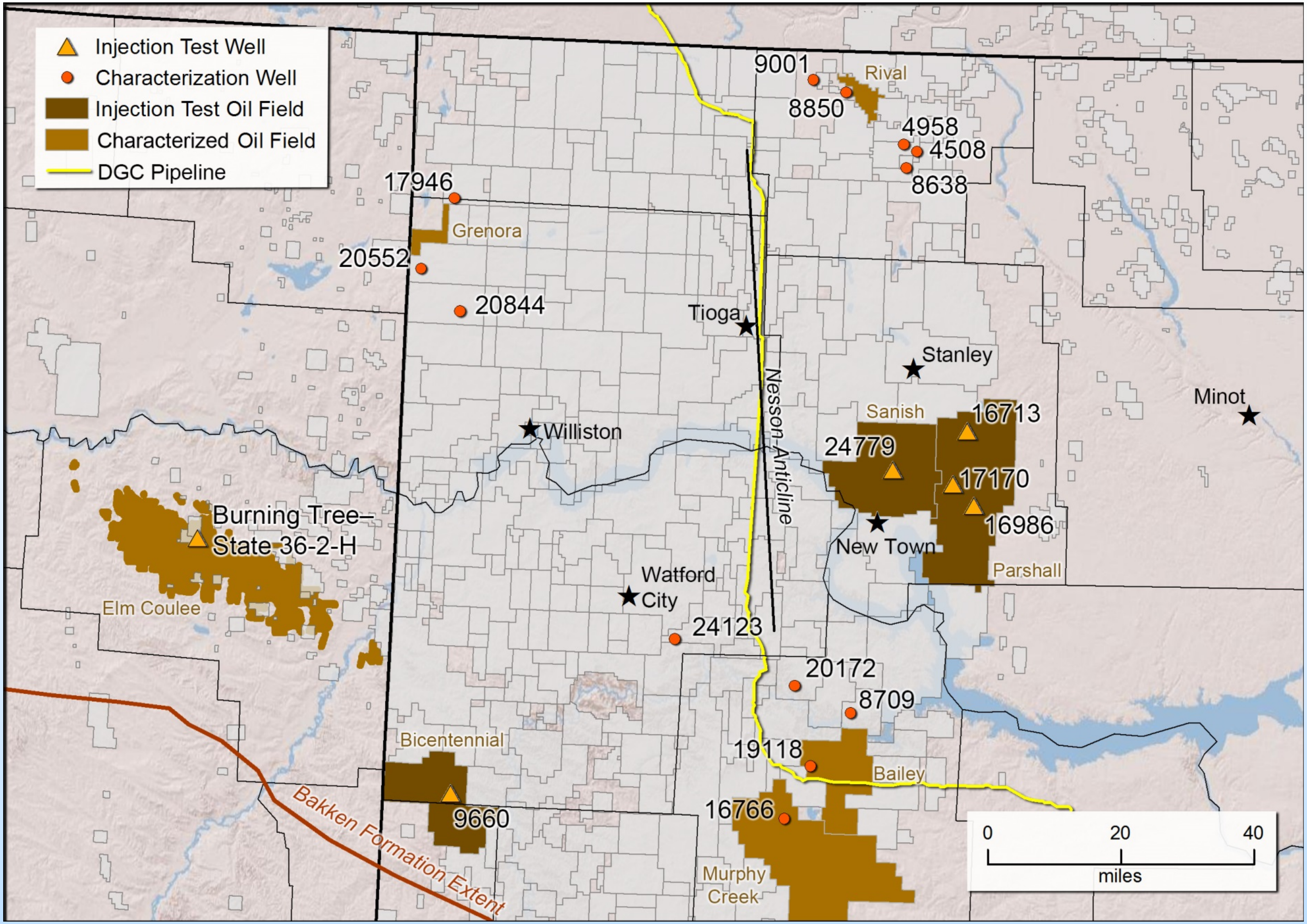
**Static and dynamic modeling.**

**Case study of a $CO_2$ huff 'n' puff (HnP) test in Montana.**

Phase I – 2012 to 2014
Phase II – 2014 to 2016

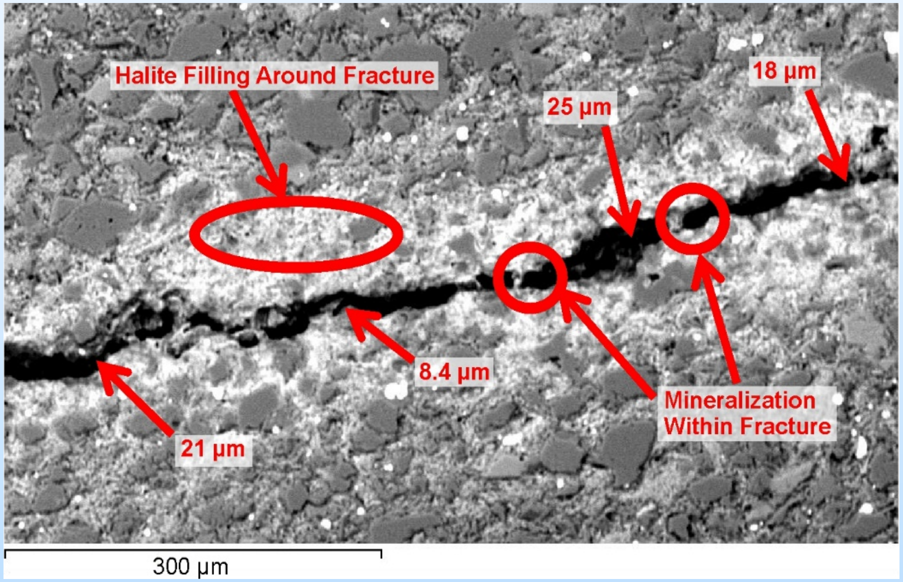


# Characterization Locations

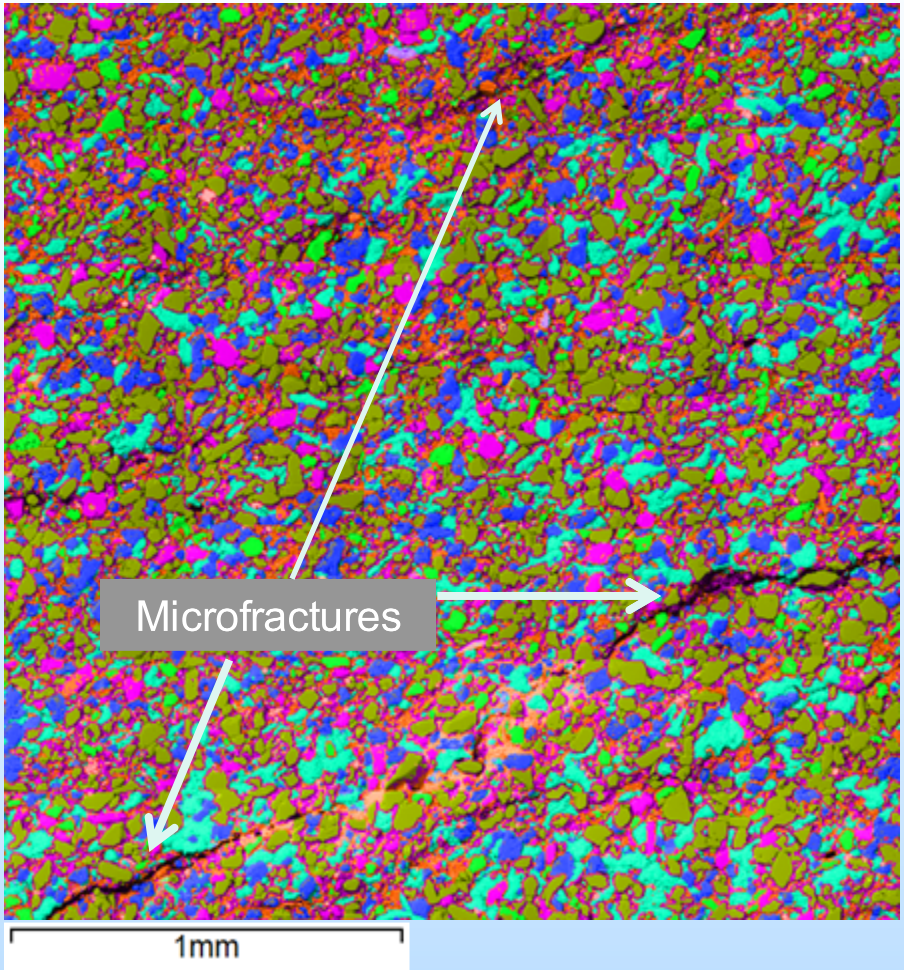


# Reservoir Characterization Key Lessons Learned

- Movement of fluids ($CO_2$ in and oil out) relies on fractures.
- Microfractures account for most of the porosity in the productive Bakken zones.
- Generating macrofracture and microfracture data and integrating those data into modeling are essential to develop effective EOR strategies.

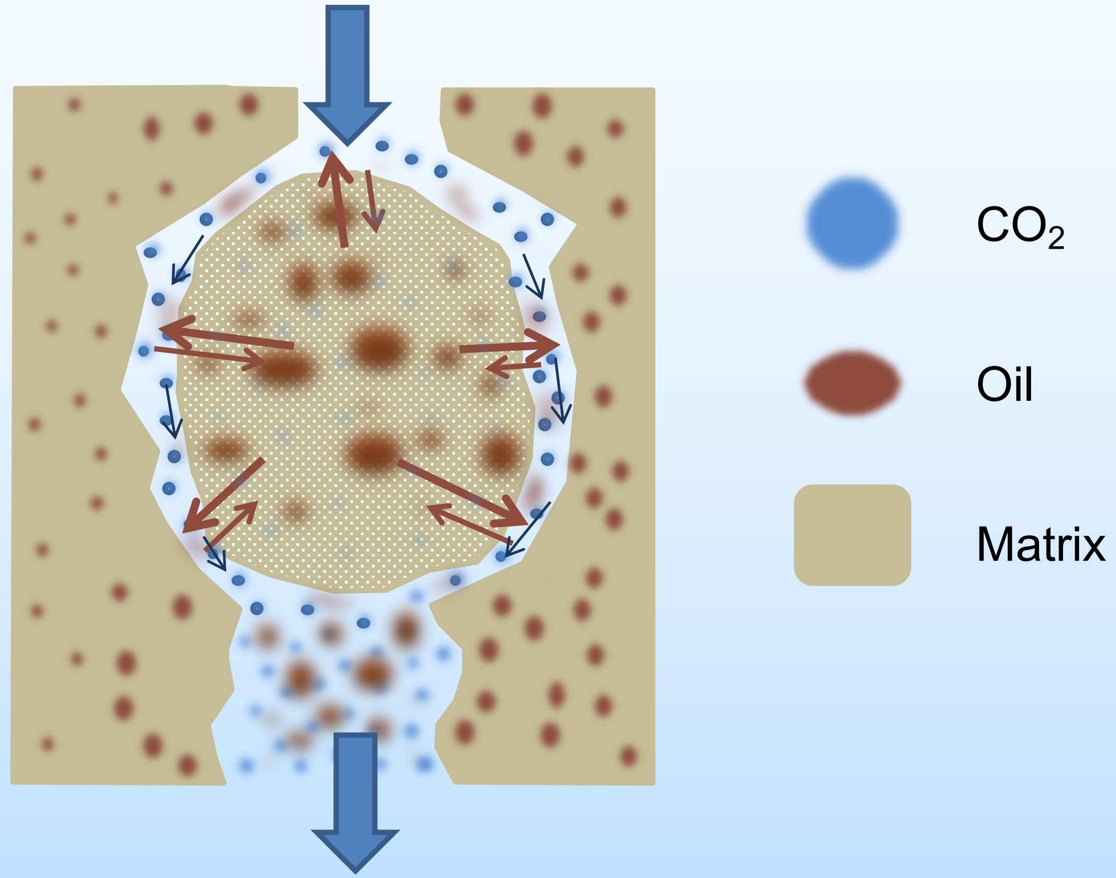



