

# ***Improved Characterization and Modeling of Tight Oil Formations for CO<sub>2</sub> Enhanced Oil Recovery Potential and Storage Capacity Estimation***

**Project Kickoff Meeting  
National Energy Technology Laboratory  
Morgantown, West Virginia  
December 4, 2014**

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**Energy & Environmental Research Center (EERC)**

# What Is Tight Oil?

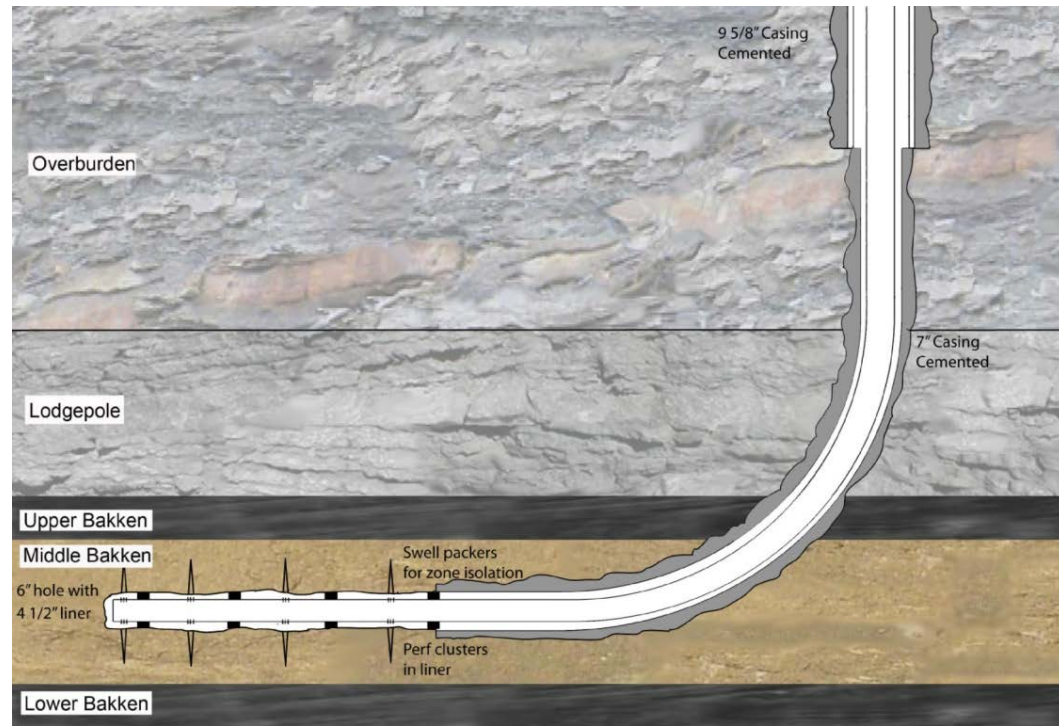
- Extremely low permeability ( $<0.1$  mD) reservoir rock, which impedes the ability of the oil in the formation to flow freely.
- Tight oil formations are associated with organic-rich shale.
- Some produce directly from shales, but much tight oil production is from low-permeability siltstones, sandstones, 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

# Tight Oil – Production Technologies

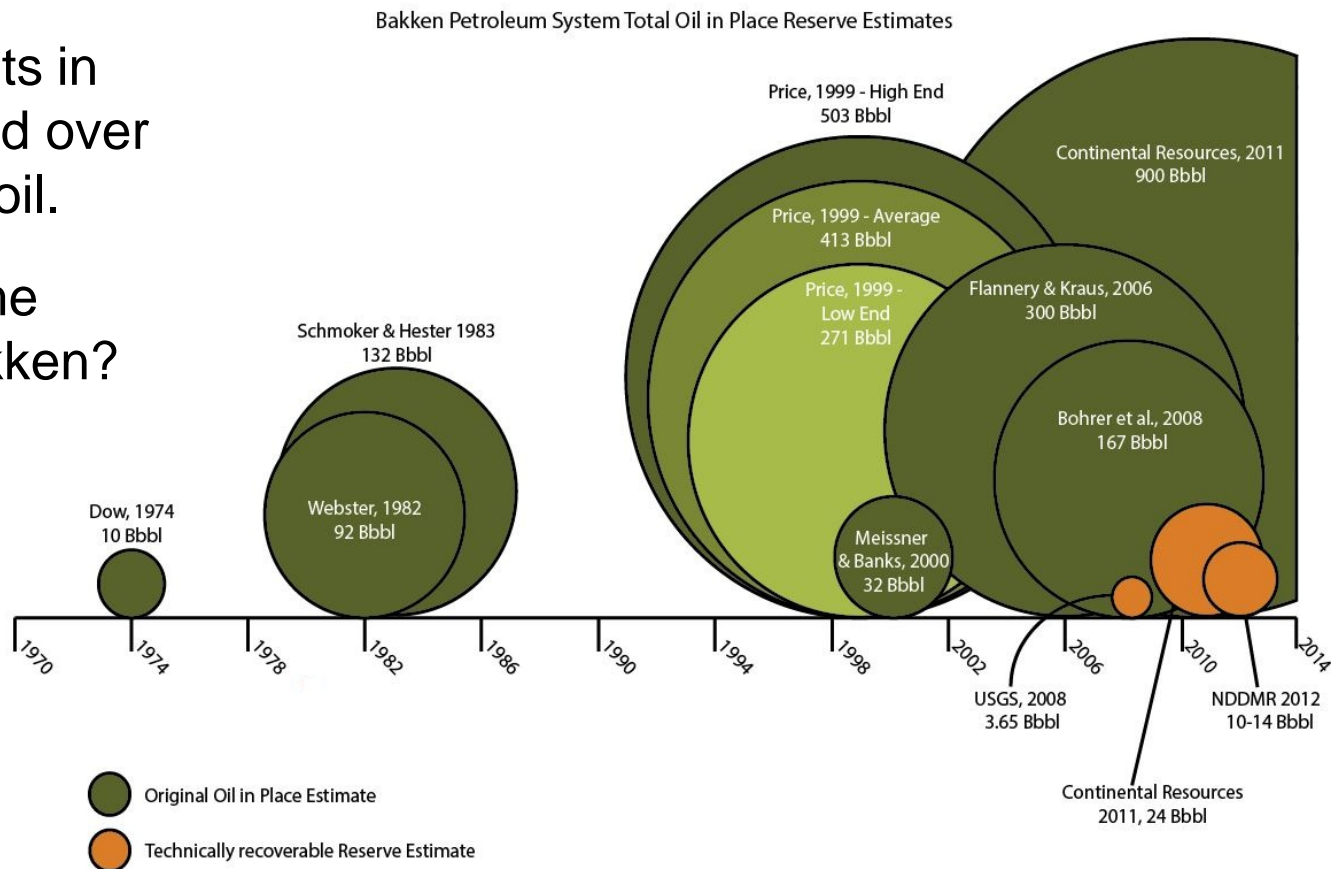
- Recent advancements in technology have spurred tight oil production.
  - Horizontal drilling and completion
  - Hydraulic fracturing
  - Proppants
  - A host of other tools for exploration, drilling, and optimization





