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

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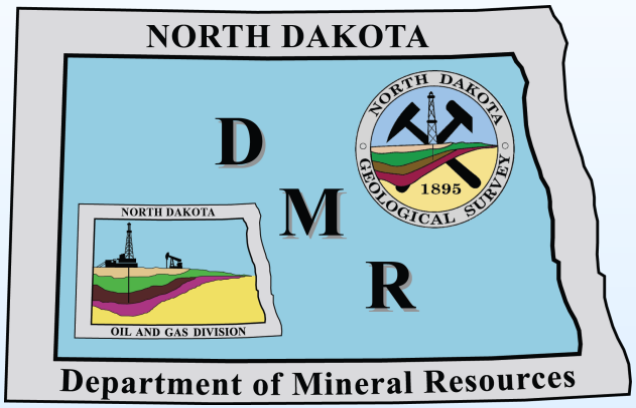
Presentation Outline

- Background
- Phase I Activities
- Accomplishments Thus Far
- Phase II Activities
- Summary
- Anticipated Outputs

Characterization and Modeling of Tight Oil Sponsoring Partners

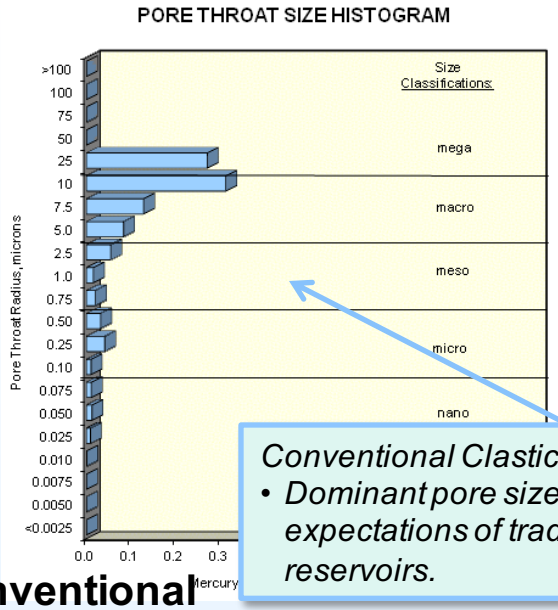
North Dakota
oil & gas research program

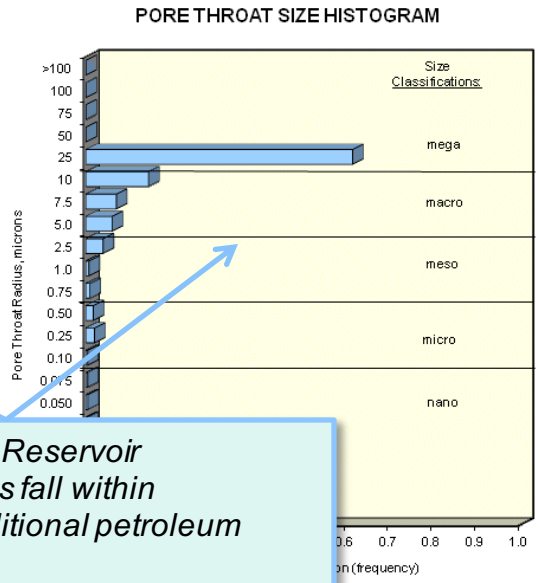
Other Supporters

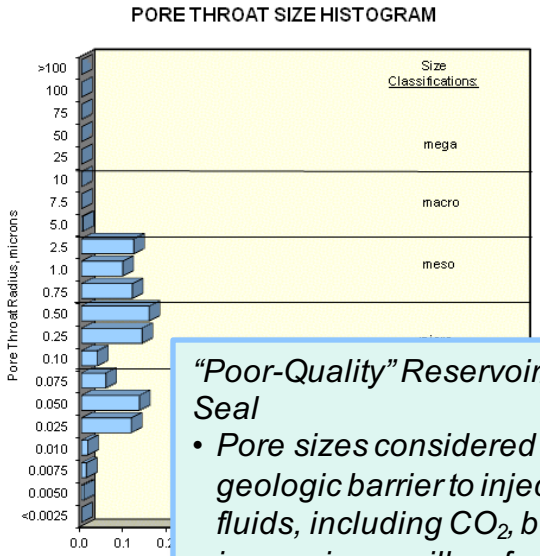


What Is Tight Oil? Comparison of Pore Throat Sizes

Conventional



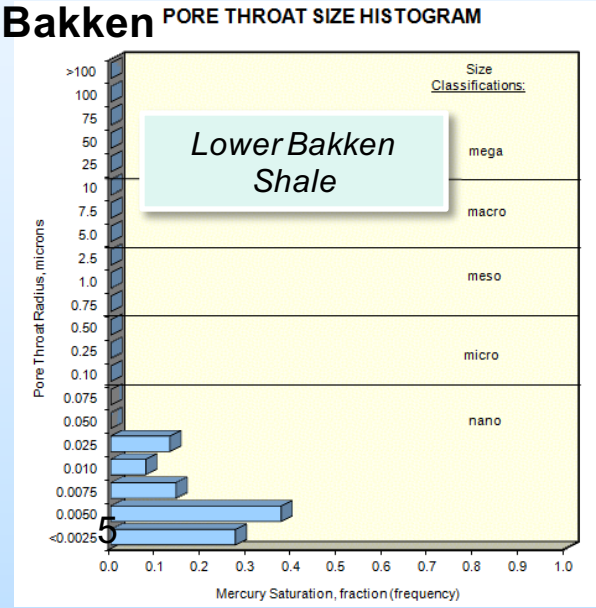




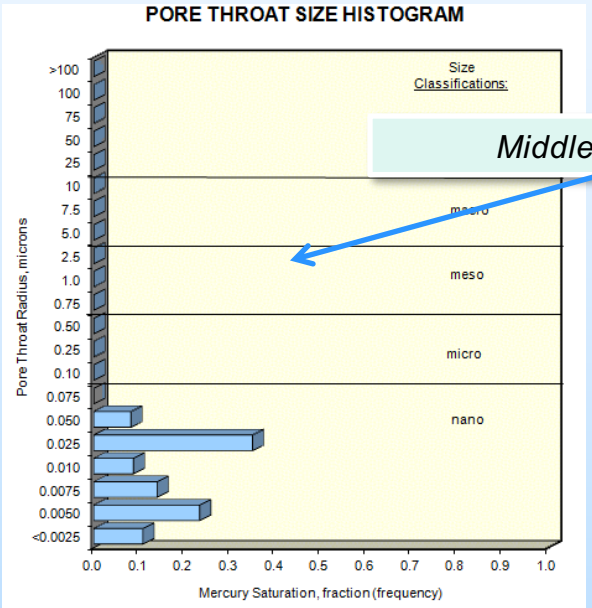
Conventional Clastic Reservoir
- *Dominant pore sizes fall within expectations of traditional petroleum reservoirs.*

"Poor-Quality" Reservoir/Lower Seal
- *Pore sizes considered to be a geologic barrier to injected fluids, including CO_2, because of increasing capillary forces.*