Scanning Electron Microscopy (SEM) Mineral Map of a Middle Bakken Sample (colors represent minerals; black represents porosity)



# $CO_2$ Interactions with Bakken Rocks and Oil

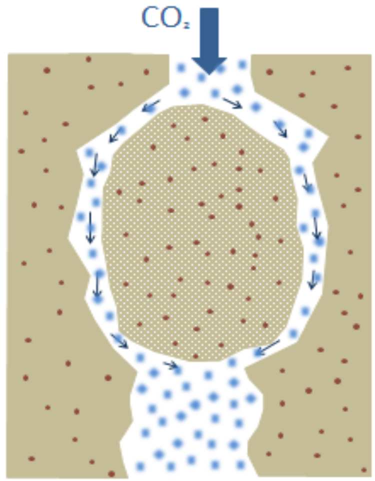
Laboratory Experiments to Examine the Ability of $CO_2$ to Extract Oil from Lower Bakken Shale and Middle Bakken Silty Packstone



# Lab-Scale Experiments
# $CO_2$ Extraction of Oil from Tight Rocks

***Step 1***

Initial injection: $CO_2$ flows rapidly through fractures.

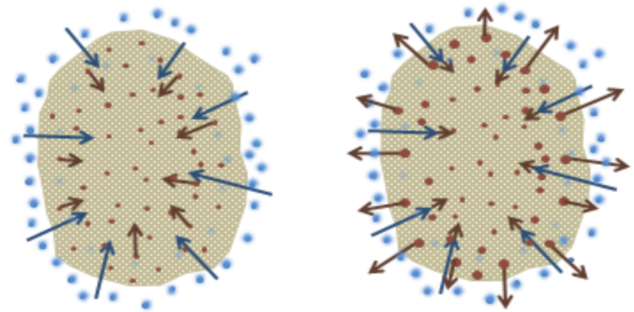



***Step 2:*** $CO_2$ starts to permeate rock based on pressure gradient.

$CO_2$ carries oil into the rock (bad).

