Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery Potential and Storage Capacity Estimation

Proposal to
The North Dakota Industrial Commission –
Oil and Gas Research Program

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Energy & Environmental Research Center (EERC)

EERC Bakken CO_2 Projects

- **Bakken CO_2 Storage and EOR Consortium – Phase I (2012-2014)**
  - Goal was to generate data and insight regarding the use of CO_2 for Bakken EOR and CO_2 storage.
  - Vast majority of characterization efforts and all of the modeling efforts were focused on Middle Bakken.
  - Hydrocarbon extraction work was roughly split between Middle Bakken and shales.
  - MMP studies were conducted, including development of new capillary rise method.
- **Bakken CO_2 Storage and EOR Consortium – Phase II (2014-2016)**
  - Goal is to support the deployment of CO_2 injection operations for storage & EOR.
  - Laboratory-, modeling-, and field-based activities.
  - Emphasis is on selected Middle Bakken lithofacies, shales, and one zone of the Three Forks Formation.
  - Improve modeling and simulation software for use in tight oil reservoirs.
  - Design, implement, and monitor injection tests into one or more Bakken reservoirs.
- **Improved Characterization and Modeling of Tight Oil Formations**
  - Goal is to assess and validate CO_2 transport and fluid flow in fractured tight oil reservoirs.
  - Determine the effects of wetting fluid on EOR and CO_2 storage.
  - Illuminate the roles that the shale members may play with respect to storage, containment, EOR, or possibly all three.
  - Advanced SEM and CT scanning techniques will be applied.
  - Geomechanical testing will be conducted.
  - Determine CO_2 permeation rates and oil extraction rates in different lithofacies.
  - Integrate laboratory data with the modeling to predict CO_2 storage capacity & EOR potential.

Ultimate Goal of the Overarching Program: Injection Test into a Bakken Reservoir

- EERC activities will include:
  - Conducting minimum miscibility pressure (MMP) and hydrocarbon extraction studies on site-specific samples.
  - Providing site-specific modeling support.
  - Working with the hosting operator to design and implement an effective monitoring scheme to determine the fate of the injected CO_2 and its impact on the reservoir.
- Site host will obtain the CO_2, conduct the injection and production activities, and provide relevant data to the project team.

Comparison of Key Elements of EERC's Past, Present, and Future Bakken Research Projects

Bakken CO_2 Storage and EOR Consortium - Phase I (2012 – 2014)

Partners	***Funding***
US DOE	$675,000 cash
NDIC	$475,000 cash
Marathon Oil Company	$50,000 cash, $163,000 in-kind
Continental Resources	$50,000 cash
TAQA North	$75,000 cash

Goals and Key Elements of Work Plan

Goal was to generate data and insight regarding the use of CO_2 for Bakken EOR and CO_2 storage. A vast majority of the characterization efforts and all of the modeling efforts were focused on the Middle Bakken. The hydrocarbon extraction work was roughly split between Middle Bakken and shales. MMP studies were conducted, including support for the development of the new capillary rise method.

Bakken CO_2 Storage and EOR Consortium - Phase II (2014 – 2016)

Partners	***Funding***
US DOE	$2,623,558 cash
CMG	$467,000 in-kind
Kinder Morgan	$250,000 in-kind
Baker Hughes	$994,407 in-kind
Schlumberger	$340,000 In-kind
Marathon Oil Company	Currently unenumerated (core and data, thus far)
Continental Resources	Currently unenumerated (oil samples and data, thus far)
XTO Energy	$150,000 cash, $100k in-kind
Hess	$250,000 cash

Goals and Key Elements of Work Plan

Goal is to support the deployment of effective CO_2 injection operations for EOR & storage in the Bakken. Conducting a series of laboratory-, modeling-, and field-based activities to quantitatively determine the effects of injecting CO_2 into the Bakken Formation from the perspectives of CO_2 storage and EOR. Emphasis is roughly equally split between work on selected lithofacies of the Middle Bakken and the shales, with one productive bench of the Three Forks also being part of the efforts. Verify and validate the phenomena and mechanisms identified in Phase I with more robust data. Working with CMG, Schlumberger, and Baker-Hughes to improve modeling and simulation software for use in tight oil reservoirs. Integrate the lab results in the improved software to more accurately model and simulate the complex processes that occur in these tight, fractured formations. Design and monitor a pilot-scale injection test into one or more Bakken Petroleum System reservoirs.

Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery & Storage (2014 – 2017)

Partners	***Funding***
US DOE	$2,500,000 cash
NDIC-Lignite Energy Council	$250,000 cash
NDIC-OGRC	$400,000 cash

Goals and Key Elements of Work Plan

Goal is to assess and validate CO_2 transport and fluid flow in fractured tight oil reservoirs. Determine the effects of the wetting fluid on EOR and CO_2 storage. Illuminate the roles that the shale members may play with respect to CO_2 storage, containment, EOR, or possibly even all three. Advanced SEM and CT scanning techniques that are not part of other efforts will be used to characterize fractures and pore networks at scales ranging from macro- to nanoscale. Geomechanical testing will be conducted to support development of improved hydraulic fracture models. Determine CO_2 permeation and oil extraction rates in tight reservoir rocks and organic-rich shales. Integrate the laboratory-based CO_2 permeation and oil extraction data and the characterization data into geologic models and dynamic simulations to predict CO_2 storage capacity and EOR in the Bakken.

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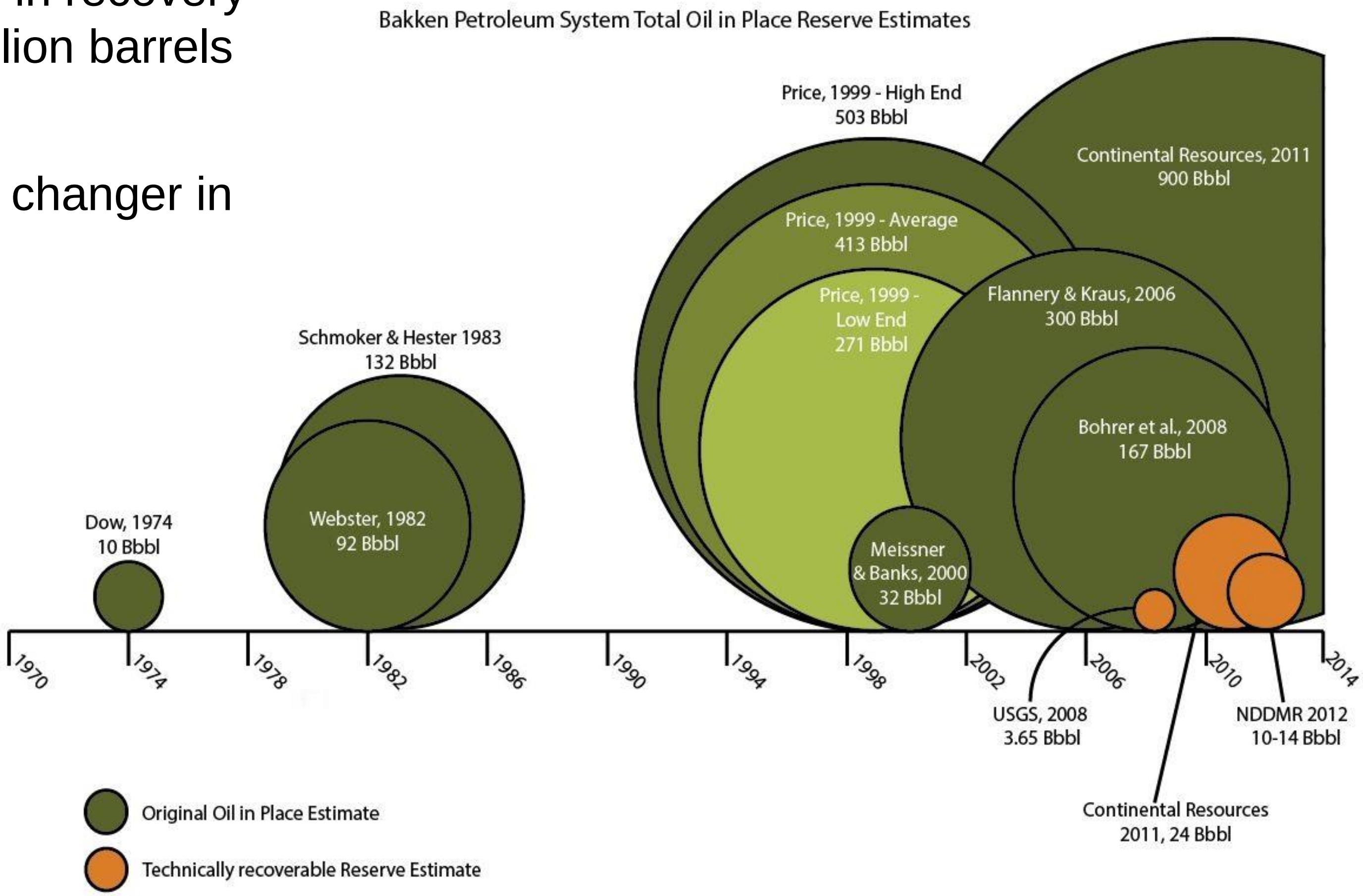
Benefit to the State: Size of the Bakken Oil Resource