# 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<sub>2</sub> be a game changer in the Bakken?



# Challenges of CO<sub>2</sub> Storage and Utilization in Tight Oil Formations

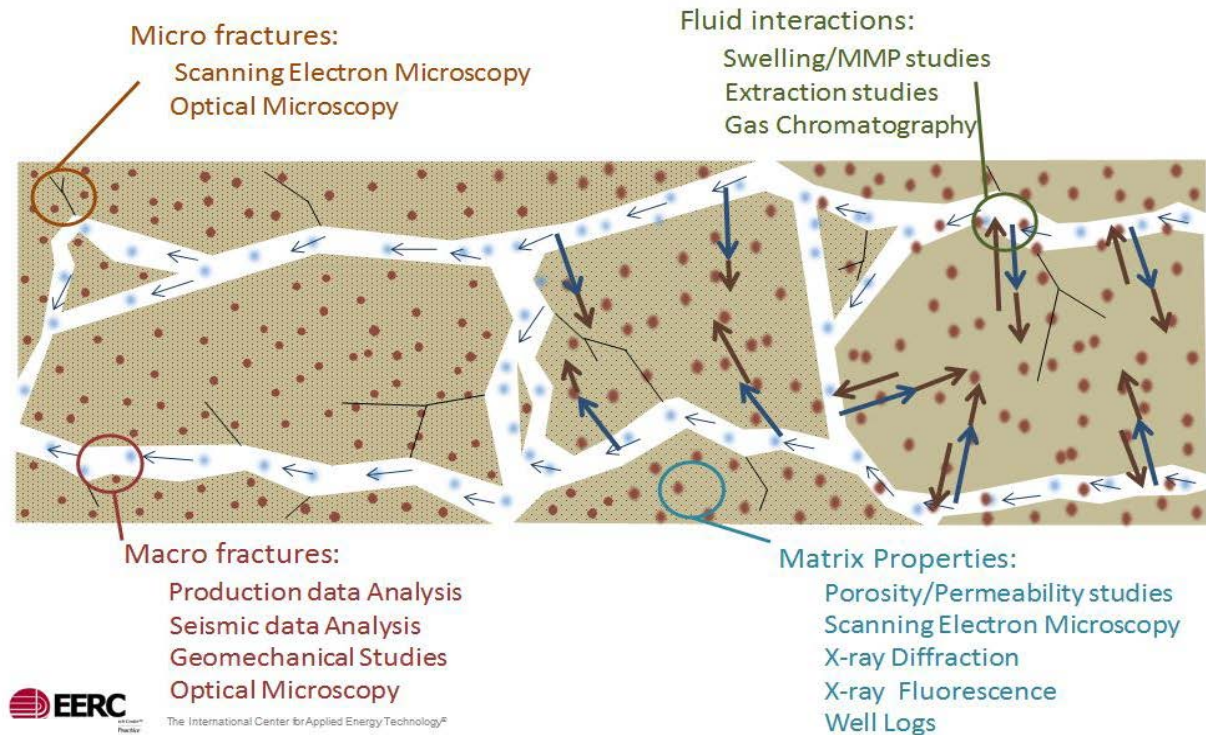
- Mobility and effectiveness of fluids through fractures relative to very low matrix permeability.
- How will clays react to CO<sub>2</sub>?
- The role of wettability (oil-wet and mixed-wet) with respect to CO<sub>2</sub> in tight oil reservoirs is not well understood.
- High vertical heterogeneity of 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<sub>2</sub> mobility, enhanced oil recovery (EOR), and storage?



# Previous EERC Research: How Does CO<sub>2</sub> Interact with a Tight Oil Reservoir?

## We need to understand:

- Rock matrix.
- Nature of fractures (macro and micro).
- Effects of CO<sub>2</sub> on oil.



## Goals of the project were to:

- Evaluate the viability of using CO<sub>2</sub> for EOR in the Bakken.
- Develop reconnaissance-level estimates of Bakken CO<sub>2</sub> storage capacity.

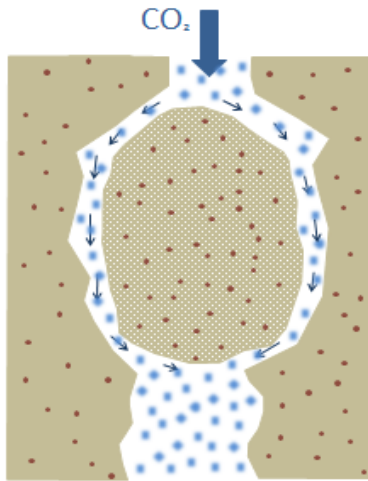


# Lab-Scale Experiments

## CO<sub>2</sub> Extraction of Oil from Tight Rocks

### Step 1

Initial injection: CO<sub>2</sub> flows rapidly through fractures.

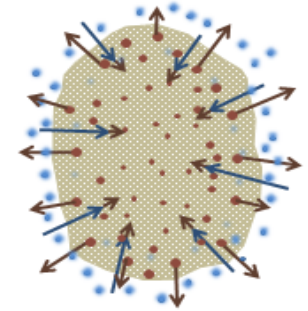
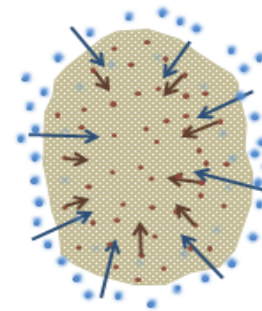


**Step 2:** CO<sub>2</sub> starts to permeate rock based on pressure gradient.

CO<sub>2</sub> carries oil into the rock (bad).

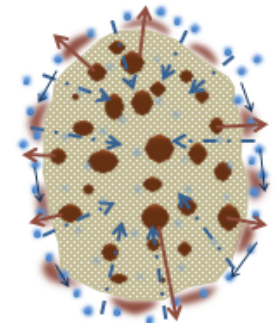
and  
or

CO<sub>2</sub> swelling pushes oil out of the rock (good).



### Step 3

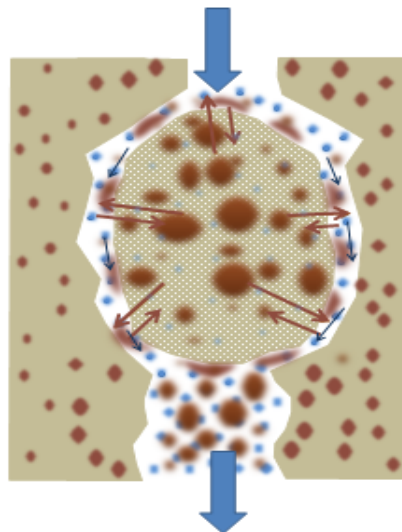
As CO<sub>2</sub> permeates into the rock, oil migrates to bulk CO<sub>2</sub> in fractures based on swelling and lower viscosity.



### Step 4

CO<sub>2</sub> pressures equalize inside of rock.

- Oil production is now based only on concentration gradient driven diffusion.
- Oil in bulk CO<sub>2</sub> is swept through fractures to production well.



# Previous Lab-Scale CO<sub>2</sub> Extraction of Oil from Middle and Lower Bakken Samples

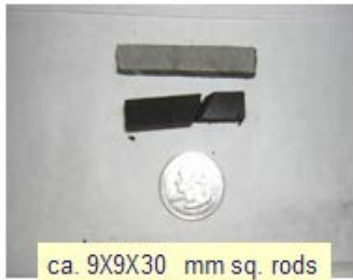
ca. 3X9X9 mm chicklets



ca. 9 mm dia rod



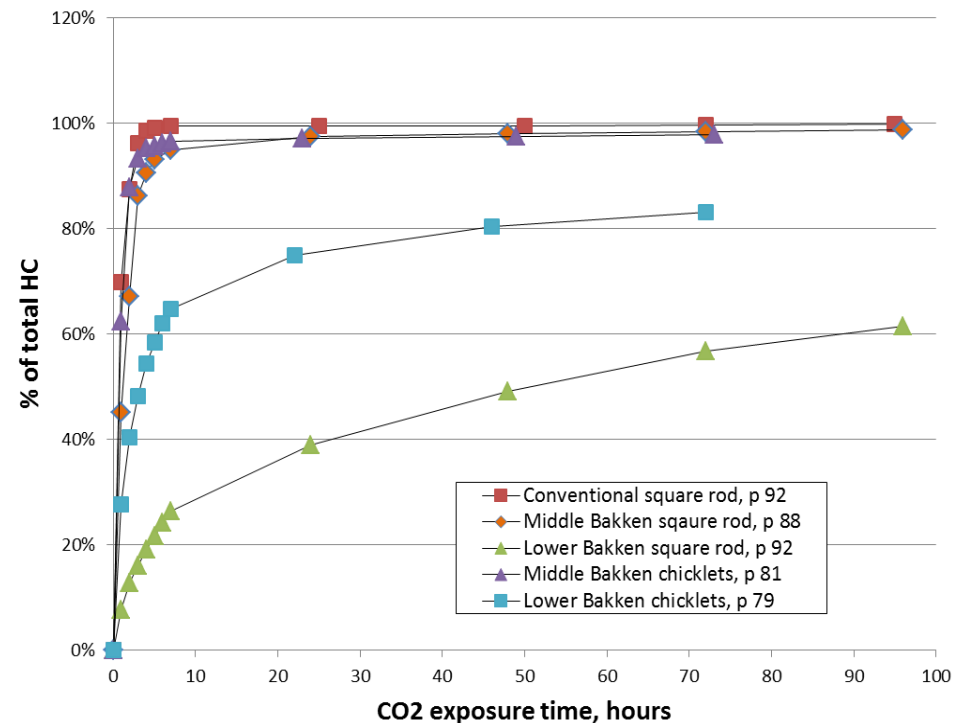
ca. 9X9X30 mm sq. rods



CO<sub>2</sub> extraction of oil from samples of undifferentiated Middle and Lower Bakken rock.