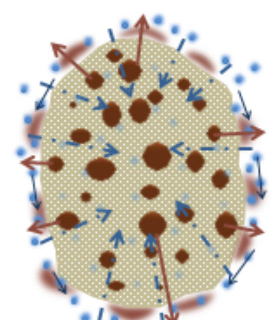
***and or***

$CO_2$ swelling pushes oil out of the rock (good).



***Step 3***

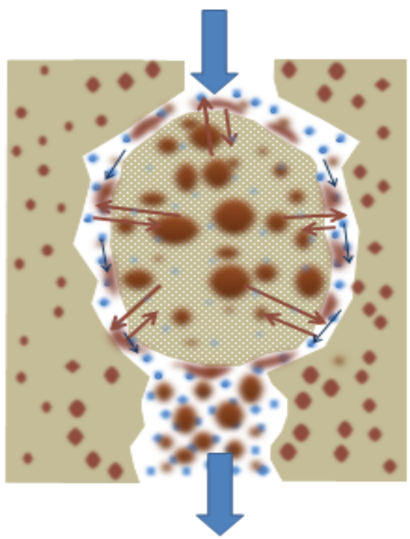
As $CO_2$ permeates into the rock, oil migrates to bulk $CO_2$ in fractures based on swelling and lower viscosity.



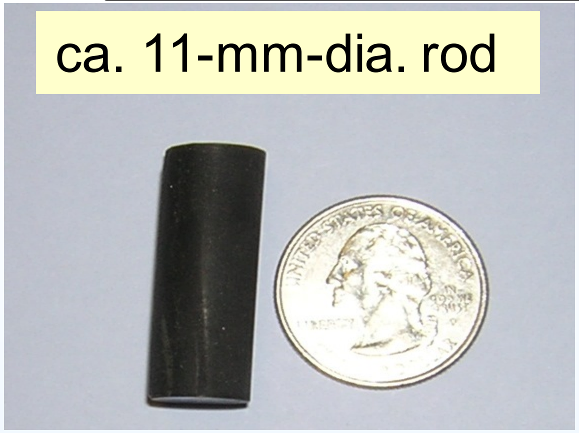
***Step 4***

$CO_2$ pressures equalize inside of rock.

- Oil production is now based only on concentration gradient driven diffusion.
- Oil in bulk $CO_2$ is swept through fractures to production well.



# $CO_2$ Extraction of Source and Reservoir Rock to Mimic Fracture-Dominated Flow Expected in Tight Systems




Laboratory Exposures Include:

>***VERY*** small core samples (11-mm rod, to <3-mm crushed rock).

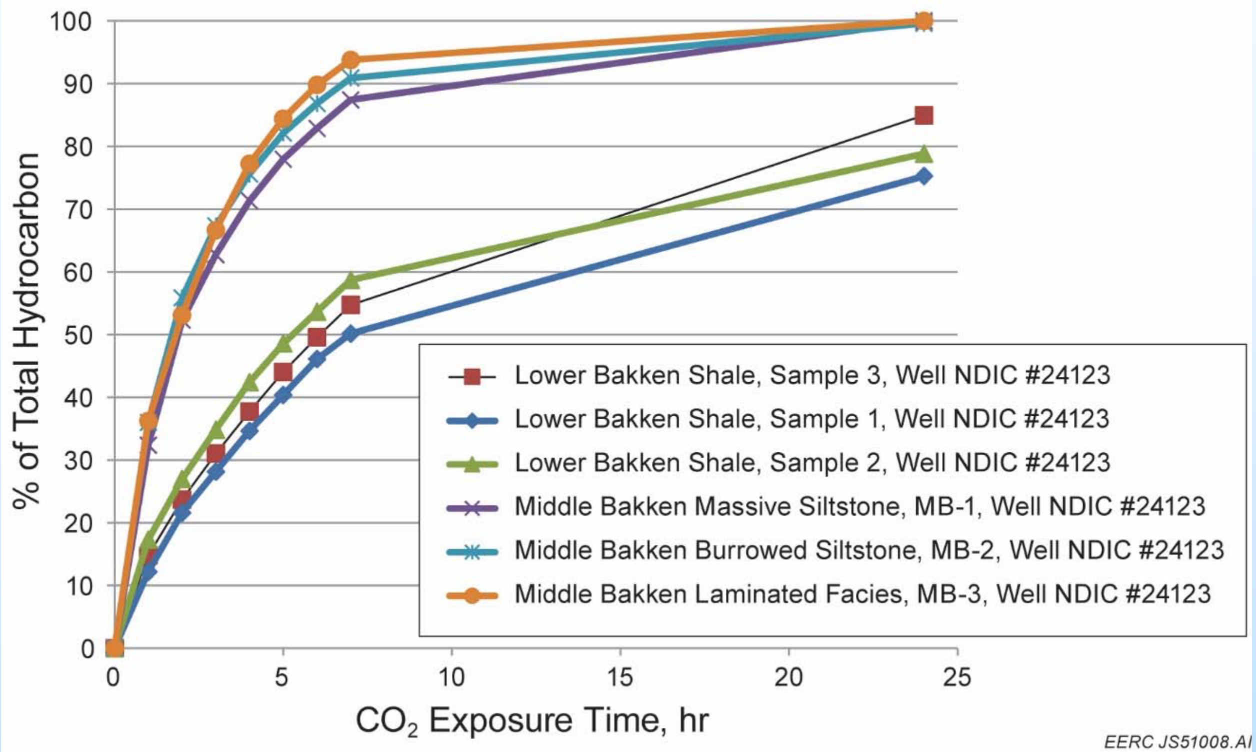
- Rock is "bathed" in $CO_2$ to mimic fracture flow, not swept with $CO_2$ as would be the case in confined flow-through tests.
- Recovered oil hydrocarbons are collected periodically and analyzed by gas chromatography/flame ionization detection (GC/FID) (kerogen not determined); 100% recovery based on rock crushed and solvent extracted after $CO_2$ exposure.
- All exposures at 5000 psi, 110°C to represent typical Bakken conditions.

# $CO_2$ Oil Recovery from Upper, Middle, and Lower Bakken from One North Dakota Well

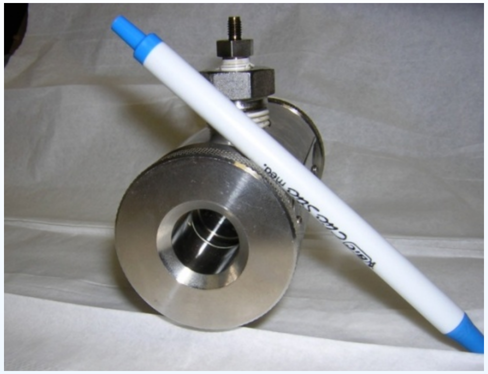
Oil can be recovered from Middle Bakken rock and Bakken Shales in the lab, but:

- Rates are *highly* dependent on exposed rock surface areas.
- Recoveries are *highly* dependent on long exposure times.