- 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?



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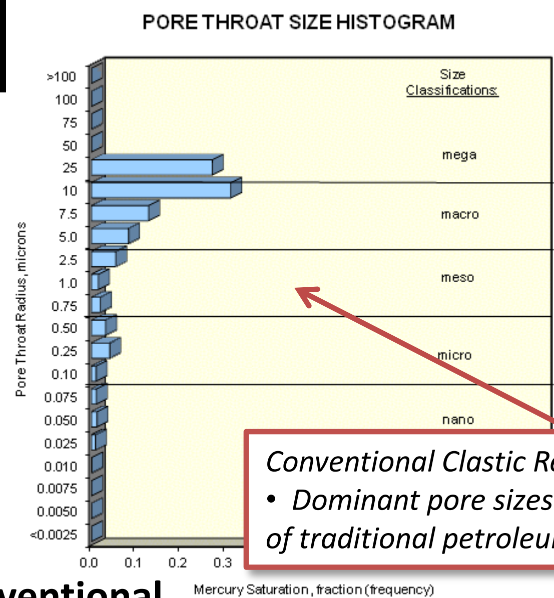
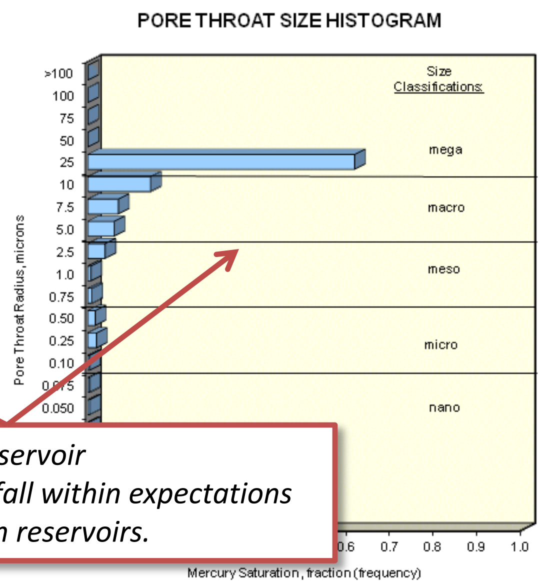
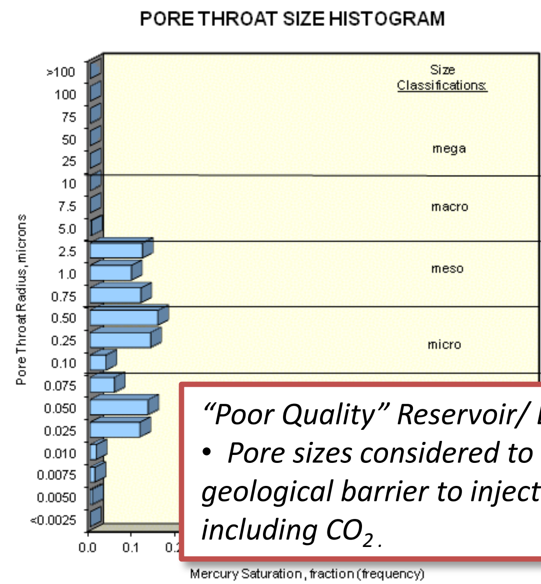
Challenges of EOR in Tight Oil Formations

- 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?