Experiments conducted at reservoir conditions, 5000 psi, 110°C (230°F).

Source: Hawthorne and others (2013) (SPE 167200-MS)

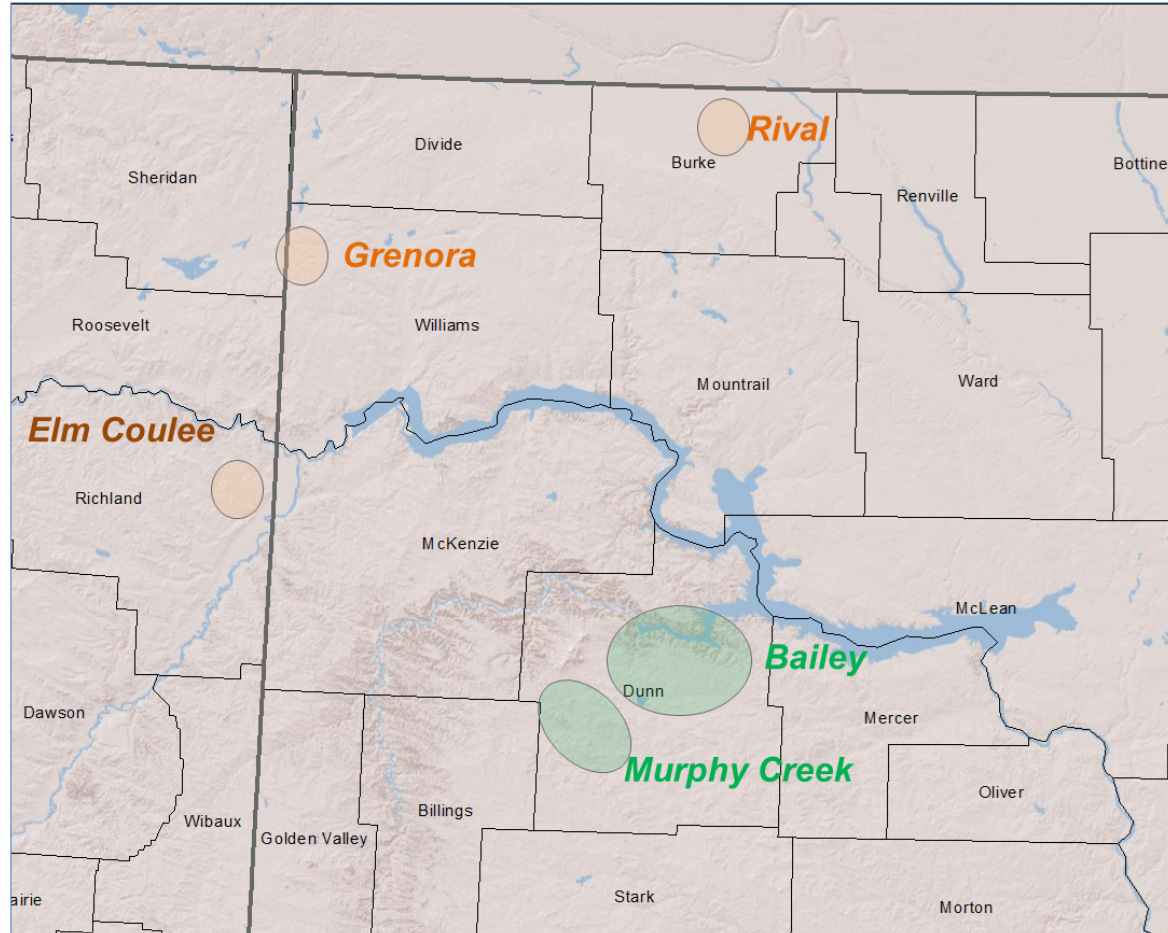


- **Over 90% hydrocarbon recovery from Middle Bakken.**
- **Over 60% from Lower Bakken shale.**
- **Primary mechanism is likely diffusion.**



# Previous Reservoir Characterization Efforts and Case Studies

- Characterization and modeling of North Dakota areas
  - Characterize core from Bailey, Murphy Creek, Rival, and Grenora.
  - Static and dynamic modeling of Bailey and Grenora.
- Evaluation of 2009 CO<sub>2</sub> huff 'n' puff (HnP) in Elm Coulee, Montana, area
  - Apply lessons learned in that test to potential future injection tests.



Sources:

Kurtoglu and others (2013) (URTeC-1619698)

Liu and others (2014) (SPE-168979-MS)

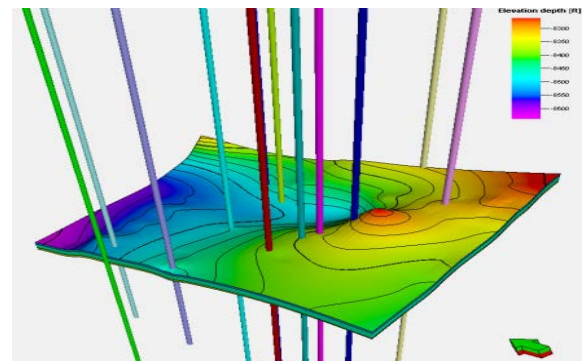
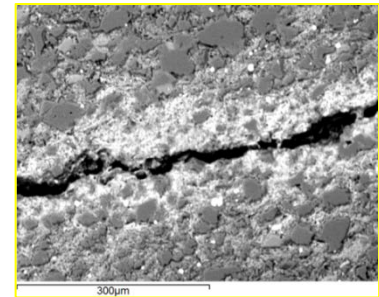
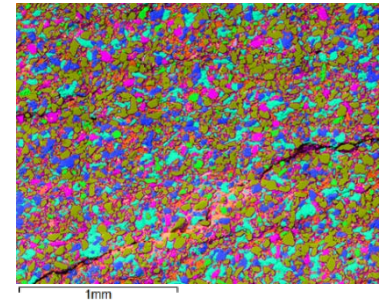
Klenner and others (2014) (URTeC-1922735)

Sorensen and others (2014) (Final Report to U.S. Department of Energy [DOE], Subtask 1.10, DE-FC26-08NT43291)