***A much deeper understanding of the mechanisms controlling oil recovery processes in tight hydraulically fractured systems MUST be obtained to exploit these lab observations in the field.***

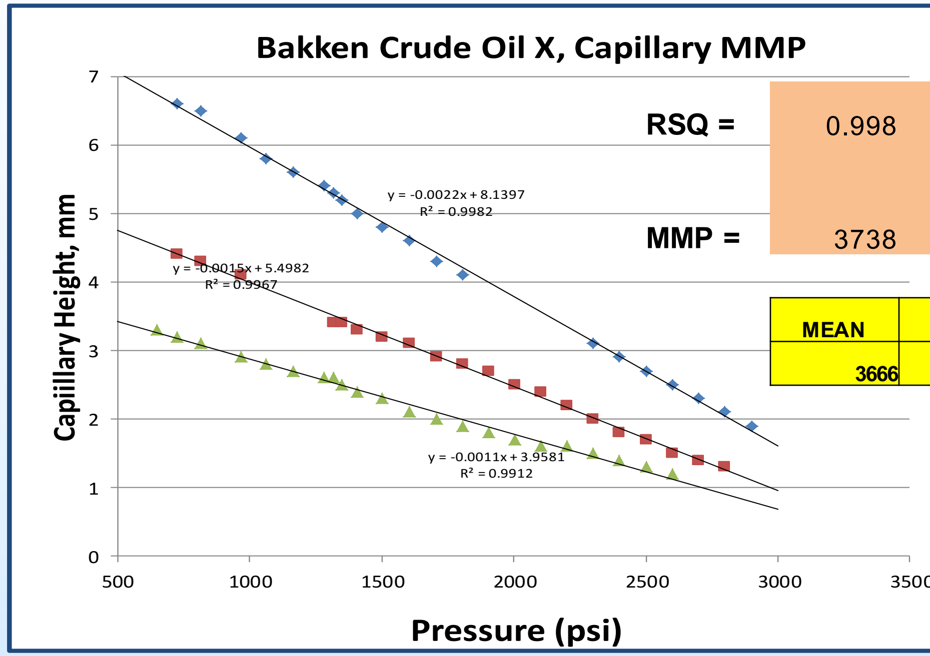


# $CO_2$ and Bakken Oil Miscibility Study



*Patent pending*

## *MMP by Capillary Rise*




| | | | |
|---|---|---|---|
| RSQ = | 0.998 | 0.997 | 0.991 |
| MMP = | 3738 | 3632 | 3628 |

| MEAN | SD | RSD |
|---|---|---|
| 3666 | 62 | 2% |

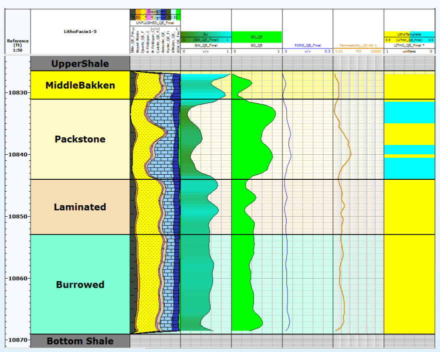
Partners provided “live” and “dead” oil samples, as well as slim-tube minimum miscibility pressure (MMP) and pressure, volume, temperature (PVT) results.

These results agree very well with slim-tube and equation of state (EOS) values.

# Characterization Informs Static Model to Support Simulations of EOR Scenarios

Core Description, X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) Analysis

## Petrophysical Modeling

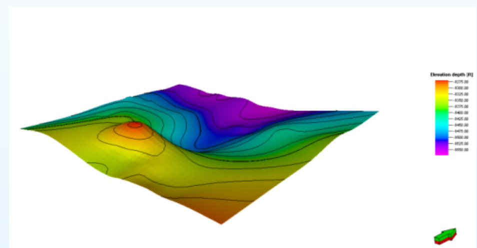



Routine Core Analysis, XRD Results

Petrophysical Model Quality Control (QC)

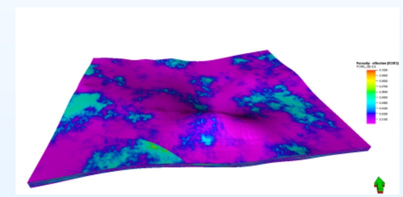
Core Description to Log Breaks

## Structural Modeling

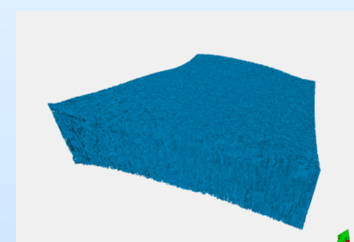


Core Permeability and Porosity

## Matrix Modeling

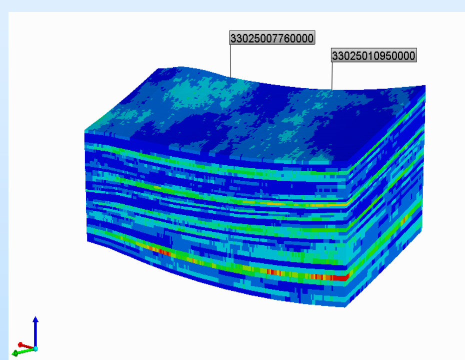


## Fracture Modeling



Core and SEM Fracture Analysis

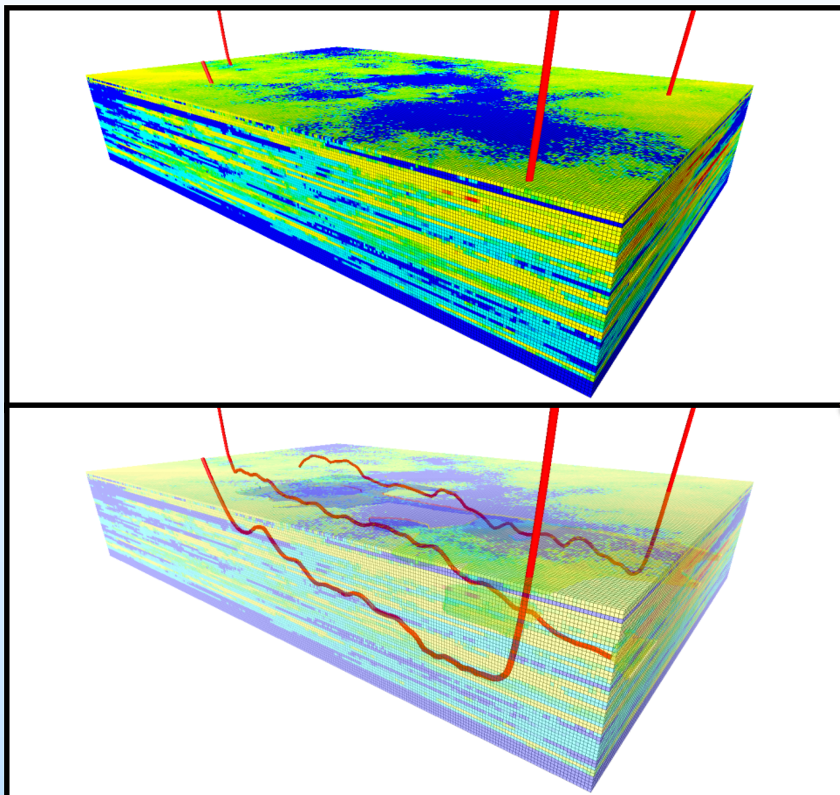
## Clip Drill Spacing Unit (DSU) Model from Larger Study Area Model