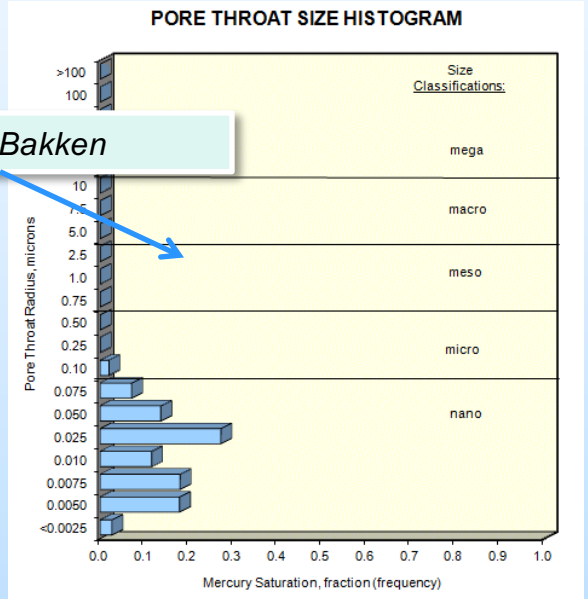
Bakken



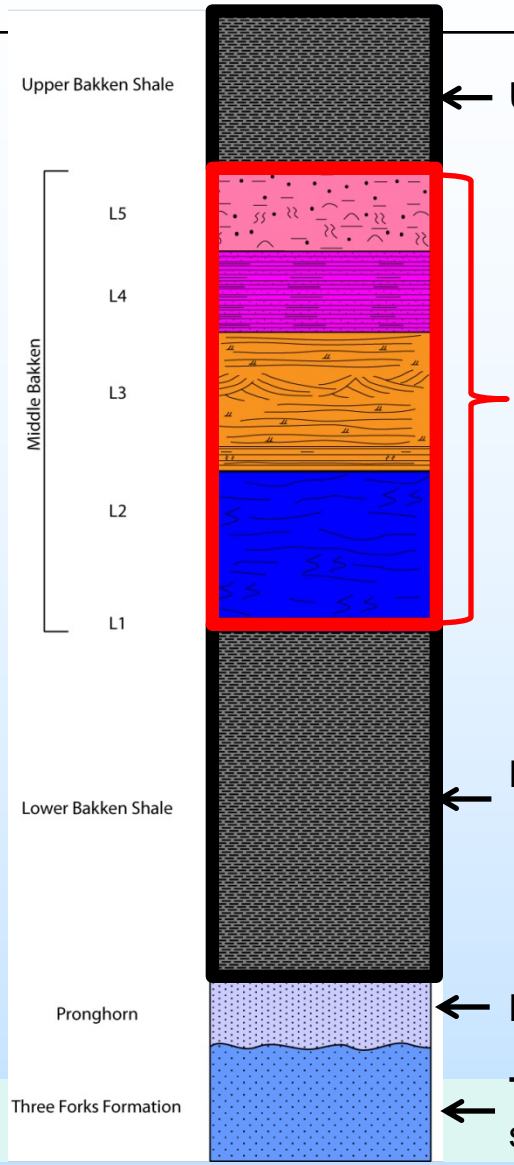
Lower Bakken Shale



Middle Bakken



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.

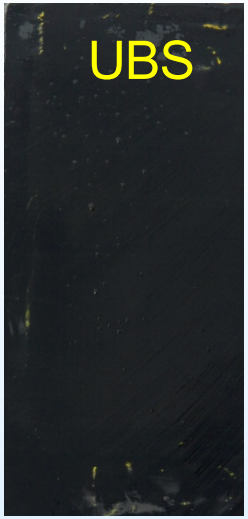
Three Forks Formation: Interbedded dolostone/limestone, siltstone/mudstone, shale, and evaporites.

The Rocks Within the System Are Complex

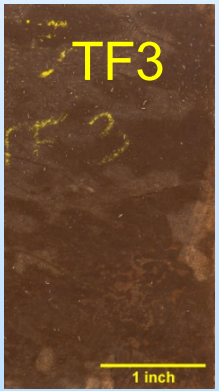
Upper Shale

Middle Bakken Lithofacies

Lower Shale

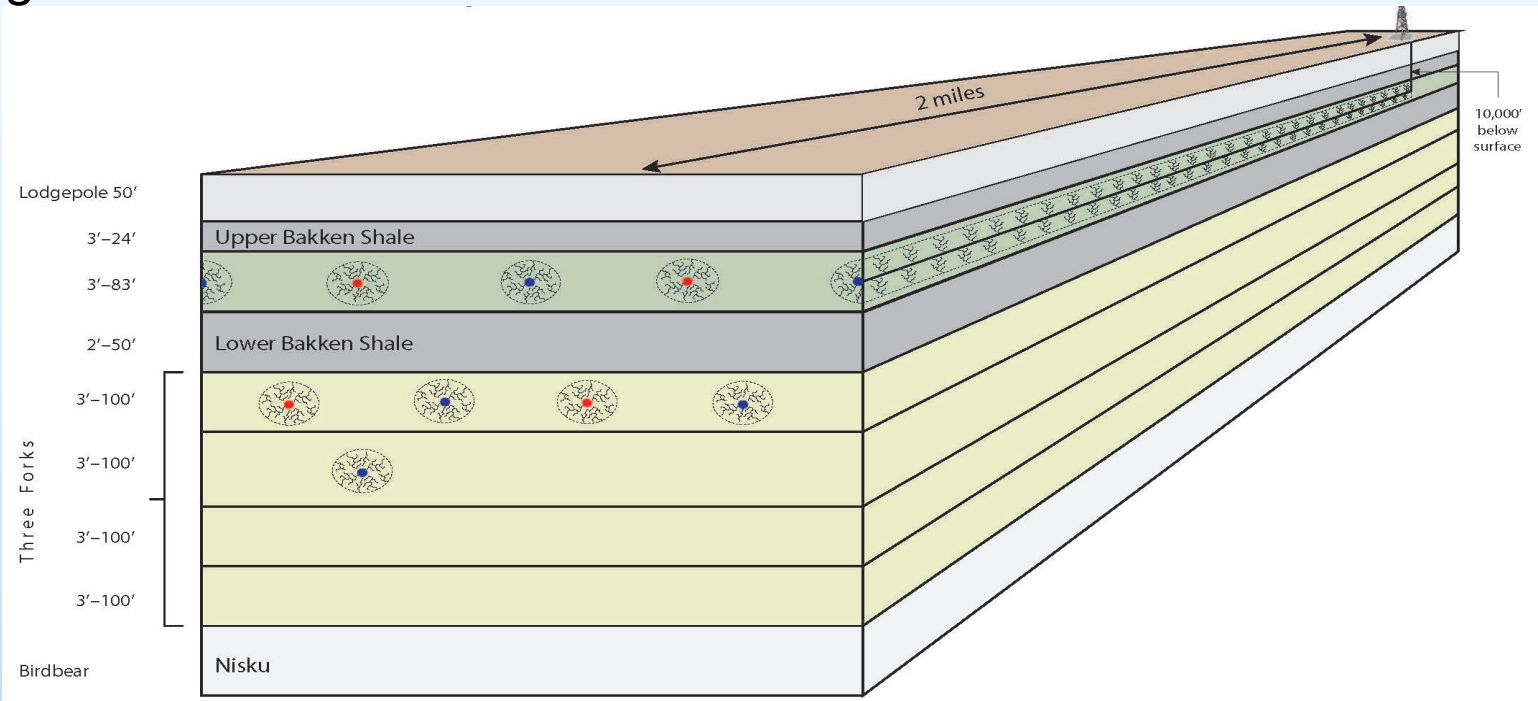


Three Forks Lithofacies



Bakken Petroleum System 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



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.

Benefit to the Program: Applicability to Many Formations

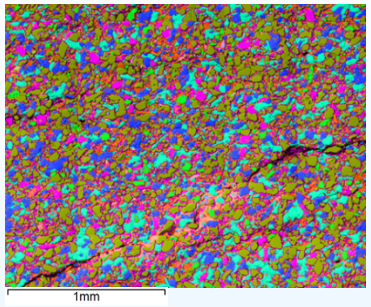
- Tight oil and gas plays are found throughout North America.
- Methods and insights gained in this project can be applied to many, if not all, of these formations.
- Understanding the movement of CO_2 within and/or through these tight formations is critical to understanding their roles in carbon capture and storage (CCS) (sinks or seals?).
- Supports industry's ability to predict CO_2 storage capacity in geologic formations within ±30%.

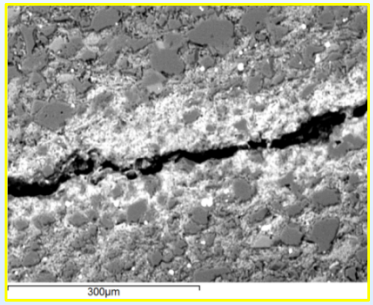
Source: Energy Information Administration based on data from various published studies.
Updated: March 21, 2011

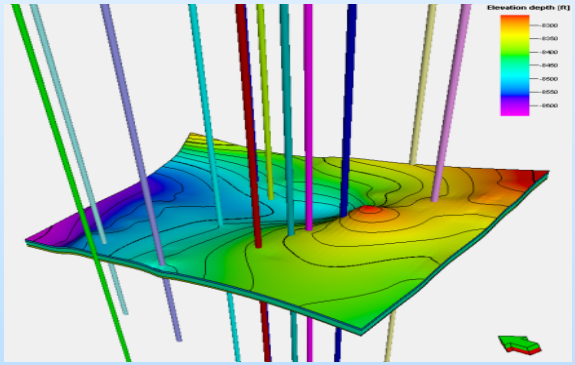
How Previous Characterization Efforts Informed This Project

Reservoir Characterization Is Key to Understanding Fluid Movements

- Movement of fluids 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.
- Generating macrofracture and microfracture data and integrating those data into modeling are essential to develop effective storage and EOR strategies.

