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
Other Supporters
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)

Middle Bakken Siltstone (250x)

Lower Bakken Shale (250x)
Bakken Petroleum System

**Lithology**

**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**

**Upper 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

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<th>Upper Shale</th>
<th>Middle Bakken Lithofacies</th>
<th>Lower Shale</th>
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Three Forks Lithofacies

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Bakken and Three Forks Production

- Production (April 2015)
  - 9570 wells in North Dakota.
  - Over 1.1 million \text{bbl/day} of oil.
  - Over 1.5 \text{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 CO₂ be a game changer in the Bakken?
- If so, what is the storage opportunity?
- Supports industry’s ability to predict CO₂ 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.

The Size of the Prize Is Tremendous!
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.

Elements of the Program

Laboratory work to evaluate:

- Rock matrix.
- Nature of fractures.
- Effects of CO\textsubscript{2} on oil.
- Ability of CO\textsubscript{2} to remove oil from rock.

Static and dynamic modeling.

Case study of a CO\textsubscript{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.
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

**CO₂ Extraction of Oil from Tight Rocks**

**Step 1**
Initial injection: CO₂ flows rapidly through fractures.

**Step 2**
- CO₂ starts to permeate rock based on pressure gradient.
- CO₂ carries oil into the rock (bad).
- CO₂ swelling pushes oil out of the rock (good).

**Step 3**
As CO₂ permeates into the rock, oil migrates to bulk CO₂ in fractures based on swelling and lower viscosity.

**Step 4**
CO₂ pressures equalize inside of rock.
- Oil production is now based only on concentration gradient driven diffusion.
- Oil in bulk CO₂ is swept through fractures to production well.
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.
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.
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

Structural Modeling

Core Description to Log Breaks

Matrix Modeling

Core Permeability and Porosity

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

Fracture Modeling

Prepare for Dynamic Simulation

Core and SEM Fracture Analysis
DSU-Scale Model

- Simulation model – DSU
- Cells – 537,000
- Grid Size – 82 × 82 ft (25 × 25 m)
- Zones – six
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 CO₂ 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 CO₂ tests
    • Two water tests
    • One water test followed by field gas test
  – Elm Coulee, Montana, Bakken CO₂ 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.
Current Modeling Efforts

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.

Hurley et. al. 2012
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 CO₂ 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 CO₂ 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


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\textsubscript{2} injection operations to simultaneously enhance oil recovery and geologically store CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} in a Bakken reservoir to further our understanding of CO\textsubscript{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 CO₂-based technologies for Bakken EOR and CO₂ 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 CO₂ storage and EOR operations in the Bakken.

• The goals and objectives of the project support industry’s ability to predict CO₂ storage capacity in geologic formations within ±30%.

• **Specific Accomplishments:**
  - A first-order estimate of the potential CO₂ storage capacity of the Bakken Formation in North Dakota suggests that it may range from 120 million tons to over 3 billion tons of CO₂.
  - The current CO₂ 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 CO₂ storage capacity estimations of tight oil formations.
  - CO₂ extraction studies on samples of Middle and Lower Bakken rocks indicate that CO₂ 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 CO₂ 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 CO₂-based technologies for Bakken EOR and CO₂ 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 CO₂ storage and EOR operations in the Bakken.
- The goals and objectives of the project support industry’s ability to predict CO₂ storage capacity in geologic formations within ±30%.
- Specific Accomplishments:
  - In the Bakken, CO₂ flow will be dominated by fracture flow, and not significantly through the rock matrix. Fracture-dominated CO₂ 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 CO₂ storage and EOR potential in the Bakken may be significant.
  - The 2009 pilot injection test conducted in the Elm Coulee Field in Montana indicates CO₂ 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 CO₂ storage and EOR performance in the field.
Organizational Chart

Project Team

- EERC
  - James Sorensen – Project Manager
  - Steven Hawthorne – Rock CO₂ 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

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<th>Year</th>
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<td><strong>Month</strong></td>
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<td>May</td>
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<td>Activity 1 – Project Management and Technology Transfer</td>
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<td>Phase II-A – Innovative Reservoir Characterization and Improved Tight Formation Modeling</td>
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<td>Activity 2 – Examinations of CO₂ Interactions with Tight Oil Formations</td>
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<td>Activity 3 – Characterization of Natural Fractures and MatrixPore Geometry</td>
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<td>Activity 4 – Development of Improved Modeling Techniques for Tight Reservoirs</td>
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<td>Phase II-B – Evaluation of Pilot-Scale CO₂ Injection Field Testing</td>
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<td>Activity 5 – Site Selection for Pilot-Scale CO₂ Injection Test into a Tight Oil Reservoir</td>
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<td>Activity 6 – Pilot-Scale Field Test of CO₂ Injection into a Tight Oil Reservoir</td>
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<td>Activity 7 – Evaluation of the Potential for Long-Term Storage of CO₂ in Tight Oil Formations</td>
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♦ = Milestone.


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