HPMI Porosity







Conventional Clastic Reservoir

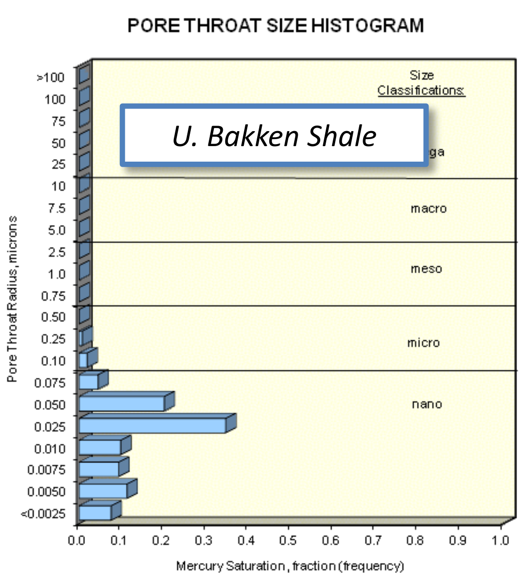
- *Dominant pore sizes fall within expectations of traditional petroleum reservoirs.*

"Poor Quality" Reservoir/ Lower Seal

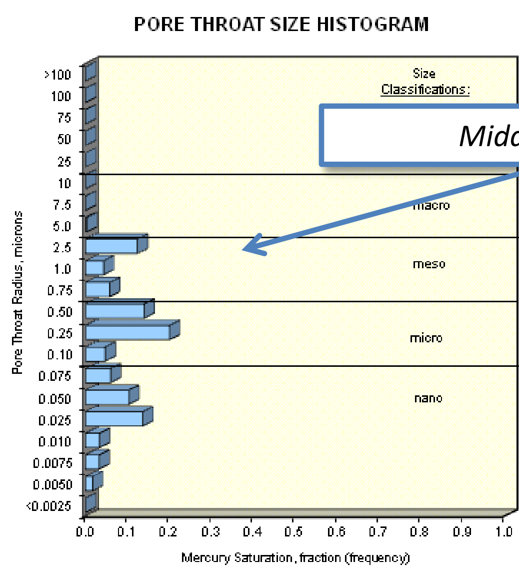
- *Pore sizes considered to be a geological barrier to injected fluids, including* CO_2.