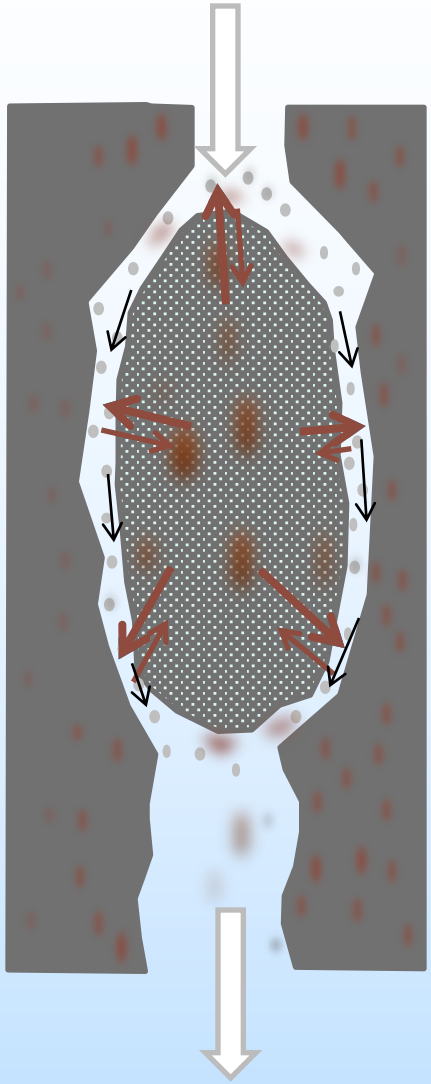




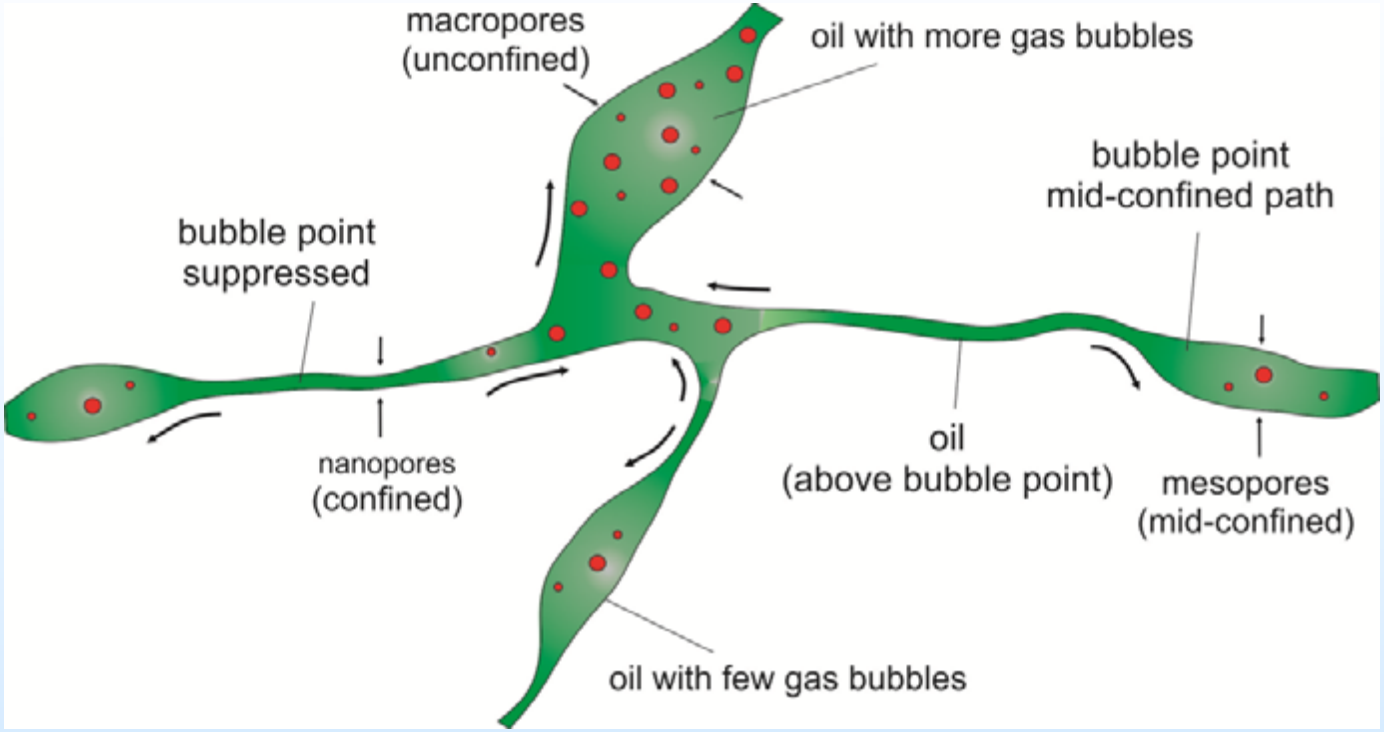


Other Relevant Observations

- **CO_2 movement and behavior in tight rocks:**
  - If the oil in the pores of the matrix can be recovered by CO_2, then CO_2 must be capable of permeating into the rock matrix.
  - Fluid viscosity and density are much different in nanoscale pores than in macroscale pores.
- **The role of rock wettability:**
  - Interfacial tension between CO_2 and oil hydrocarbons in rock will be less than between CO_2 and water in rock.
  - Therefore, it is possible that the rate of CO_2 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….



Pore Size Affects Fluid Phase Behavior



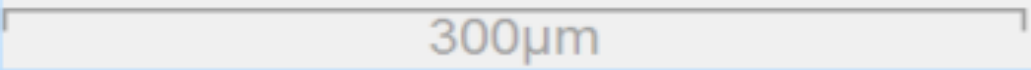
Conceptual pore network model showing different phase behavior in different pore sizes for a bubblepoint system with phase behavior shift.

Source: Alharthy, Nguyen, Teklu, Kazemi, and Graves, 2013, SPE 166306
Colorado School of Mines and CMG

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.**



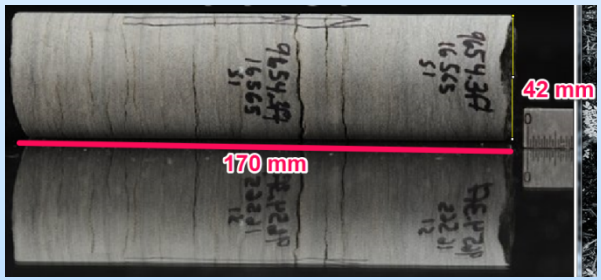
Project Approach – Phase I (November 2014 to March 2016)

- 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.