# Key Findings of Previous Characterization Efforts

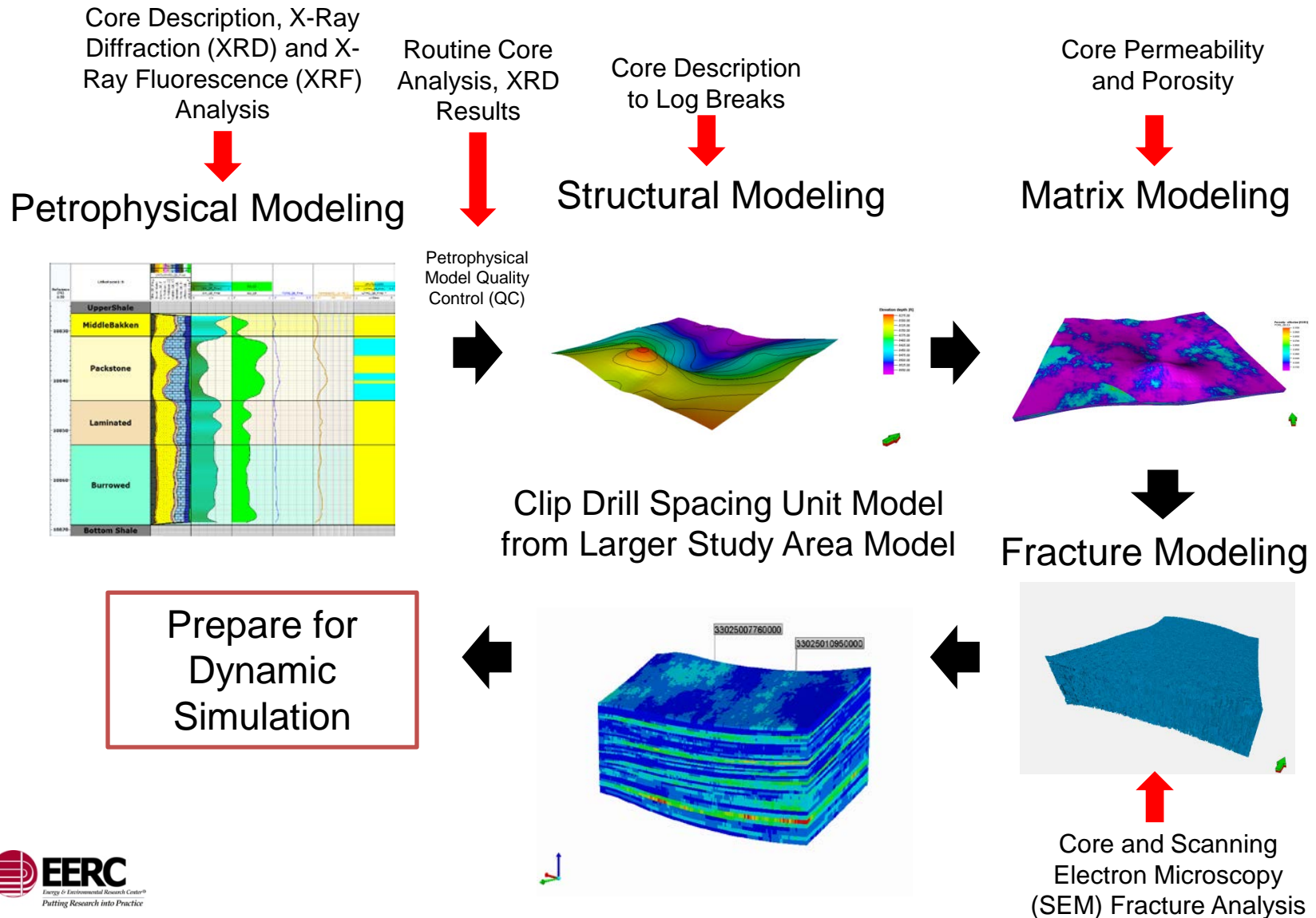
## Reservoir Characterization Is Key to Understanding Fluid Movements

- Movement of fluids ( $\text{CO}_2$  in and oil out) relies on fractures.
- Microfractures accounted for the majority of the porosity in the most productive zones of the Bakken.
- Some lithofacies are more prone to fracturing than others.
- Four to seven distinct lithofacies typically occur in the Middle Bakken, resulting in significant vertical heterogeneity.
- Generating macrofracture and microfracture data and integrating those data into modeling are essential to develop effective EOR strategies.





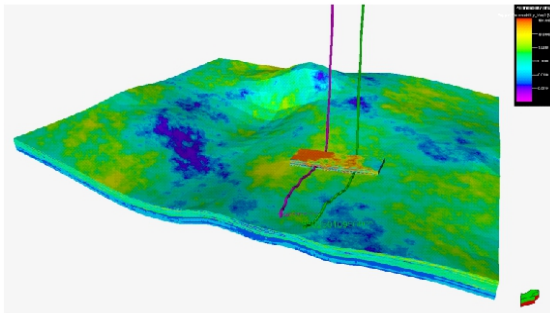
# Building a Static Model to Support Simulations of EOR Scenarios



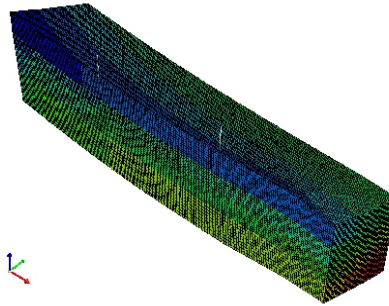


# Dynamic Simulation Workflow

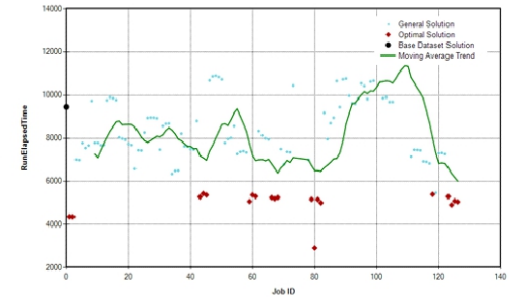
EERC GL48635.CDR



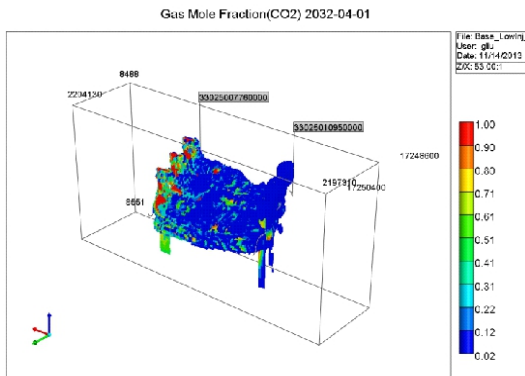
Preparation for Simulation



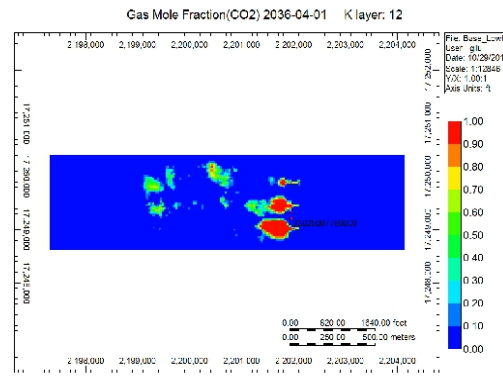
Grid Sensivity Analysis



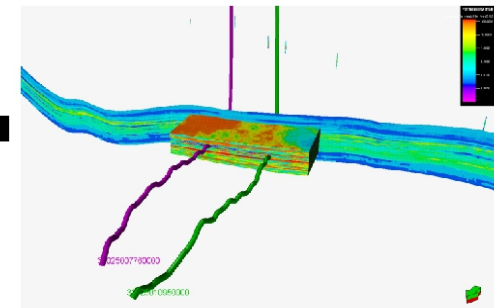
Numerical Tuning



Prediction Simulations



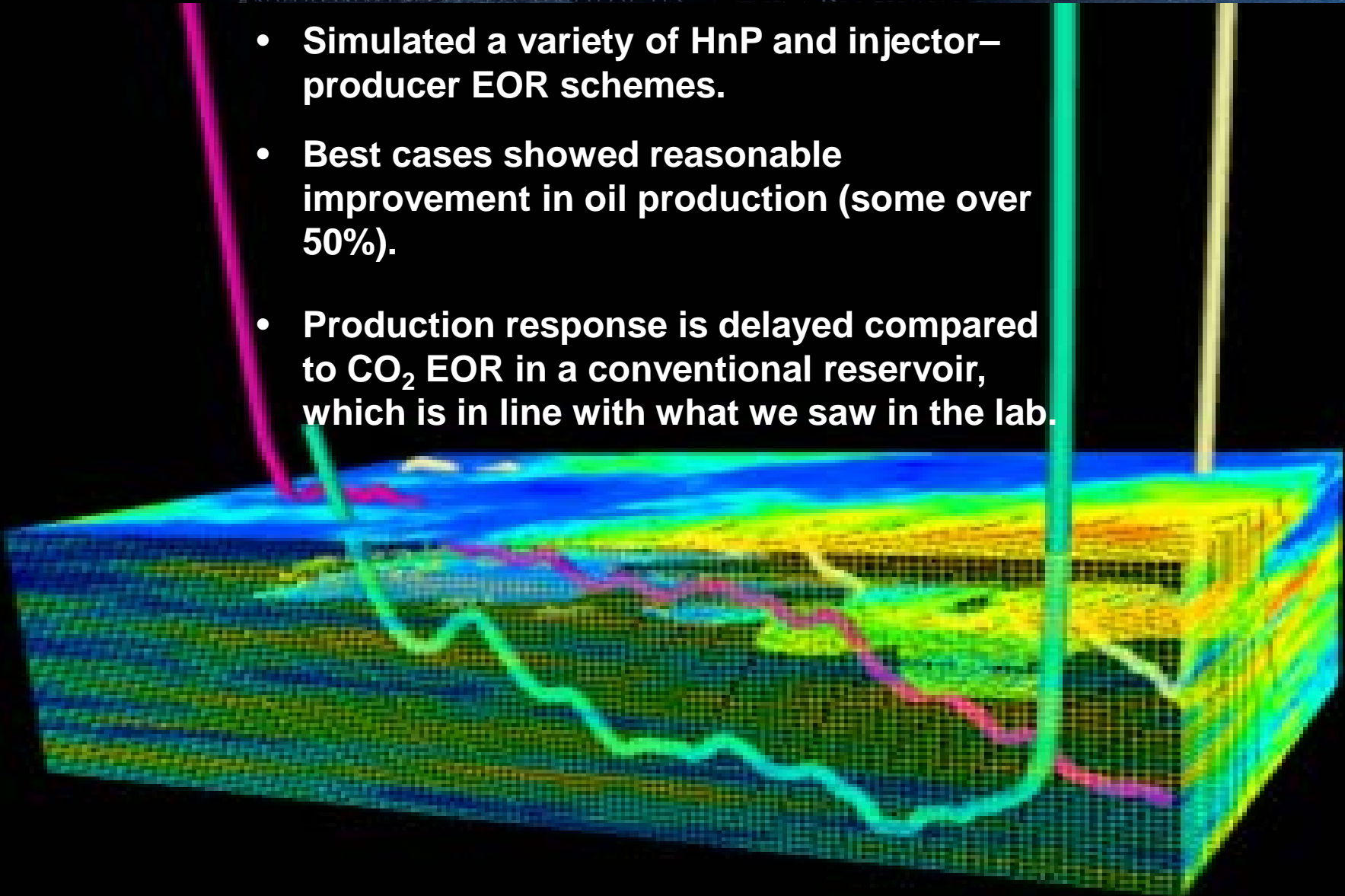
Operational Optimization for Oil Production