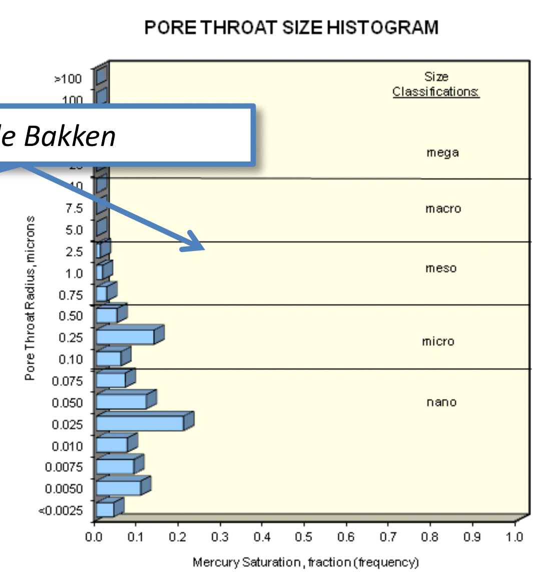
Conventional

Bakken



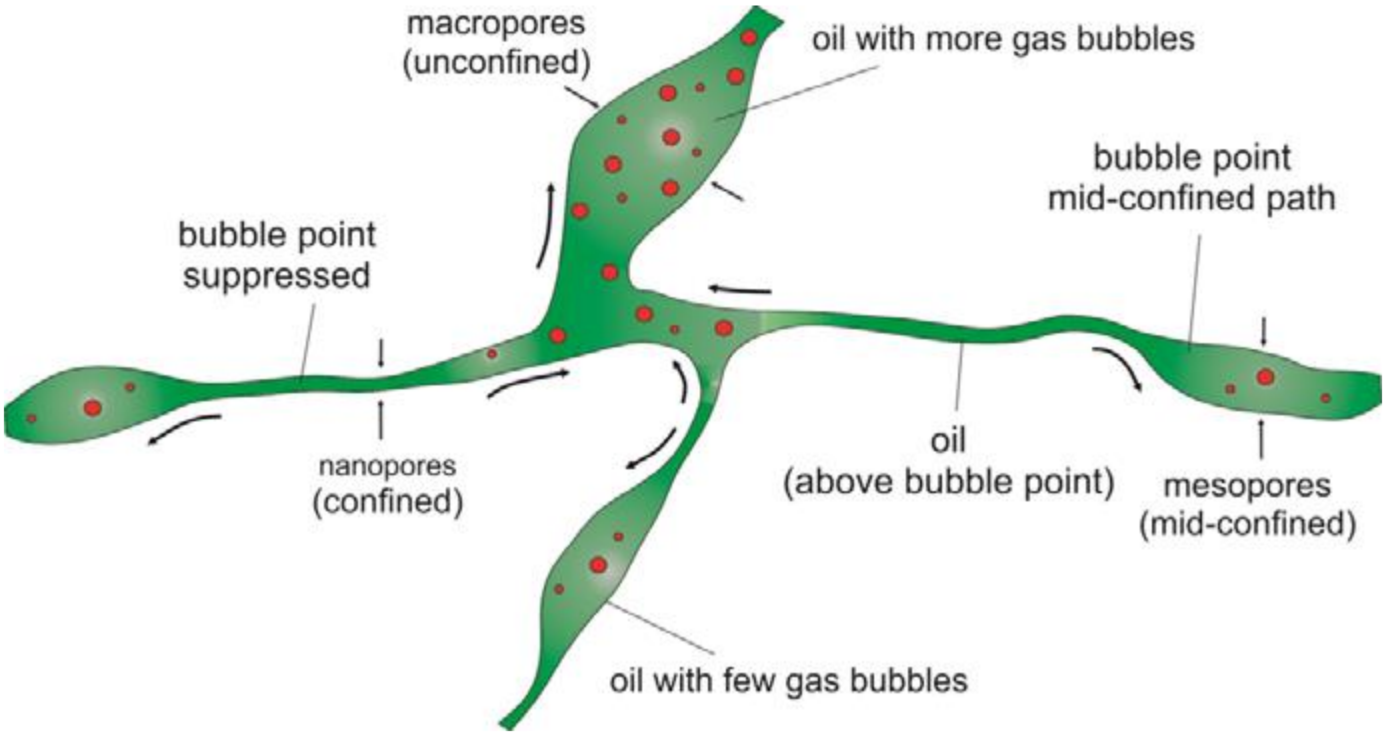
U. Bakken Shale





Middle Bakken

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.

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Improved Characterization and Modeling of Tight Oil Formations – Project Objectives

The project will result in improved tools and techniques to assess and validate fluid flow in tight oil formations resulting in an ability to better characterize and determine their potential for CO_2 storage and EOR.

- **Develop methods to better characterize fractures and pores at the macro-, micro- and nanoscale levels.**
- **Identify potential correlations between fracture characteristics and other rock properties of tight oil formations.**
- **Correlate core characterization data with well log data to better calibrate geocellular models.**
- **Evaluate CO_2 permeation and oil extraction rates and mechanisms.**
- **Integrate the laboratory-based results into geologic models and numerical simulations to assess CO_2 EOR potential and storage capacity of tight oil formations.**