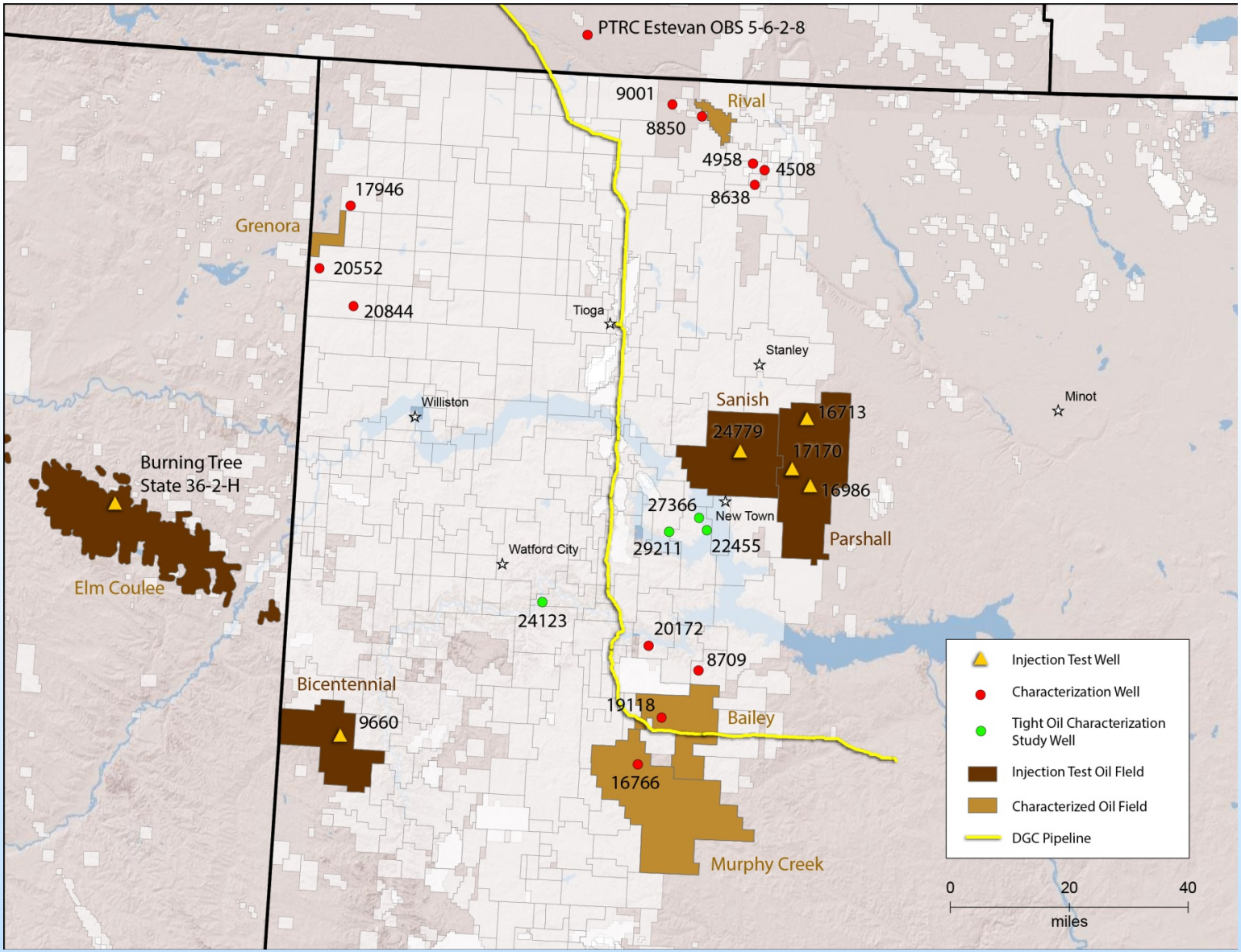
Phase I Tasks Being Performed

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 the North Dakota Geological Survey (NDGS).
- A suite of geochemical, geomechanical, and petrophysical analyses are being performed.



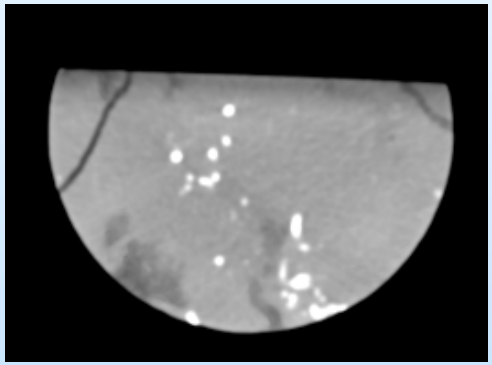
Core Sample Locations



Phase I Tasks Being Performed

Development of Improved Methodologies to Identify Multiscale Fracture Networks and Pore Characteristics

- Core-scale fracture analysis.
  - Visual fracture-logging methodology by which length, aperture, and orientation of natural fractures are measured.
  - Whole-core CT scanning fracture analysis.
  - Hydraulic fracturing of rock core plugs and subsequent analysis of fractures.
  - Results from each rock type will be compared to determine the effects that rock and fluid properties might have on fracture networks.

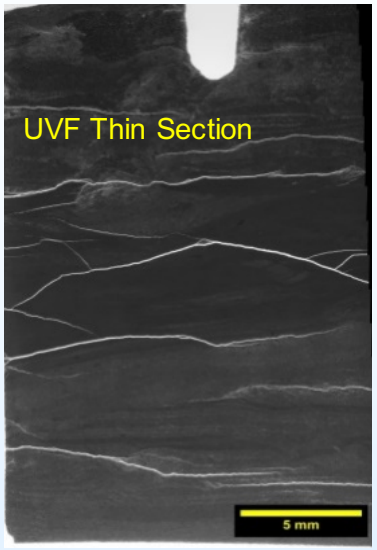


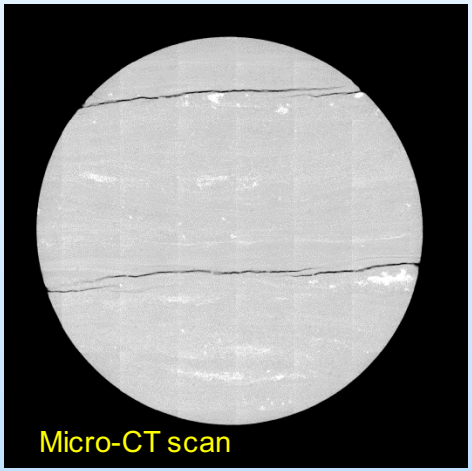
CT Scan Axial Slice
Core Diameter: 4 inches

Phase I Tasks Being Performed

Development of Improved Methodologies to Identify Multiscale Fracture Networks and Pore Characteristics (continued)

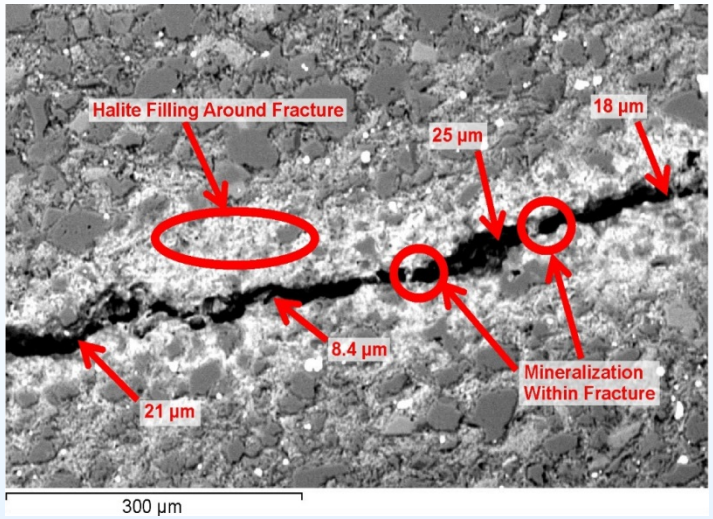
- Macrofracture characterization
  - Ultraviolet fluorescence (UVF) technique using dyes that fluoresce under UV light will help to visualize the fractures.
  - Scanning electron microscopy (SEM) methods will be used for macro- and microscale fracture analysis.
- Micro- and nanoscale fracture and pore analysis
  - Field emission (FE)–SEM, micro-CT scanning, and focus ion beam (FIB)–SEM will be used to characterize micro- and nanoscale fractures and pores.

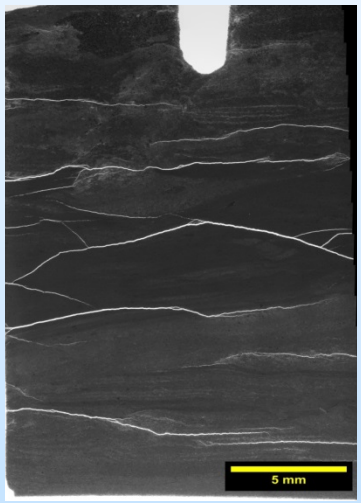


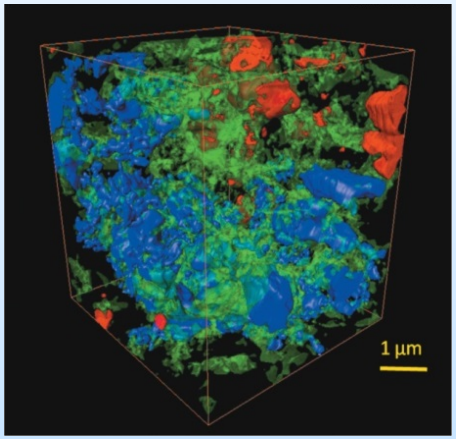


Analysis of Fractures

- Macro-, micro, and nanoscales:
  - Fracture properties
    - Measure aperture, length, and orientation
    - Open vs. closed
- Utilize macrofracture and microfracture data to help populate fracture properties in the static geologic model.