Sensitivity Analysis

# Simulation Results Highlights

- Simulated a variety of HnP and injector-producer EOR schemes.
- Best cases showed reasonable improvement in oil production (some over 50%).
- Production response is delayed compared to CO<sub>2</sub> EOR in a conventional reservoir, which is in line with what we saw in the lab.



# Initial Estimation of Bakken CO<sub>2</sub> Storage Capacity and EOR Potential

The DOE methodology for estimating CO<sub>2</sub> EOR and storage capacity (Carbon Sequestration Atlas of the United States and Canada, 2007) was applied to the Bakken petroleum system:

- The cumulative production approach yields a storage capacity ranging from **121 to 194 million tons of CO<sub>2</sub>**.
  - This could yield **420 to 670 million barrels** of incremental oil.
- The volumetrics approach, which is based largely on original oil in place (OOIP), yields a storage capacity ranging from **1.9 to 3.2 billion tons of CO<sub>2</sub>**.
  - This could yield **4 to 7 billion barrels** of incremental oil.

Source: Sorensen and others (2014), presented at GHGT-12.



# Issues with Application of Current Approaches to Tight Oil Formations

**The DOE method was developed with conventional oil fields in mind.**

- **The cumulative production approach estimates are likely too low.**
  - The Bakken and Eagle Ford plays are only a few years old.
  - Decline curves are not well established.
  - Cumulative production at this time is, therefore, not a good indicator of potential capacity.
- **The volumetric approach estimates are likely too high.**
  - High OOIP is offset by the extremely tight nature of the formation.
  - Tight rock adversely affects injectivity and storage efficiency.
- **Published studies (e.g., Nutall and others, 2005) for gas-rich shale formations use coal seam storage as an analog, with adsorption of CO<sub>2</sub> onto organic matter in shales playing a major role.**
  - However, organic-rich shales often represent a minority of the rock type found in the tight oil formations currently being developed.

# **“Take Home” Thoughts from Previous Research Efforts**

- **Unconventional resources require an unconventional approach to EOR.**
  - The tight nature of the matrix means that microscale and nanoscale characterization are essential.
  - Diffusion is more important than displacement.
  - Patience is required, but the reward may be substantial.
- **Tight oil formations need their own CO<sub>2</sub> storage capacity estimation method.**
  - More lab and field data are needed to identify, verify, and validate the mechanisms controlling CO<sub>2</sub> storage.
  - A hybrid method that combines some elements of shale gas capacity methods with conventional oilfield methods is suggested.

# Other Relevant Observations

- **Regarding CO<sub>2</sub> movement and behavior in tight rocks:**
  - If the oil in the pores of the matrix can be recovered by CO<sub>2</sub>, then CO<sub>2</sub> must be capable of permeating into the rock matrix.
  - Fluid viscosity and density are much different in nanoscale pores than in macroscale pores (Alharthy and others, 2013).
- **Regarding the role of rock wettability:**
  - Interfacial tension between CO<sub>2</sub> and oil hydrocarbons in rock will be less than between CO<sub>2</sub> and water in rock.
  - Therefore, it is possible the rate of CO<sub>2</sub> permeation through oil-wet rock will occur at lower pressures and be faster than for a water-wet rock.
  - Storage capacity (rate of storage) may be higher in an oil-wet rock than in a water-wet rock.
  - Mixed-wet rocks will obviously complicate the matter....



# 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, fractured reservoirs resulting in an ability to better characterize and determine the storage capacity for CO<sub>2</sub> and EOR potential of tight oil formations.**

- 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<sub>2</sub> permeation and oil extraction rates and mechanisms.
- Integrate the laboratory-based results into geologic models and numerical simulations to assess CO<sub>2</sub> EOR potential and storage capacity of tight oil formations.

# Project Approach – Phase I

- **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<sub>2</sub> capillary entry and breakthrough pressures at the Bakken reservoir–shale interface.**
- **Hydraulically fracture rock core plugs of different lithofacies to determine the 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

## Task 1 – Project Management and Reporting

- Maintain and, where necessary, revise the project management plan.
- Conduct a Project Kickoff Meeting
- Manage and report on activities in accordance with the plan.
- Ensure coordination and planning with the National Energy Technology Laboratory (NETL) and other project participants.
- Submit National Environmental Policy Act (NEPA) documentation for approval.
- Prepare quarterly reports, an interim report between Phases I and II, and a final report.
- Prepare task-specific reports and/or journal manuscripts.