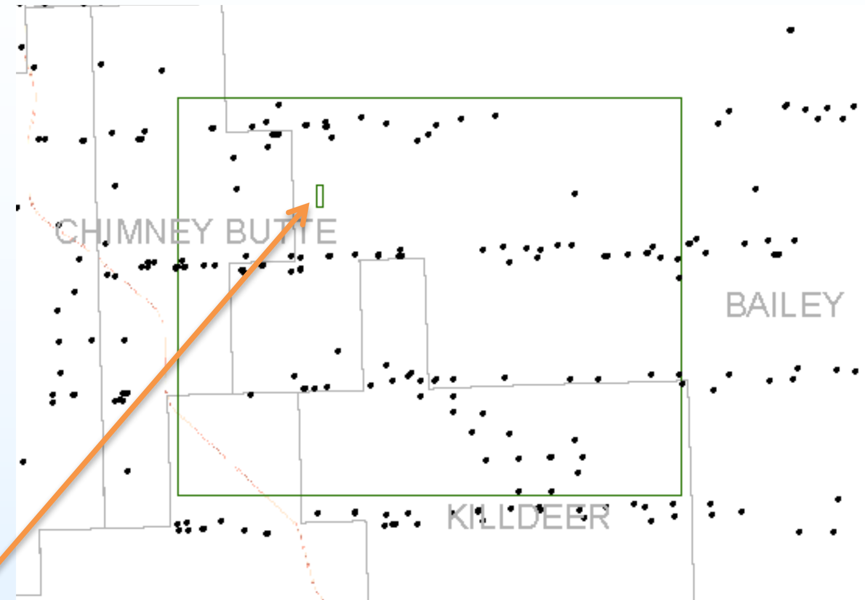


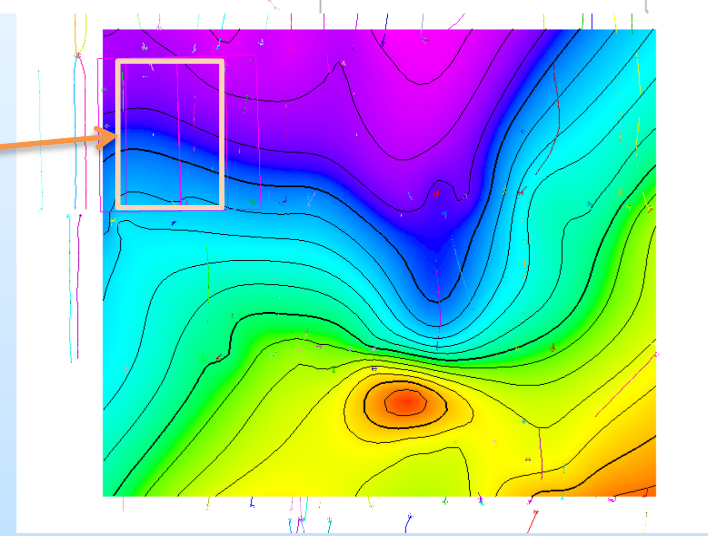

Prepare for Dynamic Simulation

# DSU-Scale Model

- Simulation model – DSU
- Cells – 537,000
- Grid Size – 82 × 82 ft (25 × 25 m)
- Zones – six





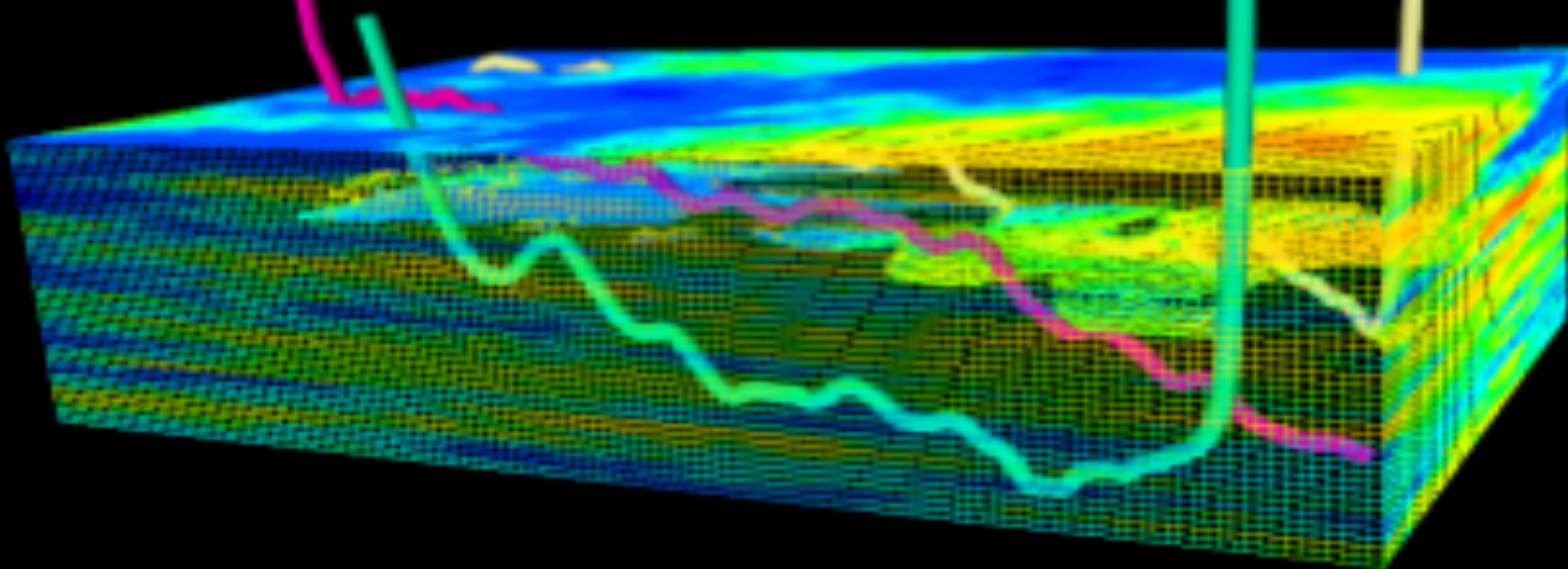



# DSU Simulation Results Highlights

**Simulated a variety of injection–production schemes.**

**Best cases showed significant improvement in total recovery factor (some over 100%).**

**Production response is delayed compared to $CO_2$ EOR in a conventional reservoir, which is in line with what we see in the lab.**



Simulation is all well and good…
but what happens in the
real world?