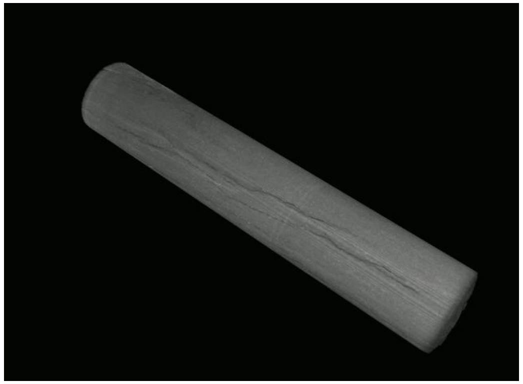
Project Approach – Phase I (November 2014 to April 2016)

- Generate baseline rock properties data.
- Use advanced analytical technologies to characterize micro- and nanoscale fracture and pore networks.
- Assess Bakken reservoir and shale rock wettability and CO_2 capillary entry and breakthrough pressures at the Bakken reservoir–shale interface.
- Hydraulically fracture rock core plugs of different lithofacies to determine effects of different rock properties on fracturing.
- Correlate rock analysis data to well log data to predict the presence and characteristics of fracture networks.

Phase I Tasks to Be Performed

Sample Selection and Baseline Characterization

- Cores come from four locations.
- Samples represent:
  - Middle Bakken reservoir lithofacies
  - Upper and Lower Bakken shale source rocks
  - Reservoir–shale interface
- Samples have been provided by Marathon and NDGS.
- A suite of geochemical, geomechanical, and petrophysical analyses are being performed.
- CT, micro-CT, and advanced SEM analyses at Ingrain and UND Hamm School of Geology & Geological Engineering



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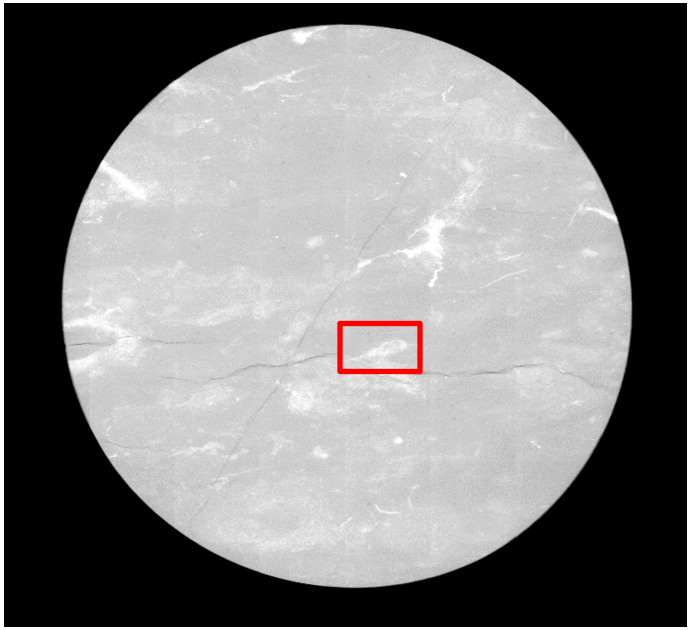
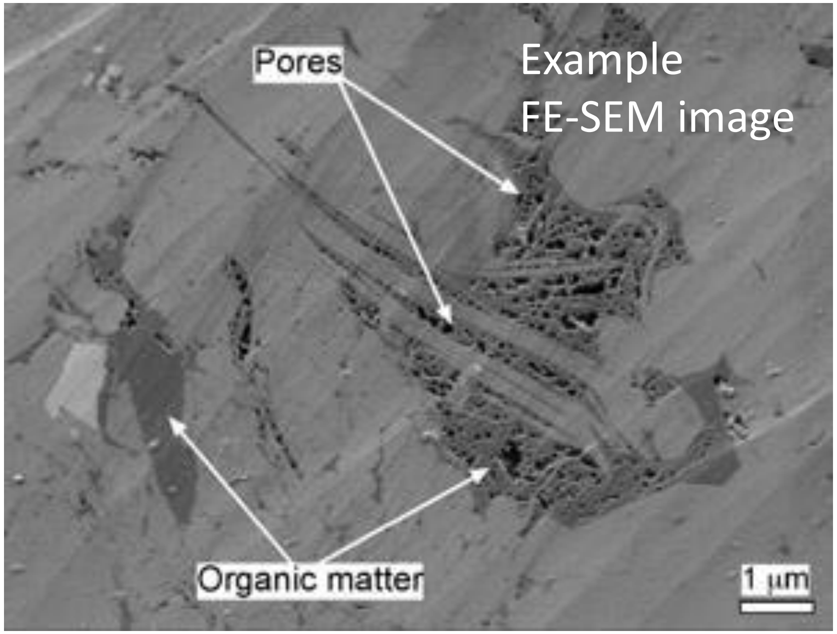
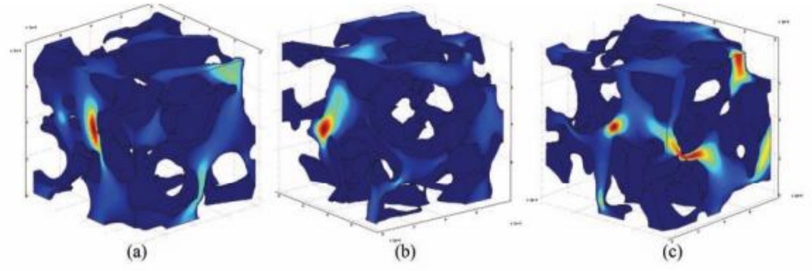
Current Phase I Activities