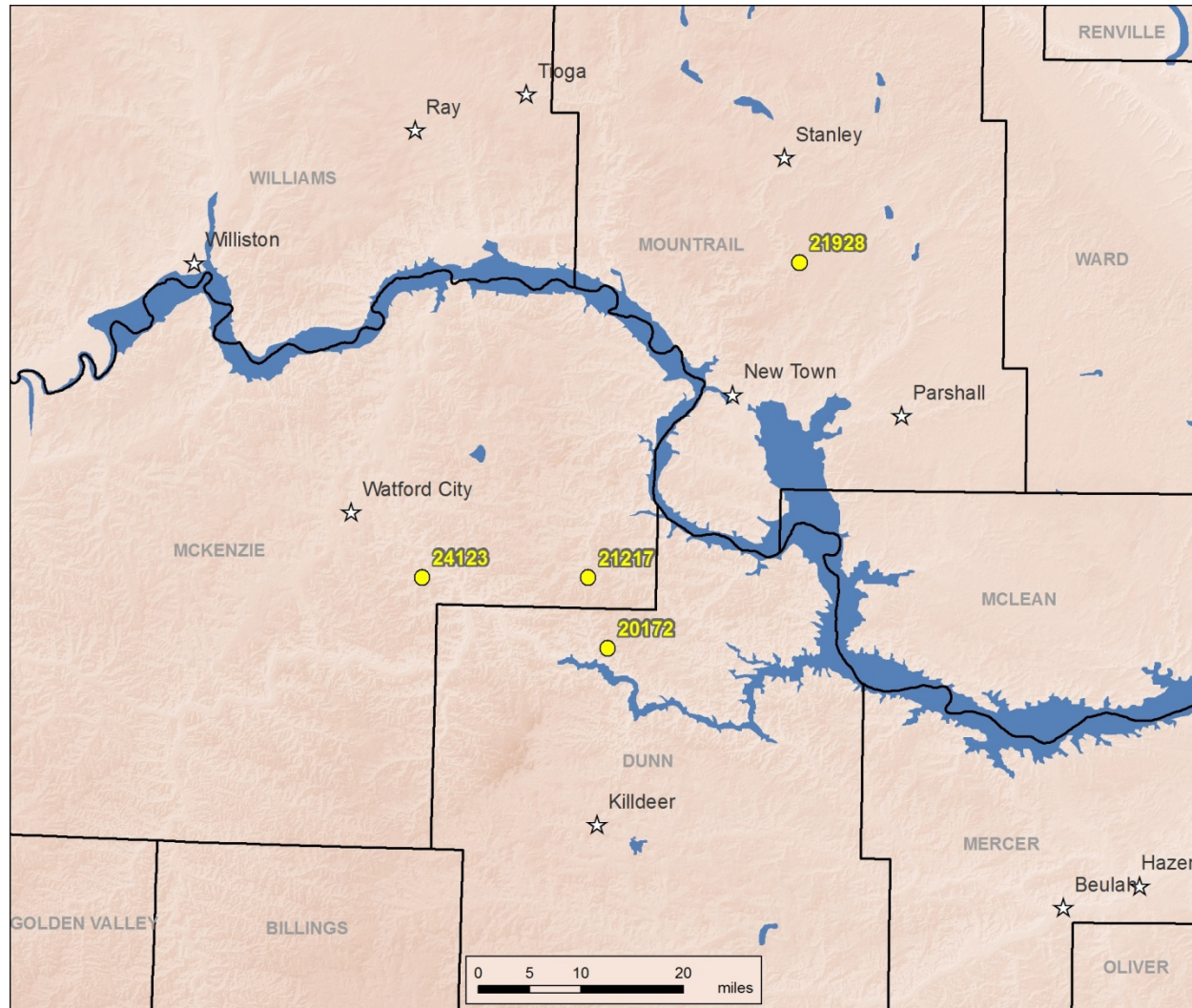
# Phase I Tasks to Be Performed

## Task 2.0 – Sample Selection and Baseline Characterization

- **Subtask 2.1 – Sample Identification and Selection.**
  - Cores will come from at least four locations.
  - At least 14 samples will be taken from each core, representing Middle Bakken reservoir lithofacies, Upper and Lower Bakken shale source rocks, and the reservoir–shale interface.
  - The number of samples will accommodate the variety of planned testing, including some destructive tests.
  - Samples will be provided by the North Dakota Geological Survey.
- **Subtask 2.2 – Laboratory Determination of Baseline Rock Properties.**
  - A suite of geochemical, geomechanical, and petrophysical analyses will be performed.



# Likely Core Sample Locations



# Phase I Tasks to Be Performed

## Subtask 2.2 – Laboratory Determination of Baseline Rock Properties

<u>Analysis Type</u>	<u>Information Derived</u>
Interfacial Tension Test	Contact angle and wettability of select samples
Breakthrough Pressure Test	Entry pressure for select fluid injection
Mercury Injection Capillary Entry Pressure Test	Pore throat size and distribution
Porosity/Grain Density	Rock porosity
XRD	Bulk mineralogy
XRF	Bulk chemistry
SEM–Energy-Dispersive Spectrometry (EDS)	General sample morphology, elemental distribution, and inferred mineralogy
Optical Petrographics	Mineral phases, grains, macrofracture characteristics, and depositional environment
Geomechanical Testing	Peak strength, Young’s modulus, Poisson’s ratio



# Phase I Tasks to Be Performed

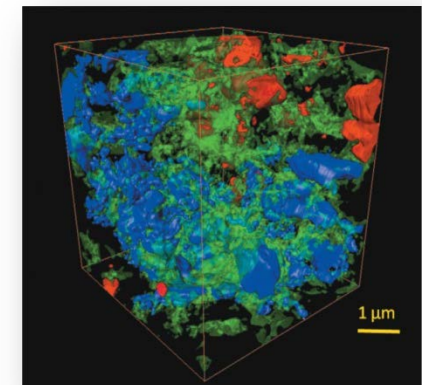
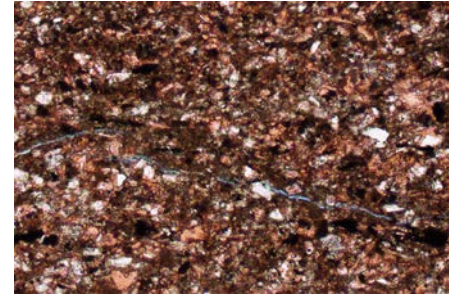
## Task 3.0 – Development of Improved Methodologies to Identify Multiscale Fracture Networks and Pore Characteristics

- **Subtask 3.1 – Corescale Fracture Analysis.**
  - Visual fracture-logging methodology (U.S. Bureau of Reclamation, 1998; Nelson, 2001) by which length, aperture, and orientation of natural fractures are measured.
  - Whole-core computerized tomography (CT) scanning fracture analysis.
  - Hydraulic fracturing of rock core plugs and subsequent analysis of fractures. This will include the creation of epoxy casts of the resulting fracture networks.
  - Results from each rock type will be compared to determine the effects that rock and fluid properties might have on fracture networks.

# Phase I Tasks to Be Performed

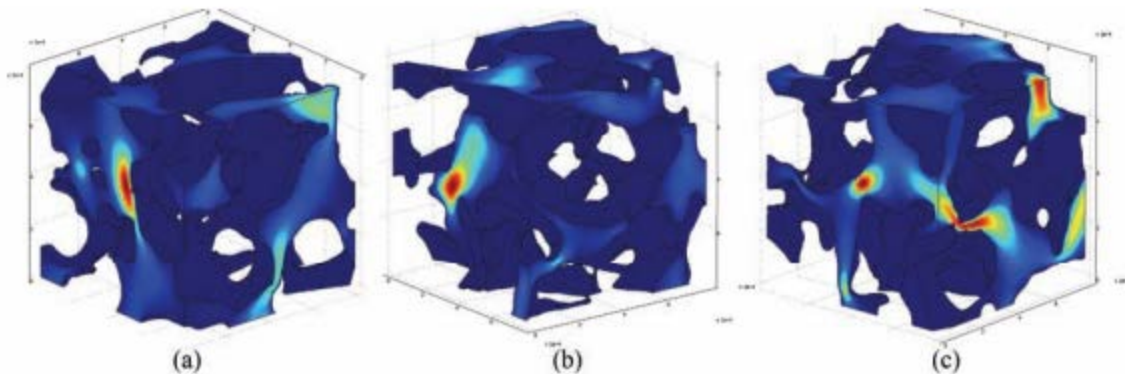
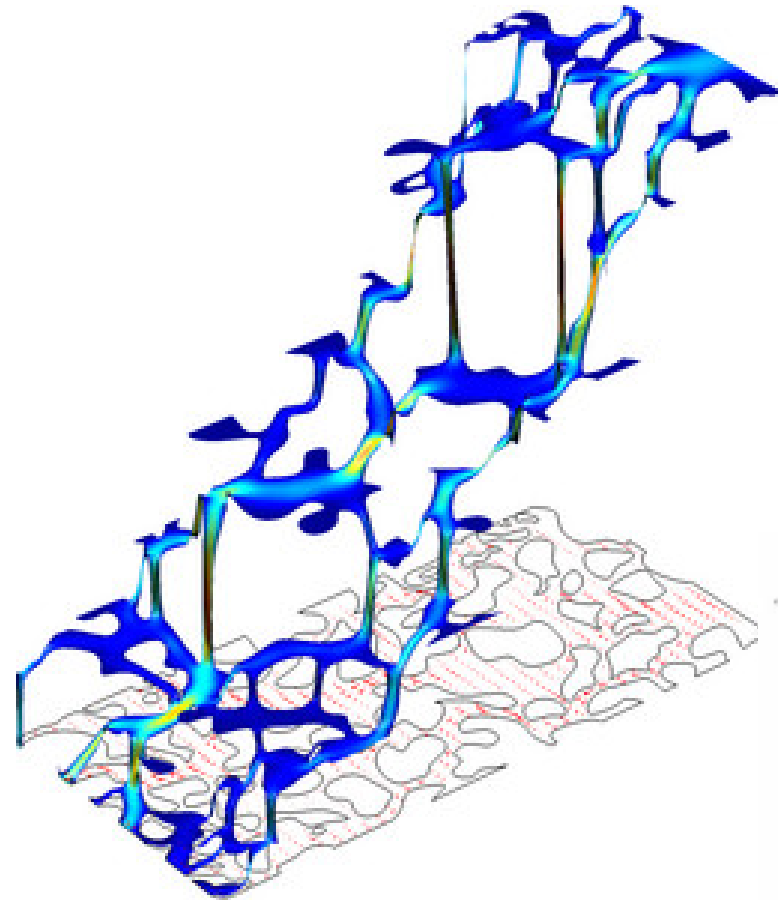
## Task 3.0 – Development of Improved Methodologies to Identify Multiscale Fracture Networks and Pore Characteristics (continued)