# Bakken Field Injection Tests to Date

- **Review of publicly available records**
  - **Five North Dakota Bakken injection tests**
    - **Two $CO_2$ tests**
    - **Two water tests**
    - **One water test followed by field gas test**
  - **Elm Coulee, Montana, Bakken $CO_2$ test**

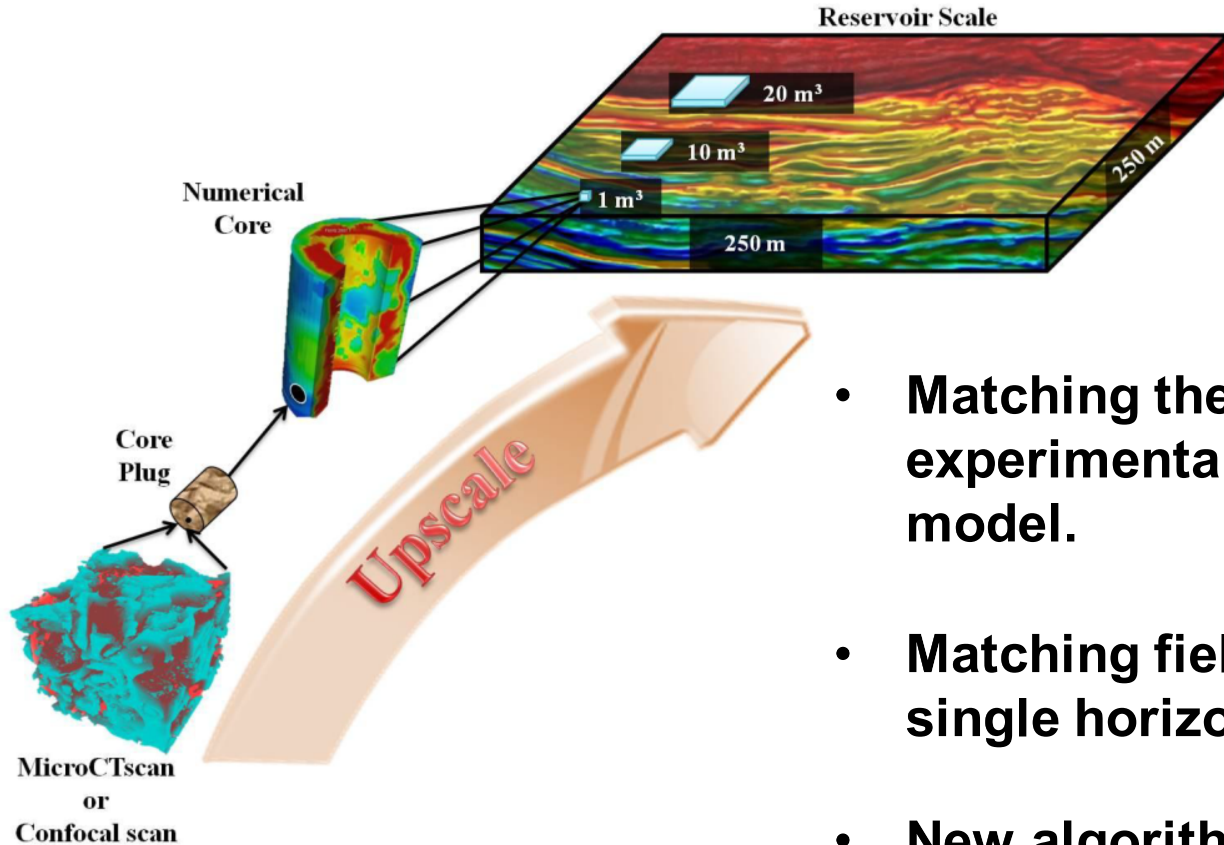
# Bakken Field Injection Tests to Date

- **Lessons learned**
  - **Injectivity has been demonstrated.**
  - **Production responses have been observed, so fluid movement can be influenced.**
  - **But the improvements that have been predicted by models have NOT been observed.**

- **Clearly there are gaps between the modeling and the reality in the field.**

*www.bakkendispatch.com*

# Current Modeling Efforts



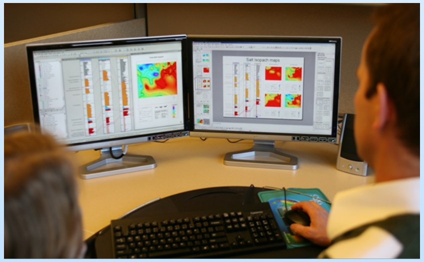

Hurley et. al. 2012

**The goal is to close the gaps between modeling and reality in the field.**

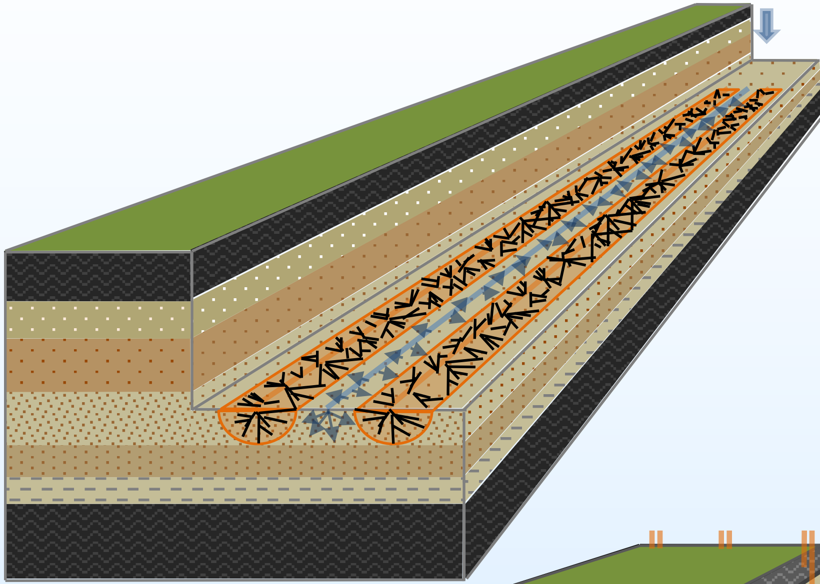
- **Matching the rock extraction experimental results to a small-scale model.**
- **Matching field production data to a single horizontal well model.**
- **New algorithms for phase behavior.**

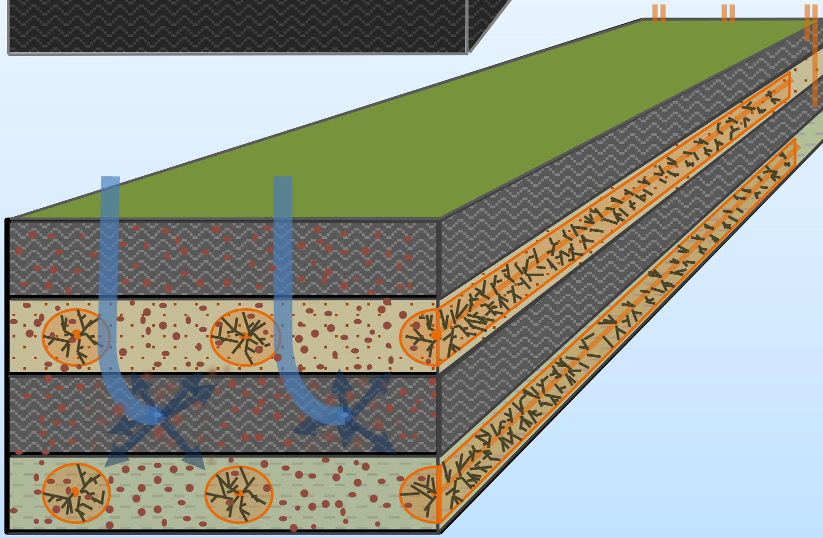
# Future Efforts Focused on Advanced Characterization and Modeling