- Use CT scans to build matrix and fracture rock properties
- Lithofacies and variogram ranges from thin sections
- Pore quantification from SEM
- Import data into pore and core scale models

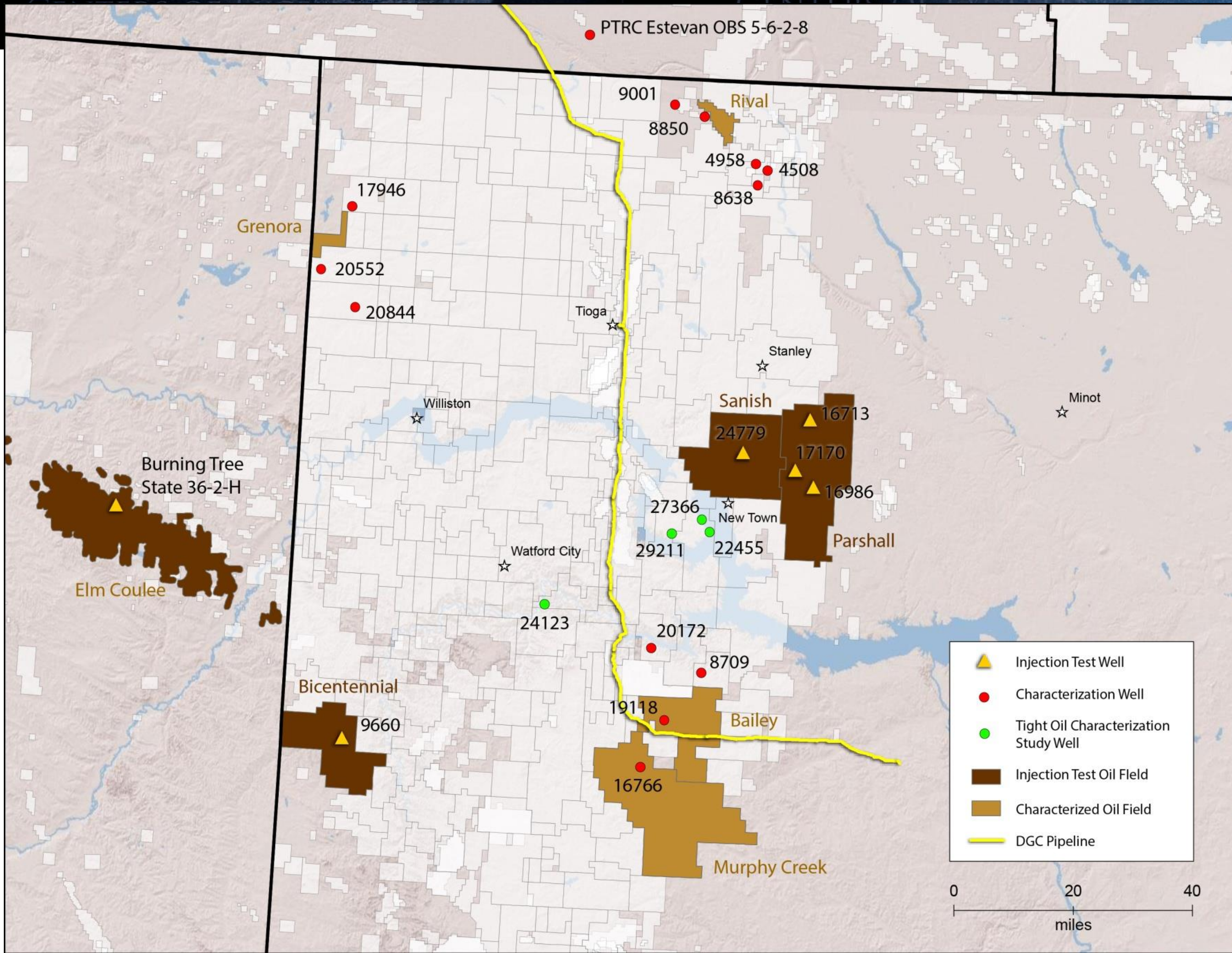






Pore scale modeling

Core Sample Locations



Project Approach – Phase II (May 2016 to October 2017)

- **Determine CO_2 permeation rates and oil extraction rates from samples of Bakken reservoir and shales using flow-through and static exposure testing.**
- **Use multimineral petrophysical analysis (MMPA) to correlate well logs with lab characterization data, thereby more accurately distributing reservoir properties throughout the static geomodels.**
- **Construct a geocellular model, and use it as the basis for numerical simulations to estimate the CO_2 EOR and storage potential of the Bakken.**
- **Integrate the results of the characterization and modeling activities to predict CO_2 storage capacities and EOR potential in tight oil formations.**
- **Develop best practices manual (BPM) on the characterization and modeling of tight oil formations for CO_2 EOR and storage.**

Phase II Laboratory Activities

CO_2 Transport, Permeation, and Oil Extraction Testing

- **Determination of Permeation Rates in Reservoir Rocks**
  - **Flow-through permeability studies will be conducted to generate CO_2–brine relative permeability data.**
- **Determination of Permeation Rates in Shales**
  - **Innovative methods will be applied to generate CO_2 permeation rate data for samples of Upper and/or Lower Bakken shales.**
- **Evaluation of CO_2-Soluble Tracers**
  - **Attempts to identify CO_2 flow patterns will be made using a variety of CO_2-soluble tracers. Fluorescent dyes, UV-visible dyes, and organometallic compounds will be tested.**