- **Subtask 3.2 – Macrofracture Characterization**
  - Ultraviolet fluorescence (UVF) technique using dyes that fluoresce under UV light will help to visualize the fracture network morphology in thin sections.
  - SEM methods will be used for macro- and microscale fracture analysis.
- **Subtask 3.3 – Micro- and Nanoscale Fracture and Pore Analysis**
  - Field Emission (FE)–SEM, micro-CT scanning, and focused-ion beam (FIB)–SEM will be used to characterize micro- and nanoscale fractures and pores.
- **Subtask 3.4 – Development of Multiscale Pore and Fracture Models**
  - Rock characterization data will be upscaled into a multiscale pore and fracture model for geologic model development and pore- and core-scale simulations.
  - Fractal analysis techniques will be used.



# Subtask 3.4 – Pore- and Core-Scale Models and Simulations

- Use CT scans to build matrix and fracture rock properties.
- Lithofacies and variogram ranges from thin sections.
- Pore quantification from SEM.



<http://www.comsol.com/model/pore-scale-flow-488>



# Go/No-Go Decision Point and Criteria

## Go/No-Go Decision Point

- Occurs at the end of BP1.
- The successful identification and characterization of pore and fracture networks in both the reservoir rock (Middle Bakken) and the oil-wet shales (Upper and/or Lower Bakken) will support a “Go” decision.

## Decision Point Criteria

- Fracture characterization data obtained using different methods on the same (or very similar) samples will be compared.
- Data sets that are well correlated using statistically measured differences in key criteria (e.g. mean aperture, intensity, orientation), would support a “Go” decision.
- A decision will then be made in conjunction with NETL on whether or not to proceed to BP2.

# Project Approach – Phase II

- **Determine CO<sub>2</sub> 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<sub>2</sub> EOR and storage potential of the Bakken.**
- **Integrate the results of the characterization and modeling activities to predict CO<sub>2</sub> storage capacities and EOR potential in tight oil formations.**
- **Develop a best practices manual (BPM) on the characterization and modeling of tight oil formations for CO<sub>2</sub> EOR and storage.**

# Phase II Tasks to Be Performed

## Task 4.0 – CO<sub>2</sub> Transport, Permeation, and Oil Extraction Testing

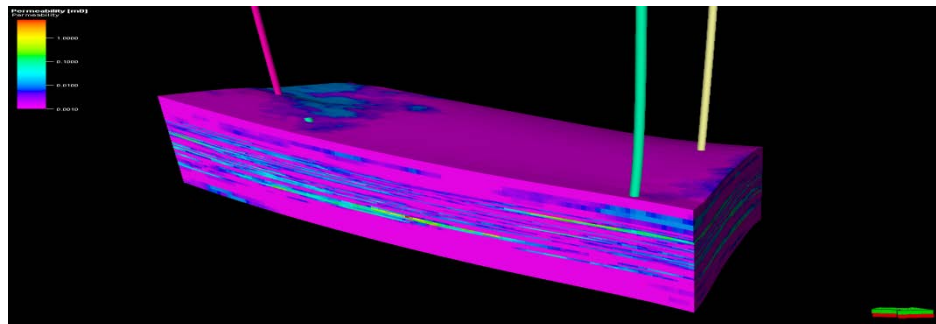
- **Subtask 4.1 – Determination of Permeation Rates in Reservoir Rocks**
  - Flow-through permeability studies will be conducted to generate CO<sub>2</sub>-brine relative permeability data.
- **Subtask 4.2 – Determination of Permeation Rates in Shales**
  - Innovative methods will be applied to generate CO<sub>2</sub> permeation rate data for samples of Upper and/or Lower Bakken shales.
- **Subtask 4.3 – Evaluation of CO<sub>2</sub>-Soluble Tracers**
  - Attempts will be made to identify CO<sub>2</sub> flow patterns and, by extension, determine permeation rates, using a variety of CO<sub>2</sub>-soluble tracers. Fluorescent dyes, UV-visible dyes, and organometallic compounds will be tested using various microscopy techniques.
- **Subtask 4.4 – 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 Tasks to Be Performed

## Task 5.0 – MMPA, Modeling, and Simulation

- **Subtask 5.1 – MMPA Analysis**
  - Core analysis data from Phase I will be integrated with well log data for core-to-log calibration, using approach presented in Klenner and others (2014).
- **Subtask 5.2 – Geocellular Modeling**
  - All of the characterization data and well log correlation results will be brought together to develop a geocellular model.
  - Both matrix and fracture petrophysical modeling will be conducted and the results integrated to create a static model of a Bakken reservoir and shale system in a single drill spacing unit.



# Phase II Tasks to Be Performed

## Task 5.0 – MMPA, Modeling, and Simulation (continued)

- **Subtask 5.3 – Dynamic Simulation of Tight Oil Reservoirs and Shales**
  - Injection simulations will be performed on both Middle Bakken reservoirs and Lower Bakken shales.
  - CO<sub>2</sub> storage efficiency, CO<sub>2</sub> and oil sweep efficiency, and CO<sub>2</sub> storage capacities and potential for EOR will be evaluated.
  - Sensitivity analysis will be run on a variety of parameters to examine their relative effects on CO<sub>2</sub> storage and EOR processes.
  - Injection and production schemes to be simulated include single-well HnP, sequential multiwell HnP, and injector–producer pairs.
  - Middle Bakken simulations will use both oil-wet and mixed-wet systems to examine the effects of wettability on storage and EOR.
  - Shale simulations will be oil-wet, but total organic content and hydrogen index will be varied to examine the effects of shale maturity.

# Phase II Tasks to Be Performed

## Subtask 5.4 – Best Practices Manual for CO<sub>2</sub> Storage and EOR Potential Estimation of Tight Oil Formations

- **Using the Bakken as a case study, a BPM will be developed that includes:**
  - Detailed descriptions of the methods developed and used under this project and their potential application to tight oil formations.
  - Key considerations related to the characterization and modeling of tight oil formations.
  - A summary of the limitations of current analytical techniques and technologies.



# Improved Characterization and Modeling of Tight Oil Formations – Partners Roles

## EERC

- Project management and reporting.
- Porosity and permeability testing.
- Geomechanical testing.
- SEM, XRD, and XRF.
- Thin-section interpretation.
- CO<sub>2</sub> permeation and hydrocarbon extraction experiments.
- Static and dynamic modeling.