- **Detailed reservoir characterization will be key.**
  - Hydrocarbon extraction data from the various lithofacies to derive a realistic range of diffusion rates.
  - Knowledge of $CO_2$–oil multiphase behavior to improve modeling and scheme designs.
- **Existing modeling and simulation software packages do not adequately address or incorporate the unique properties of tight oil formations:**
  - Microfractures
  - High organic content
  - Combined diffusion, adsorption, and Darcy flow mechanisms
  - Physical interactions between $CO_2$ and formation fluids



# Summary: Today's "Take Home" Thoughts





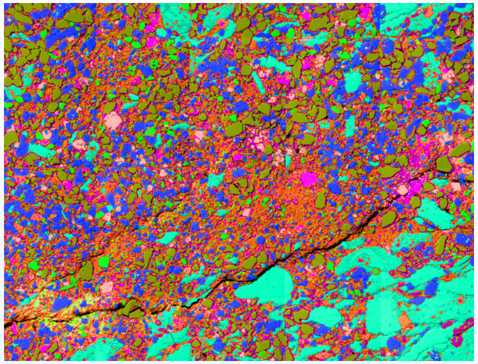
- Unconventional resource will take unconventional approach to EOR.
  - Mechanisms that play a minor role in conventional $CO_2$ EOR, such as diffusion, will play a major role in Bakken EOR.
  - Patience is required, but reward may be substantial.
- Innovative injection and production schemes.
  - Use unfractured wells as injectors; rely on natural fracture system for slower movement of $CO_2$ through the reservoir and improved matrix contact time.
  - Injectors in the shale paired with producers in the Middle Bakken and/or Three Forks.

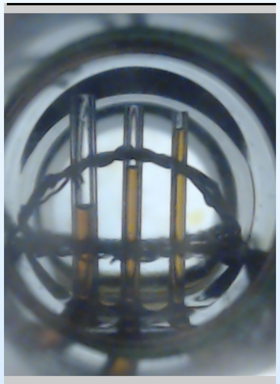
# Summary: Looking to the Future

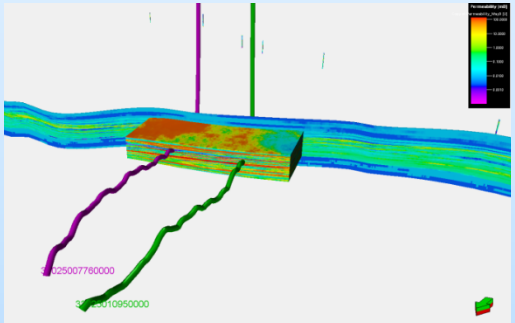
- **The EERC is working with partners to identify specific locations for a pilot-scale field test.**
  - **Thoughtfully planned and executed field monitoring activities will set this program apart from previous field tests.**
  - **Biggest hurdle to partners is a lack of readily available, proximal $CO_2$ in North Dakota.**
  - **Goal is to move forward with field test before the end of 2015.**

# Synergy Opportunities

- Methods and insights developed by this project can be directly applicable to projects in many North American tight oil formations.
  - Fracture analysis techniques
  - Novel approaches to rock $CO_2$ permeation and hydrocarbon extraction and MMP studies
  - Improved modeling workflows and enhancements to existing software packages







# Papers & Reports Generated by the Program


Hawthorne, S.B., Gorecki, C.D., Sorensen, J.A., Steadman, E.N., Harju, J.A., Melzer, S., 2013, Hydrocarbon mobilization mechanisms from Upper, Middle, and Lower Bakken reservoir rocks exposed to $CO_2$: Paper presented at the SPE Unconventional Resources Conference – Canada, Society of Petroleum Engineers, SPE 167200-MS.

Hawthorne, S.B., Gorecki, C.D., Sorensen, J.A., Miller, D.J., Melzer, L.S., Harju, J.A., 2014, Hydrocarbon mobilization mechanisms using $CO_2$ in an unconventional oil play: Paper presented at GHGT-12, Energy Procedia, v. 63, p. 7717–7723, Elsevier.

Klenner, R.C.L., Braunberger, J.R., Sorensen, J.A., Eylands, K.E., Azenkeng, A., and Smith, S.A., 2014, A formation evaluation of the Middle Bakken Member using a multimineral petrophysical analysis approach: Paper presented at Unconventional Resources Technology Conference – Denver, Colorado, USA, August 25–27, 2014, 9 p., URTeC: 1922735.

Kurtoglu, B., Sorensen, J., Braunberger, J., Smith, S., and Kazemi, H., 2013, Geologic characterization of a Bakken reservoir for potential $CO_2$ EOR: Paper presented at 2013 Unconventional Resources Technology Conference, Denver, Colorado, August 12–14, URTeC 1619698.

Liu, G., Sorensen, J.A., Braunberger, J.R., Klenner, R., Ge, J., Gorecki, C.D., Steadman, E.N., and Harju, J.A., 2014. $CO_2$-based enhanced oil recovery from unconventional resources: a case study of the Bakken Formation: Presented at SPE Unconventional Resources Conference, The Woodlands, Texas, April 1–3, 2014, SPE-168979-MS, 7 p.

Sorensen, J.A., Hawthorne, S.A., Smith, S.A., Braunberger, J.R., Liu, G., Klenner, R., Botnen, L.S., Steadman, E.N., Harju, J.A., and Doll, T.E., 2014, $CO_2$ Storage and Enhanced Bakken Recovery Research Program: Subtask 1.10 final report for U.S. Department of Energy Cooperative Agreement No. DE-FC26-08NT43291, May, 79 p.

Sorensen, J.A., Braunberger, J.R., Liu, G., Smith, S.A., Klenner, R.C.L., Steadman, E.N., Harju, J.A., 2014, $CO_2$ storage and utilization in tight hydrocarbon-bearing formations: a case study of the Bakken Formation in the Williston Basin. Paper presented at GHGT-12, Energy Procedia, v. 63, p. 7852–7860, Elsevier.

Sorensen, J.A., Hawthorne, S.B., Kurz, B.A., Braunberger, J.R., Liu, G., Smith, S.A., Hamling, J.A., Smith, S.A., Steadman, E.N., Harju, J.A., 2015, Characterization and evaluation of the Bakken Petroleum System for $CO_2$ enhanced oil recovery. Paper to be presented at 2015 Unconventional Resources Technology Conference, San Antonio, Texas, July 20–22, URTeC 2169871.