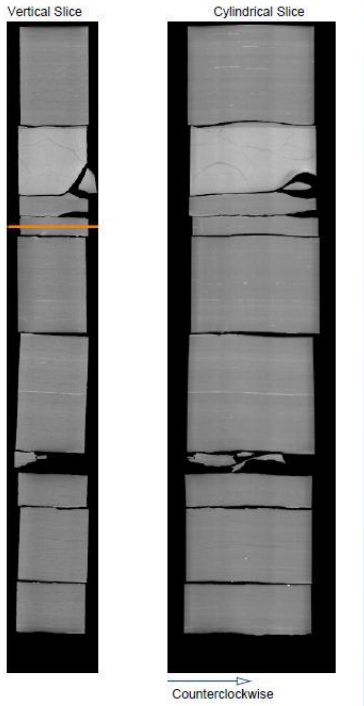


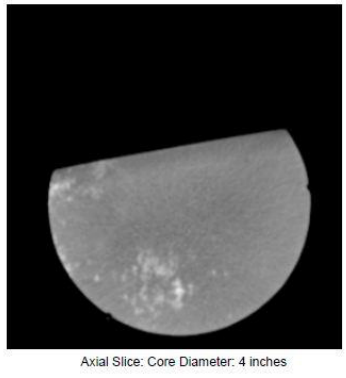




Project Accomplishments Thus Far

Whole-Core CT Scan



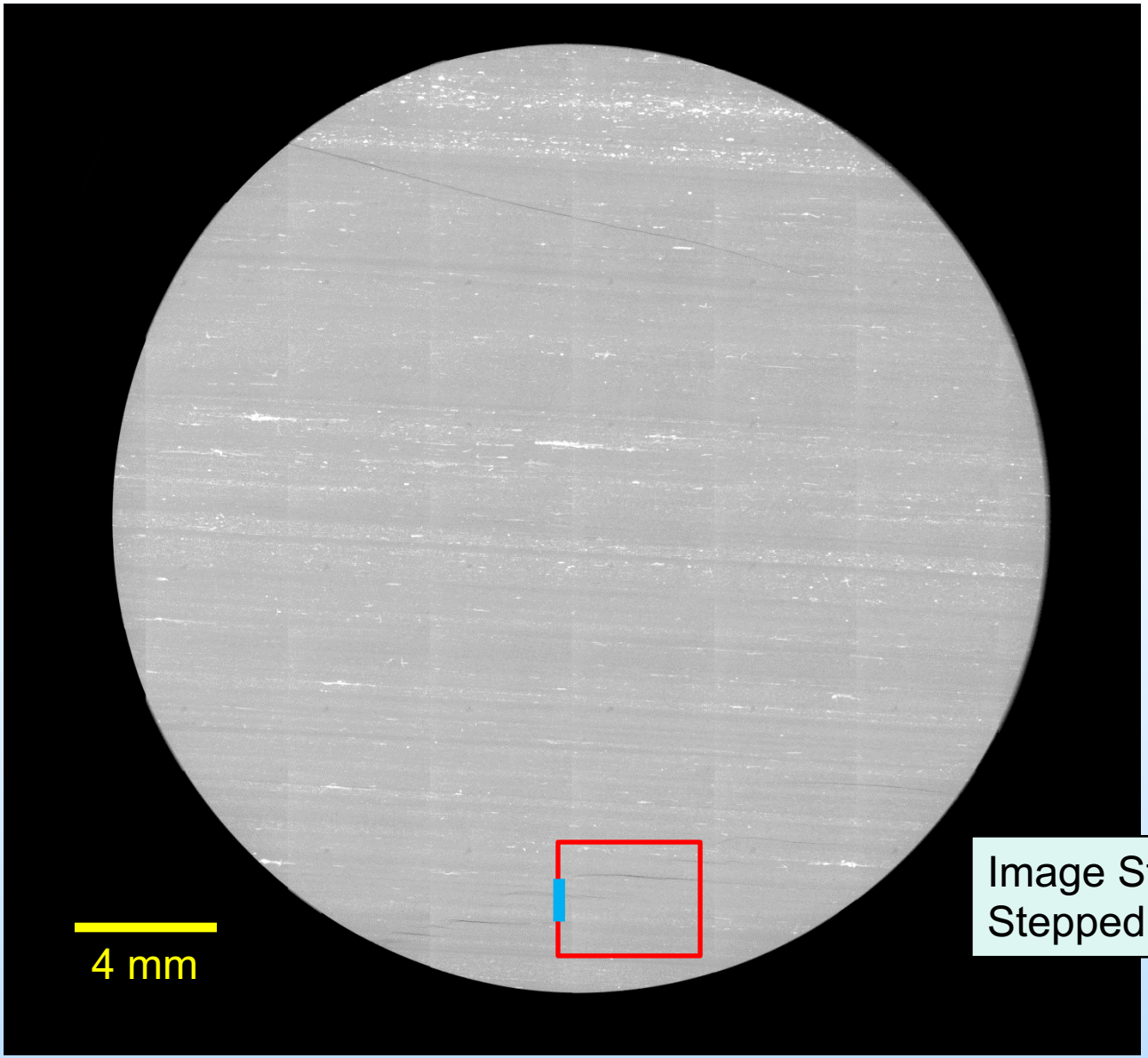


Core samples have been obtained.

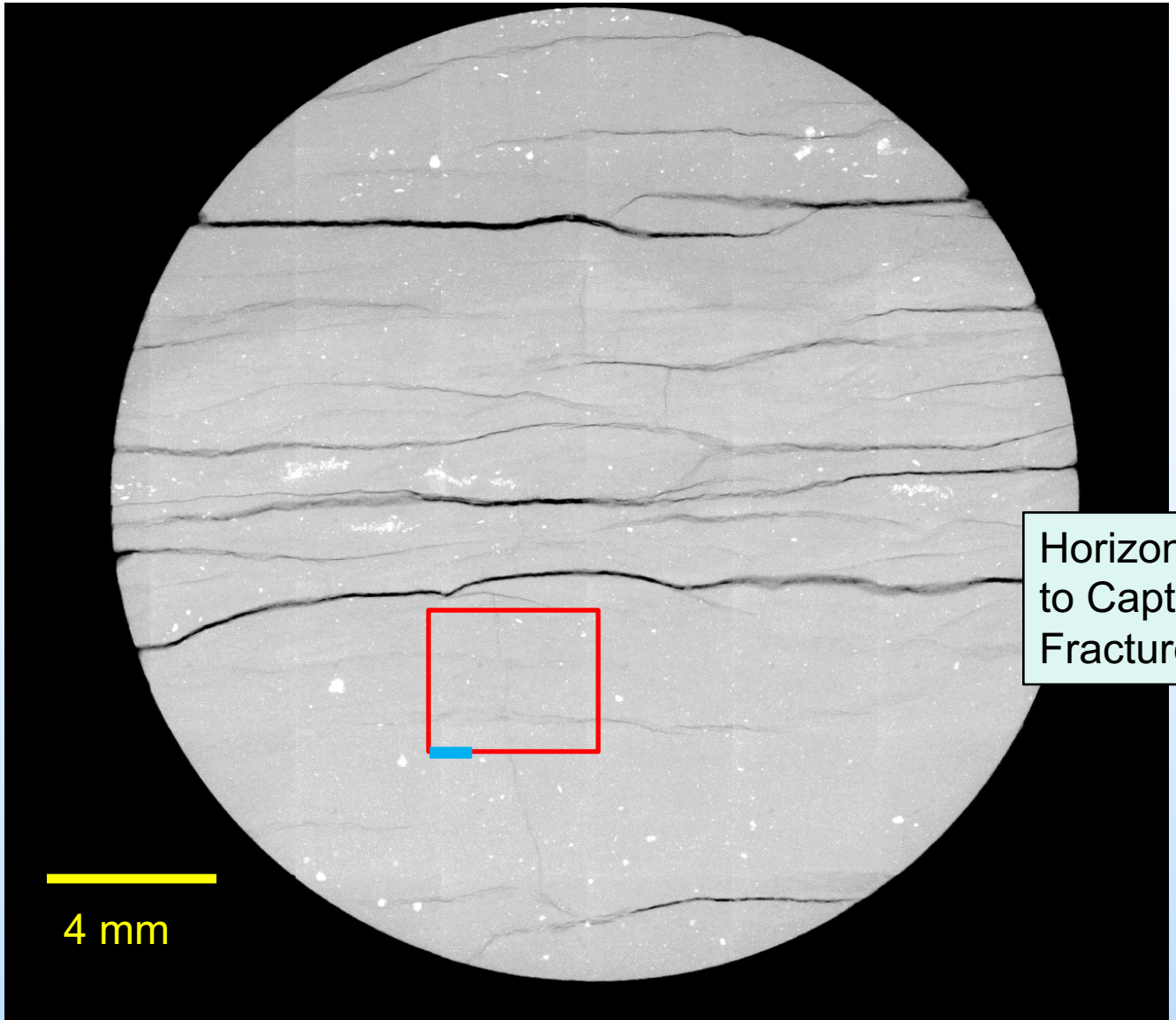
- Marathon has provided core from three wells; NDGS has provided core from one well.
  - “Standard” porosity, permeability, grain density, and fluid saturation data have been generated for all four wells.
  - Whole-core CT scanning has been performed for three wells.
  - Micro-CT scanning has been performed on cores from two wells.
  - Geomechanical studies have been initiated.