## North Dakota Geological Survey

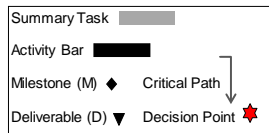
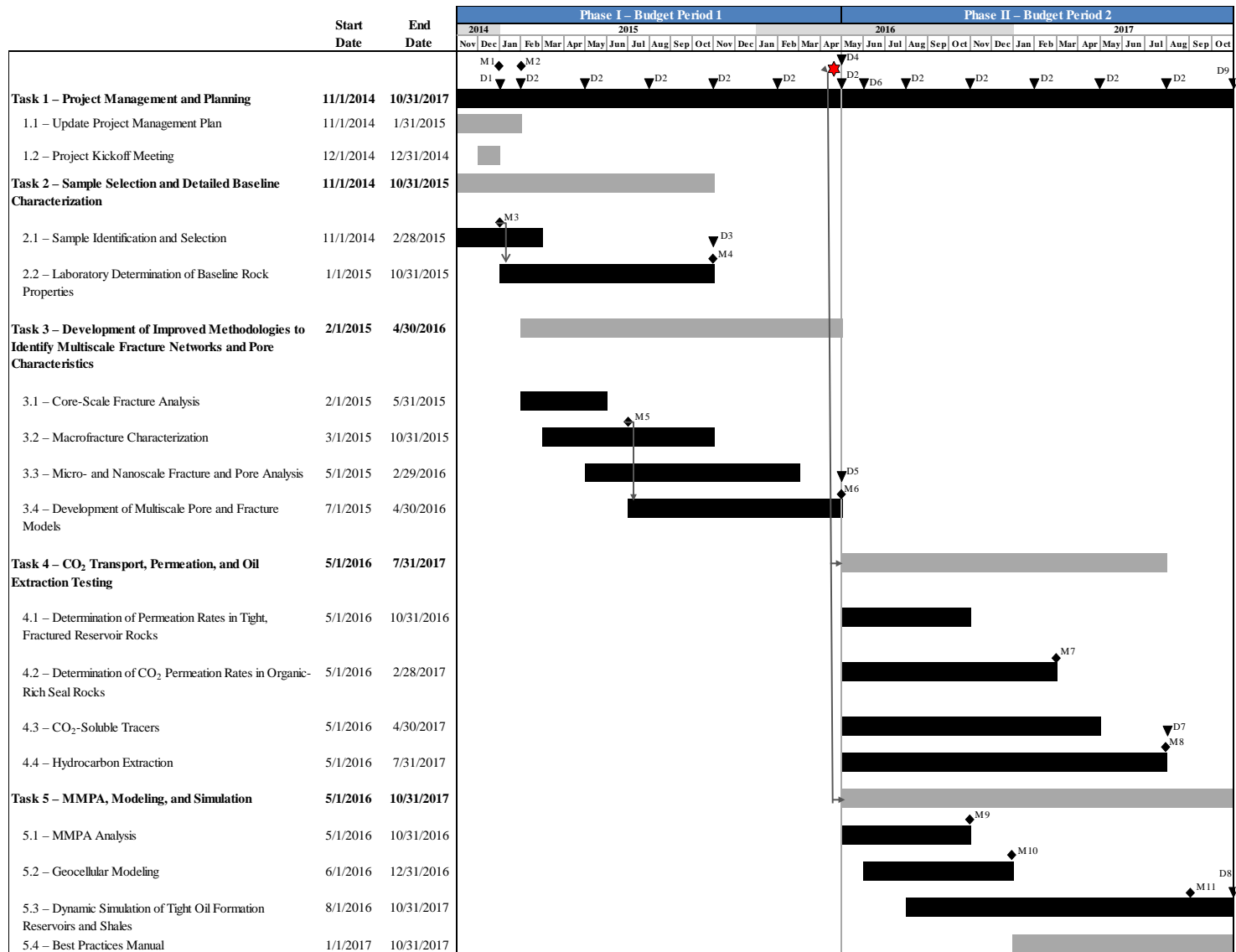
- Providing access to core samples for all project activities.

## Ingrain

- Whole-core CT scanning.
- Micro-CT scanning.
- High-resolution SEM analysis, including 3-D FIB SEM.

# Project Resources

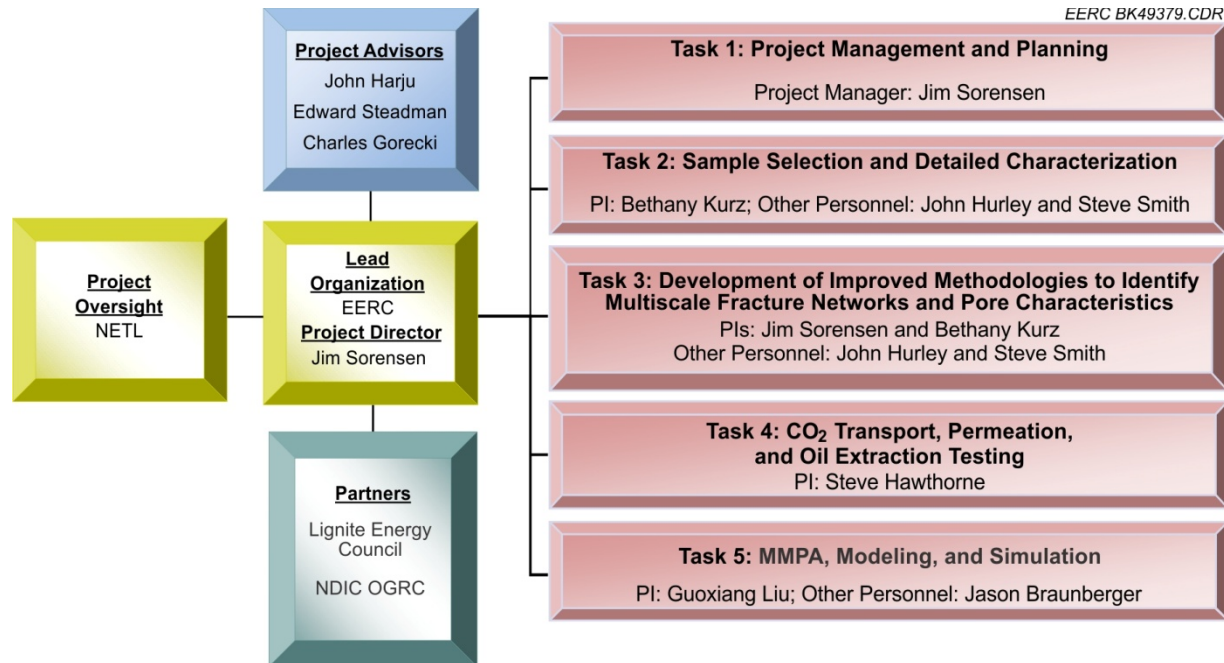
Sponsors	Dollar Value
DOE (cash)	\$2,000,000
Lignite Energy Council (cash)	\$250,000
North Dakota Oil and Gas Research Council (cash)	\$250,000
<b>TOTAL</b>	<b>\$2,500,000</b>



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 <sub>2</sub> Permeation and Oil Extraction Rates in Tight Oil Formations	M7 – Completion of CO <sub>2</sub> Permeation Testing
D8 – Best Practices Manual – Estimation of CO <sub>2</sub> 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



# Organization Chart and Communication Plans



Internal and external kickoff meetings will be held to communicate project goals, objectives, and technical work plans to the relevant project participants.

Monthly meetings between project advisors, task managers, and key personnel will be held throughout the course of the project.

Regularly scheduled calls with the NETL Federal Project Manager will be conducted.

Monthly and quarterly progress reports will be provided to project partners.

# Risk Matrix

## Risk Management

- **Technical Risks:**
  - Inability to adequately identify and characterize nanoscale features. This is mitigated by:
    - Using literature and equipment specifications to ensure that FE-SEM and FIB-SEM have the necessary resolution.
    - Using other techniques (i.e. micro-CT scans) combined with the other characterization data to help verify and validate results.
  - Inability to model, with confidence (because of lack of data) all of the formation characteristics that are important to CO<sub>2</sub> storage and EOR in tight oil formations.
    - The modeling-related risks do not threaten the success of the project.
    - Challenges that arise with the modeling will set the bounds on what can currently be technically accomplished as dictated by the current state of modeling software relative to its use in tight oil formations for CO<sub>2</sub> EOR and storage.

# Benefits of the Work To the Program

## **Goal 1– Develop and validate technologies to ensure 99% storage permanence**

- The lab data on CO<sub>2</sub> permeation into tight oil formations will help determine the suitability of these rocks to serve as storage formations. The data will enable more accurate modeling which will support efforts to design injection and monitoring schemes that ensure 99% storage permanence.

## **Goal 2 – Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness**

- Using both fractured reservoir rocks and oil-wet shales for this effort will yield understanding of both the storage capacity and EOR potential of tight oil reservoirs and the ability of oil-wet shales to serve as seals for CO<sub>2</sub> storage.

## **Goal 3 – Support the ability to predict CO<sub>2</sub> storage capacity to within $\pm 30\%$**

- To meet this goal, improved characterization techniques for tight oil formations must be developed. This effort will result in methodologies to better characterize tight oil formations.

## **Goal 4 – Develop BPMs for site screening, selection, and characterization**

- A direct outcome of this project will be the development of a BPM for estimating the CO<sub>2</sub> storage capacity and potential for EOR of tight oil formations using the advanced characterization techniques and methods previously discussed.



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