- **Hydrocarbon Extraction**
  - **Hydrocarbon extraction experiments will be performed on samples of reservoir rocks and shale using the methods described in Hawthorne and others (2013).**

Phase II Modeling Activities

- MMPA Analysis
  - Core analysis data will be integrated with well log data for core-to-log calibration.
- Geocellular Modeling
  - MMPA results will be applied to develop a of a Bakken reservoir and shale system geocellular models in a single drill spacing unit.
- Simulations
  - Will be conducted on both Middle Bakken reservoirs and Lower Bakken shales.
  - Single-well HnP, sequential multiwell HnP, and injector–producer pairs.
  - Middle Bakken simulations will examine the effects of wettability.
  - Shale simulations will be oil-wet, but total organic content and hydrogen index will be varied to examine the effects of shale maturity.

Tight Oil Characterization and Modeling Project Schedule

Task	Start Date	End Date
Task 1 – Project Management and Planning	**11/1/2014**	**10/31/2017**
Task 2 – Sample Selection and Detailed Baseline Characterization	**11/1/2014**	**10/31/2015**
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
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 Seal 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	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
	M10 – Completion of Geocellular Models
	M11 – Completion of Simulations

Papers Generated By EERC Bakken CO_2 Efforts

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, CO2 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.

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Thank You!

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