Epoxy Cast of Induced Fracture Network in Shale Plug Sample

Micro-CT – Upper Bakken Shale



Micro-CT – Middle Bakken Laminated Zone



Horizontal Polish to Capture Vertical Fracture in Matrix

Micro-CT – Middle Bakken Burrowed Zone

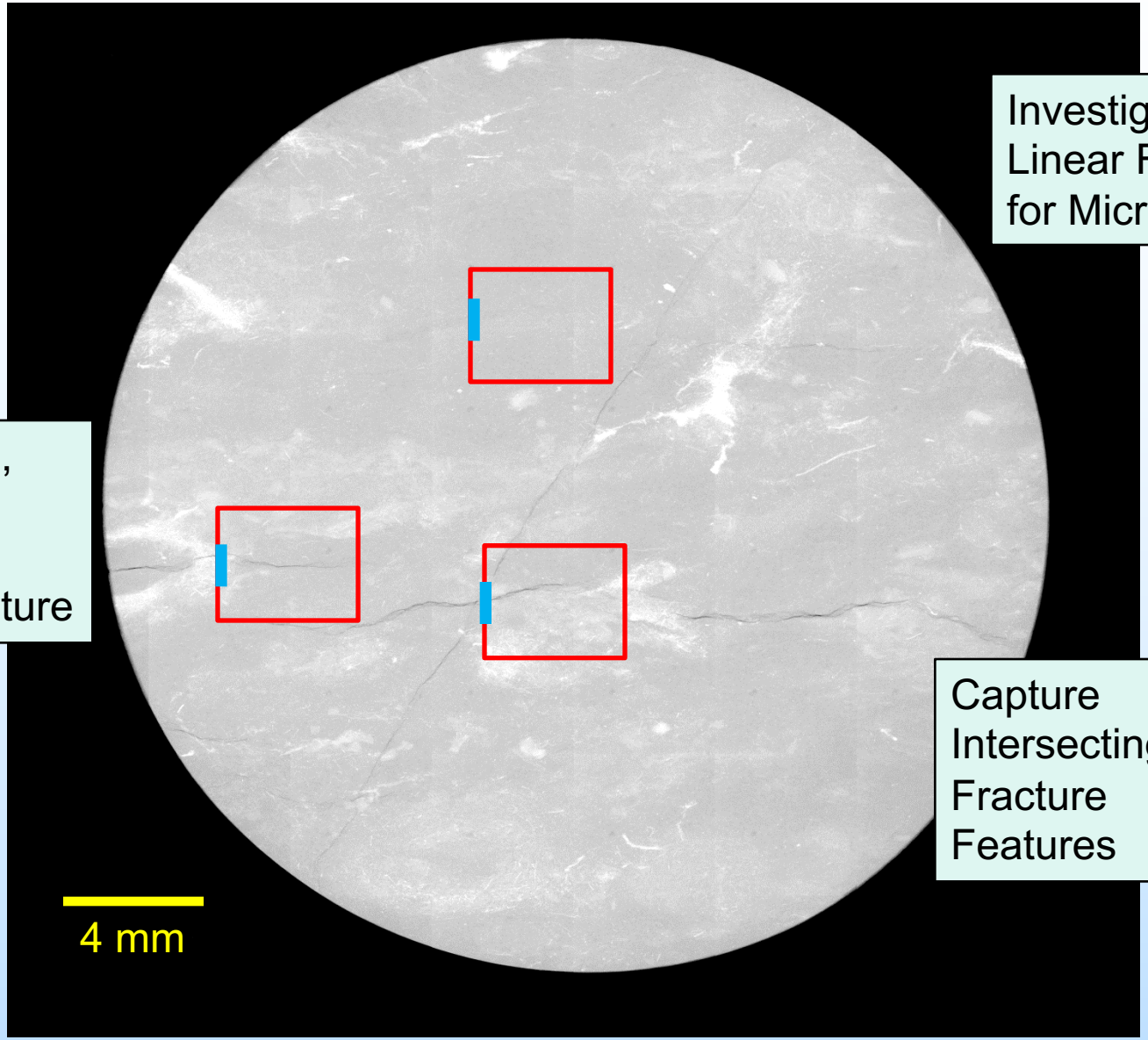


Image Fibrous, High-Density Features near Shell-Like Feature

Investigate Faint Linear Feature for Microfractures

Capture Intersecting Fracture Features

Micro-CT – Lower Bakken Shale

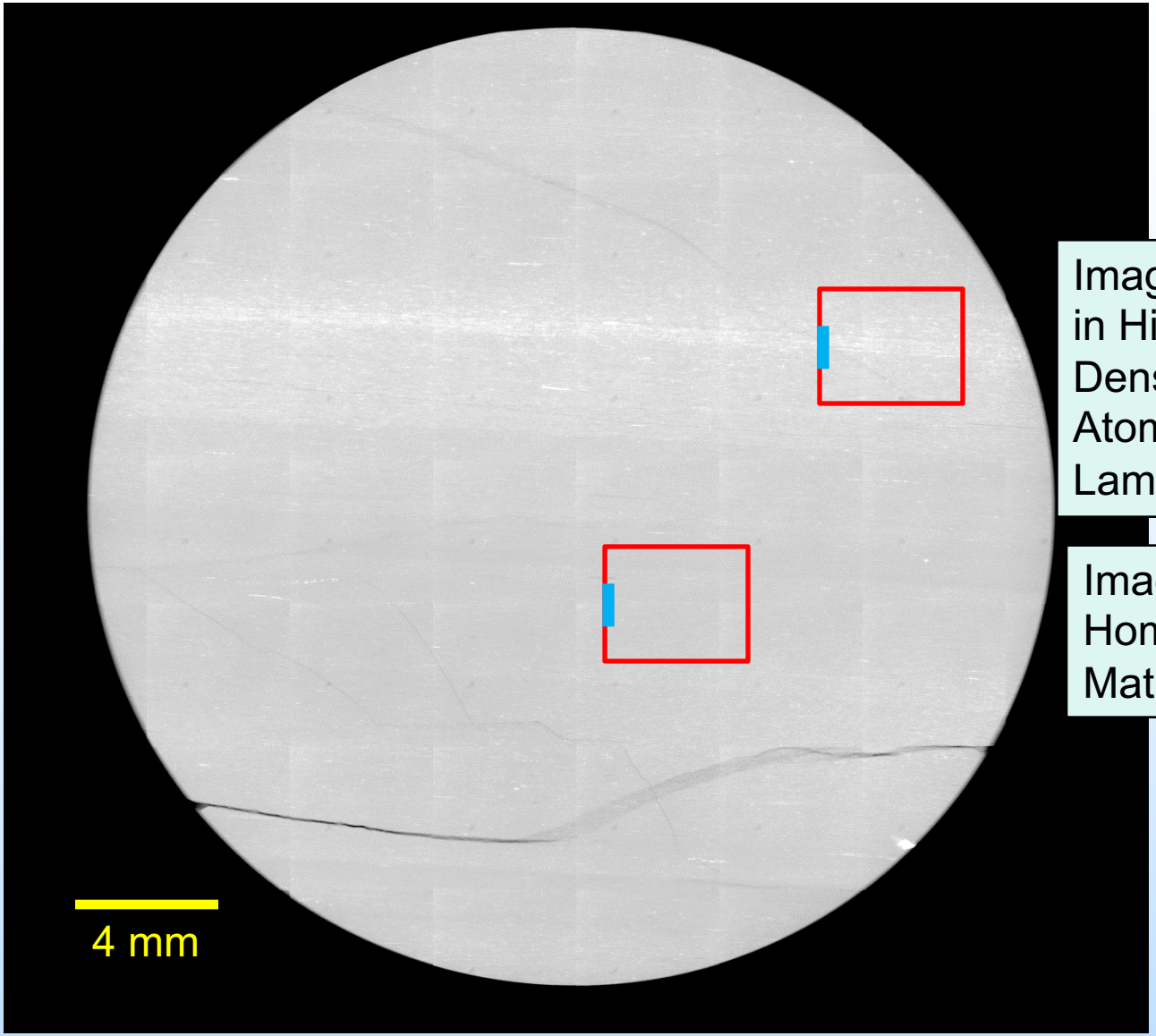
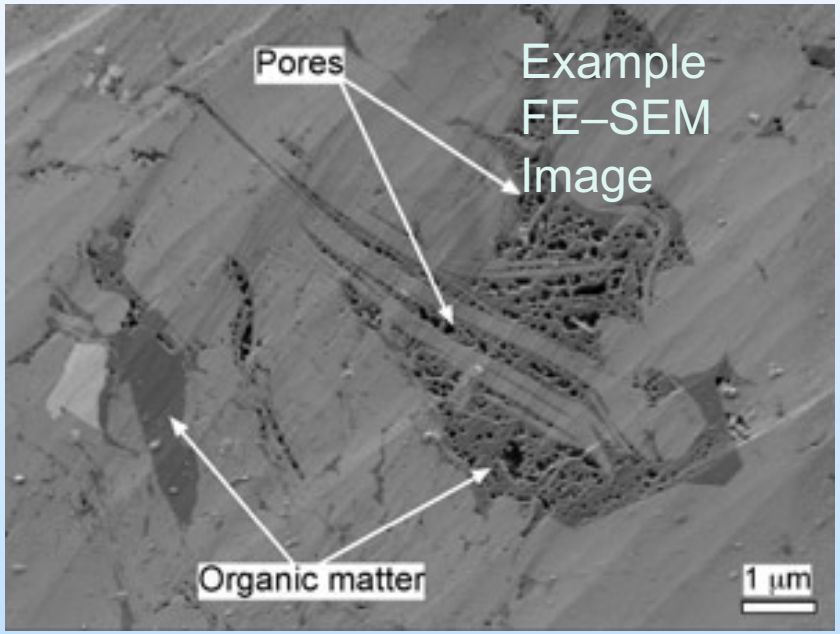