# Thank You!

# Appendix

Supplemental Slides

# Project Overview: Goals and Objectives

- Describe the project goals and objectives:
  - To develop knowledge that will support the deployment of commercially viable $CO_2$ injection operations to simultaneously enhance oil recovery and geologically store $CO_2$ in tight oil-bearing formations.

- How do the project goals and objectives relate to the program goals and objectives?
  - Support industry's ability to predict $CO_2$ storage capacity in geologic formations within ±30%.
  - Support the development of best practice manuals.
    - Especially with respect to site screening, selection, and initial characterization.

- Identify success criteria:
  - Generate first-order estimates of $CO_2$ storage capacity and EOR potential in the Bakken.
  - Develop previously unavailable data and insight that are valuable to project stakeholders.
  - Transfer the knowledge gained by the project to the carbon capture and storage (CCS) and EOR technical community at large through final reports, presentations, and published papers.
  - Inject and monitor $CO_2$ in a Bakken reservoir to further our understanding of $CO_2$ storage and EOR potential in a tight oil formation.

# Accomplishments to Date

- The goal of the project was to generate data and insight that will enable stakeholders to make informed decisions regarding the use of $CO_2$-based technologies for Bakken EOR and $CO_2$ storage. The objective is to use new and existing reservoir characterization and laboratory analytical data and state-of-the-art modeling to determine the viability of conducting $CO_2$ storage and EOR operations in the Bakken.
- The goals and objectives of the project support industry's ability to predict $CO_2$ storage capacity in geologic formations within ±30%.
- Specific Accomplishments:
  - A first-order estimate of the potential $CO_2$ storage capacity of the Bakken Formation in North Dakota suggests that it may range from 120 million tons to over 3 billion tons of $CO_2$.
  - The current $CO_2$ capacity estimation methodologies are limited in their applicability to tight oil formations because they have unique reservoir properties relative to other conventional CCS targets. A methodology that considers the effects of those unique properties as part of the equation should be developed for future $CO_2$ storage capacity estimations of tight oil formations.
  - $CO_2$ extraction studies on samples of Middle and Lower Bakken rocks indicate that $CO_2$ can permeate the tight rocks and remove over 90% of hydrocarbons from Middle Bakken reservoir rocks and over 60% of hydrocarbons from Lower Bakken shales in small-scale experiments.
  - A rising capillary approach appears to offer a cost-effective, quick-turnaround means of evaluating the effects of $CO_2$ on Bakken oil under a broad range of conditions, including changes in pressure, temperature, and hydrocarbon gas content.

# Accomplishments to Date, continued

- The goal of the project was to generate data and insight that will enable stakeholders to make informed decisions regarding the use of $CO_2$-based technologies for Bakken EOR and $CO_2$ storage. The objective is to use new and existing reservoir characterization and laboratory analytical data and state-of-the-art modeling to determine the viability of conducting $CO_2$ storage and EOR operations in the Bakken.
- The goals and objectives of the project support industry's ability to predict $CO_2$ storage capacity in geologic formations within ±30%.
- <u>Specific Accomplishments</u>:
  - In the Bakken, $CO_2$ flow will be dominated by fracture flow, and not significantly through the rock matrix. Fracture-dominated $CO_2$ flow could essentially eliminate the displacement mechanisms responsible for increased recovery in conventional reservoirs. As such, other mechanisms must be optimized in tight reservoirs such as the Bakken.
  - A variety of techniques, including SEM, ultraviolet fluorescence (UVF), and standard optical microscopy, showed promise with respect to identifying and describing microfractures.
  - Accurate geomodeling of the Bakken requires the development of triple-porosity–triple-permeability models that factor in the porosity and permeability of the matrix, natural fractures, and hydraulically induced fractures.
  - Dynamic simulation modeling suggests that $CO_2$ storage and EOR potential in the Bakken may be significant.
  - The 2009 pilot injection test conducted in the Elm Coulee Field in Montana indicates $CO_2$ injectivity rates can be achieved that are reasonable for both storage and EOR operations. However, incremental oil productivity was substantially less than predicted by models.
  - There is a wide gap between modeling-based predictions of injection and production performance and actual results from pilot-scale tests that have been conducted in the field.
  - Future modeling efforts need to better accommodate the unique characteristics of tight oil formations in order to develop more accurate predictions of $CO_2$ storage and EOR performance in the field.

# Organizational Chart

**Project Team**

- EERC
  - James Sorensen – Project Manager
  - Steven Hawthorne – Rock $CO_2$ interaction and oil miscibility experiments
  - Beth Kurz – Rock characterization efforts
  - Charles Gorecki – Geomodeling and simulations
- Schlumberger, CMG, and Baker Hughes – Provide software and support for geomodeling and simulation efforts.
- Kinder-Morgan – Provides personnel support for geomodeling and simulation efforts.
- Marathon – Provides oil and core samples and personnel support for reservoir characterization efforts.
- Continental Resources – Provides oil samples and proprietary data sets on previous field tests and personnel support for reservoir characterization efforts.
- Hess, XTO, and NDIC OGRC – Provide technical guidance and cash cost share.

# Gantt Chart

Period of Performance: April 1, 2014 – March 31, 2016

| **Year** | **2014** | | | | | | | | | **2015** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Month** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** |
| Activity 1 – Project Management and Technology Transfer | | M1 ♦ | | | | | | | | | | | | | |
| Phase II-A – Innovative Reservoir Characterization and Improved Tight Formation Modeling | | | | | | | | | | | | | | | |
| Activity 2 – Examinations of $CO_2$ Interactions with Tight Oil Formations | | | | | | | | | | | | | | | |
| Activity 3 – Characterization of Natural Fractures and MatrixPore Geometry | | | | | | | | | | | | | | | |
| Activity 4 – Development of Improved Modeling Techniques for Tight Reservoirs | | | | | | | | | | | | | | | |
| Phase II-B – Evaluation of Pilot-Scale $CO_2$ Injection Field Testing | | | | | | | | | | | | | | | |
| Activity 5 – Site Selection for Pilot-Scale $CO_2$ Injection Test into a Tight Oil Reservoir | | | | | | | | | M2 ♦ | | | | | | |
| Activity 6 – Pilot-Scale Field Test of $CO_2$ Injection into a Tight Oil Reservoir | | | | | | | | | | | | | | | |
| Activity 7 – Evaluation of the Potential for Long-Term Storage of $CO_2$ in Tight Oil Formations | | | | | | | | | | | | | | | |

| **Year** | **2015** | | | | | | **2016** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Month** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **Mar** |
| Activity 1 – Project Management and Technology Transfer | | | | | | | | | |
| Phase II-B – Evaluation of Pilot-Scale $CO_2$ Injection Field Testing | | | | | | | | | |
| Activity 6 – Pilot-Scale Field Test of $CO_2$ Injection into a Tight Oil Reservoir | | M3 ♦ | | | | | | | |
| Activity 7 – Evaluation of the Potential for Long-Term Storage of $CO_2$ in Tight Oil Formations | | | | | | | M4 ♦ | | |

♦ = Milestone.

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