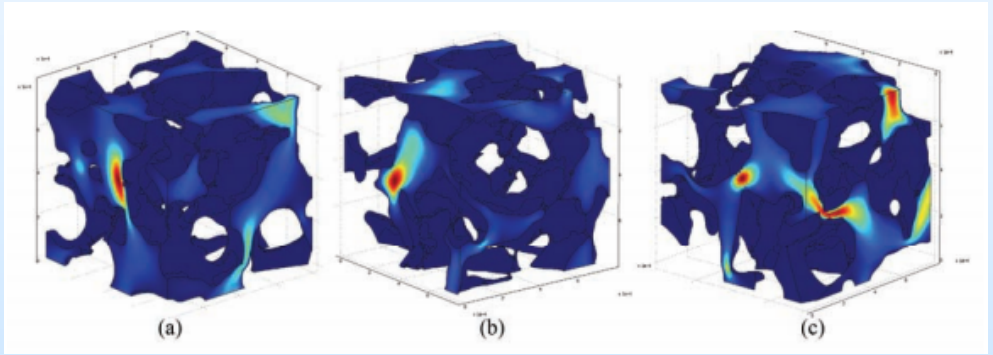
Image Fracture in Higher-Density or Atomic Number Lamination

Image Homogeneous Matrix

Next Step 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.
- Fractal analysis techniques will be used.





Pore-Scale Modeling

Future Activities – Phase II (April 2016 to October 2017)

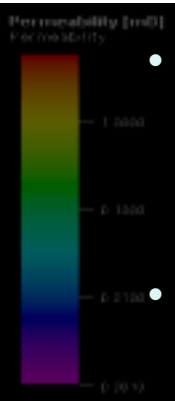
- **Determine CO_2 permeation rates and oil extraction rates from samples of Bakken reservoir and shales using flow-through and static exposure testing.**
- **Use multimineral petrophysical analysis (MMPA) to correlate well logs with lab characterization data, thereby more accurately distributing reservoir 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



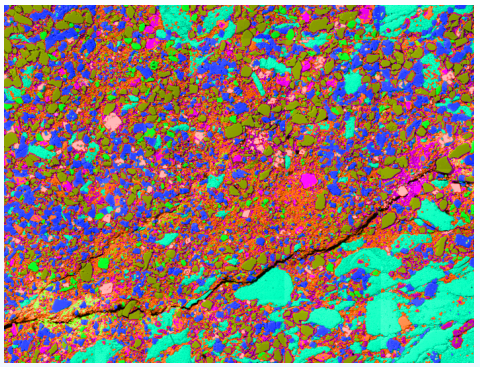
- MMPA
  - Core analysis data will be integrated with well log data for core-to-log calibration.
- Geocellular modeling
  - MMPA results will be applied to develop Bakken reservoir and shale system geocellular models in a single drill spacing unit.
- Simulations
  - Will be conducted on both Middle Bakken reservoirs and Lower Bakken shales.
  - Single-well huff ‘n’ puff (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.

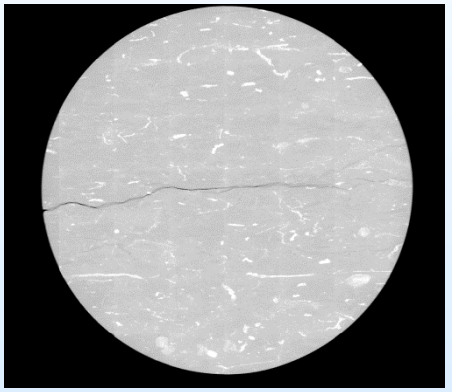
Anticipated Outputs

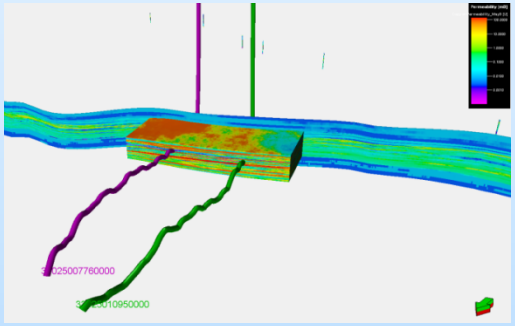
- Successful completion of these laboratory and modeling efforts will yield:
  - Multiscale fracture characterization data that support the development of multiscale pore and fracture models.
  - Improved characterization methods through comparison of fracture data obtained using different methods on the same samples.
  - New knowledge of the pore and fracture networks in both the fractured reservoir samples and the oil-wet shale samples.
  - Development of CO_2 permeation data on different lithofacies and different wettability conditions.
  - Development of geostatic models and simulation results that yield estimates of CO_2 storage and EOR potential.

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
  - Improved knowledge of nanoscale pore networks
  - Novel approaches to rock CO_2 permeation and hydrocarbon extraction studies
  - Improved modeling workflows and enhancements to existing software packages







Key Deliverable Product from the Project

BPM for CO_2 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.

Thanks!

EERC
Energy & Environmental Research Center

Appendix

Supplemental Slides

Project Overview: Goals and Objectives

- Describe the project goals and 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_2 and EOR potential of tight oil 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 BPMs
    - BPM on CO_2 Storage and EOR Potential Estimation of Tight Oil Formations
- Success criteria
  - Collection of rock samples.
  - Generation of macroscale and microscale fracture characterization data.
  - Development of multiscale pore and fracture models using image analysis.
  - Comparison of fracture data obtained using different methods on the same samples.
  - The go/no-go decision point to initiate Phase II is the successful identification and characterization of the pore and fracture networks in both the fractured reservoir samples and the oil-wet shale samples.
  - Development of CO_2 permeation data on different lithofacies and different wettability conditions.
  - Development of geostatic models and simulation results that yield estimates of CO_2 storage and EOR potential.
  - Transfer the knowledge gained by the project to the CCS and EOR technical community at large through final reports, presentations, and published papers.

Improved Characterization and Modeling of Tight Oil Formations – Partner Roles

EERC

- Project management and reporting
- Porosity and permeability testing
- Geomechanical testing
- SEM, x-ray diffraction (XRD), and x-ray fluorescence (XRF)
- Thin-section interpretation
- CO_2 permeation and hydrocarbon extraction experiments
- Static and dynamic modeling

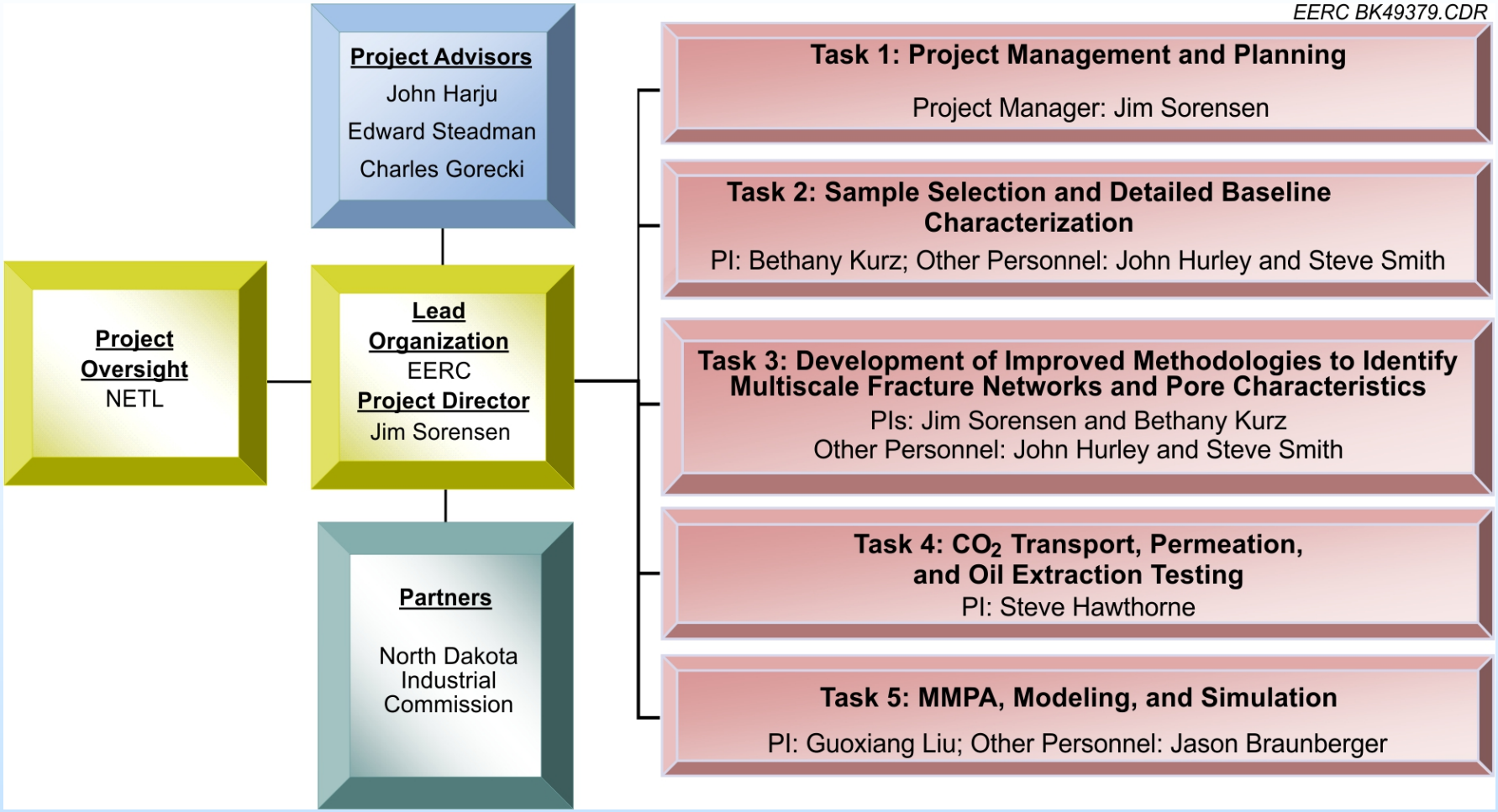
NDGS and Marathon Oil Company

- Access to core samples for all project activities

Ingrain

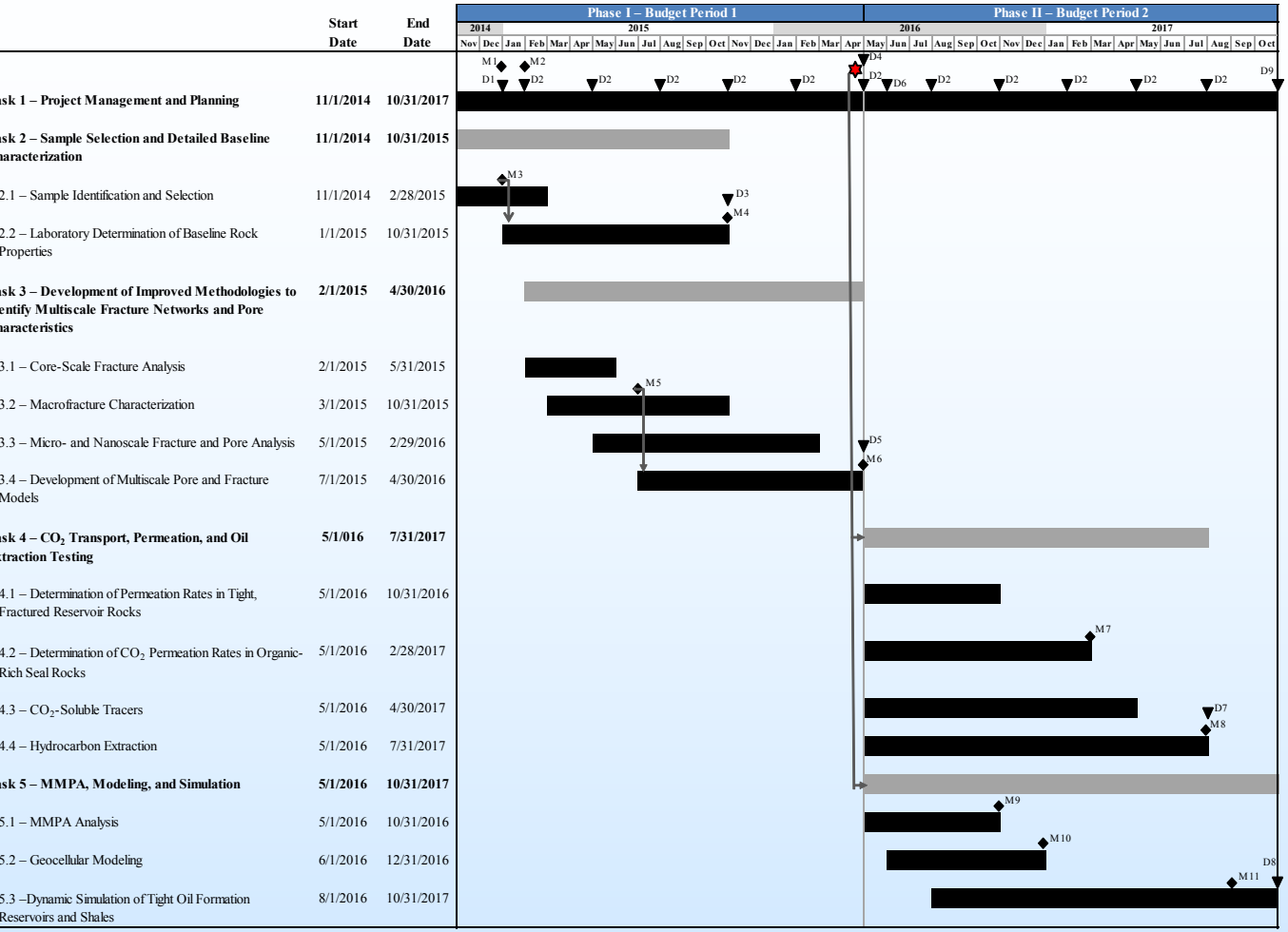
- Whole-core CT scanning
- Micro-CT scanning
- High-resolution SEM analysis, including 3-D FIB–SEM

Improved Characterization and Modeling of Tight Oil Formations – Organizational Chart



Project Schedule

	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
	M6 – Completion of Fracture Network Characterization
D6 – Phase I Interim Report	M7 – Completion of CO_2 Permeation Testing
D7 – Manuscript – Laboratory-Measured CO_2 Permeation and Oil Extraction Rates in Tight Oil Formations	M8 – Completion of Hydrocarbon Extraction Testing
	M9 – MMPA Analysis Completed
D8 – Best Practices Manual – Estimation of CO_2 Storage Resource of Fractured Reservoirs	M10 – Completion of Geocellular Models
D9 – Final Report	M11 – Completion of Simulations

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 and 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 and EOR potential.

Bibliography

No papers or reports have been developed yet from this project.

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