How Do We Get More Oil Out of the Bakken? An Overview of the EERC's Bakken CO_2 Storage and Enhanced Recovery Research Program

Presented to
North Dakota Association of Oil & Gas Producing Counties

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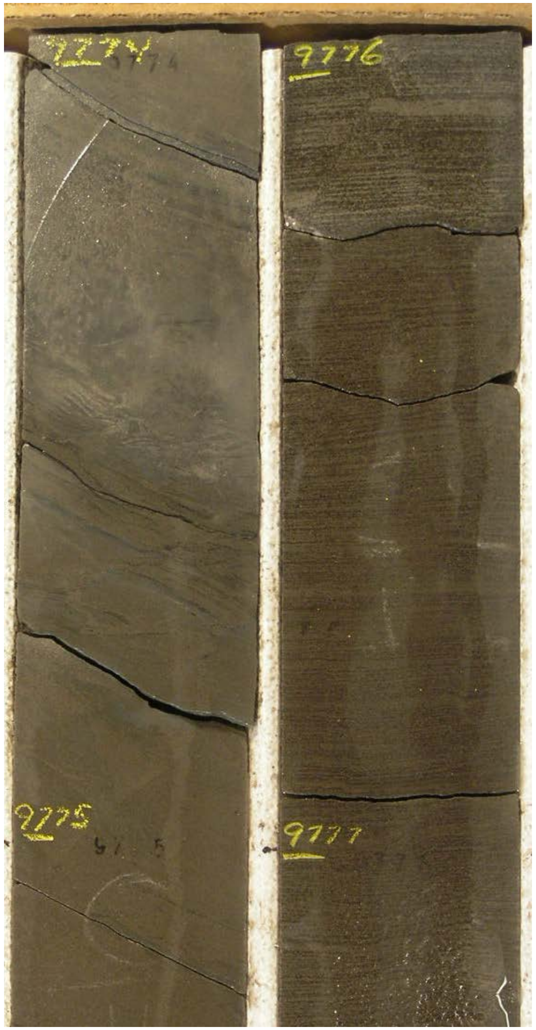
The Bakken Is a Tight Oil Formation

- Extremely low permeability (<0.1 mD) reservoir rock.
- 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

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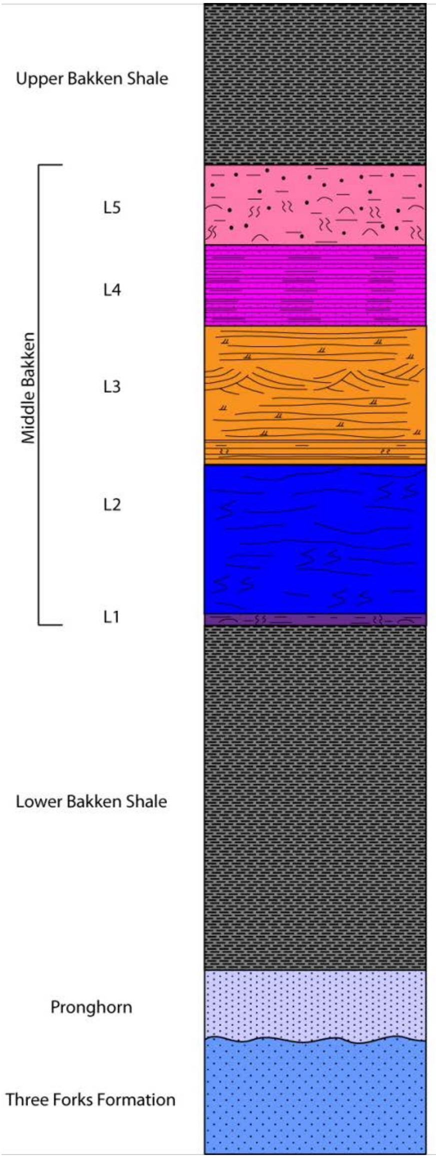
Bakken Petroleum System Lithology



Upper Bakken Shale: Brown to black, noncalcareous, organic rich.

L5: Siltstone, massive, dense, mottled, fossiliferous, slightly bioturbated.

L4: Packstone to fine-grained sandstone with interbeds of shale.

L3: Sandstone, fine-grained, to gray limestone. Sandstone contains cross-bedding and few fossils.

L2: Siltstone to silty sandstone. Siltstone is bioturbated, fossils, and dolomitic.

L1: Siltstone. Massive dense, very calcareous, highly fossiliferous.

Lower Bakken Shale: Brown to black, fissile, noncalcareous, organic-rich, where present fractures are smooth and conchoidal.

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

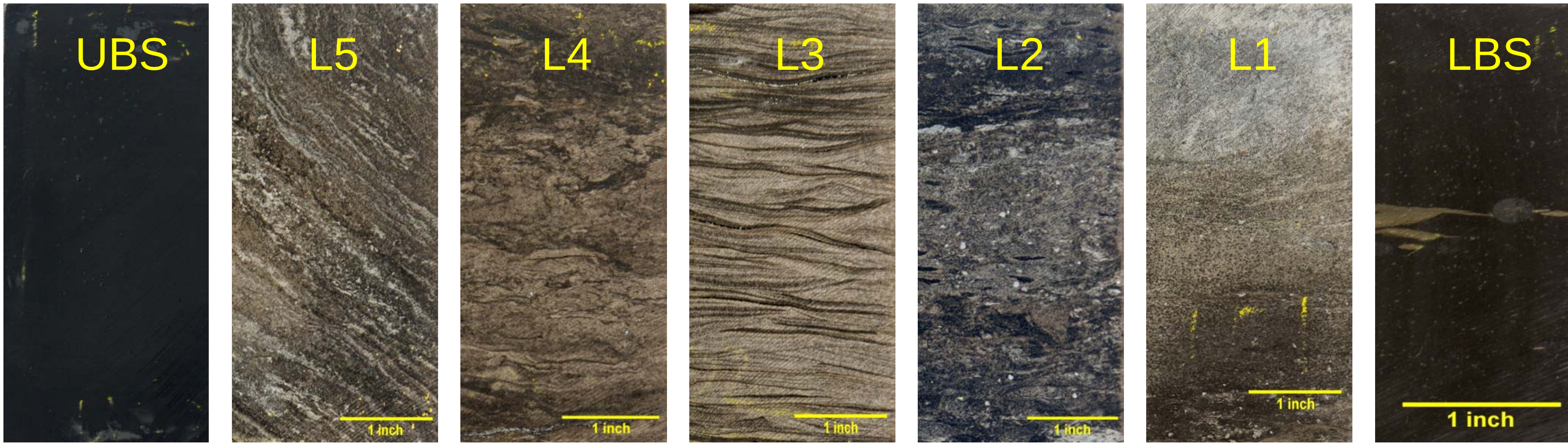
Three Forks Formation: Interbedded dolostone and limestone; argillaceous, silty, cross-laminated, mottled, with mud cracks; anhydritic, pyritic, fossiliferous, and with shale interbeds.

The Rocks Within the System Are Complex

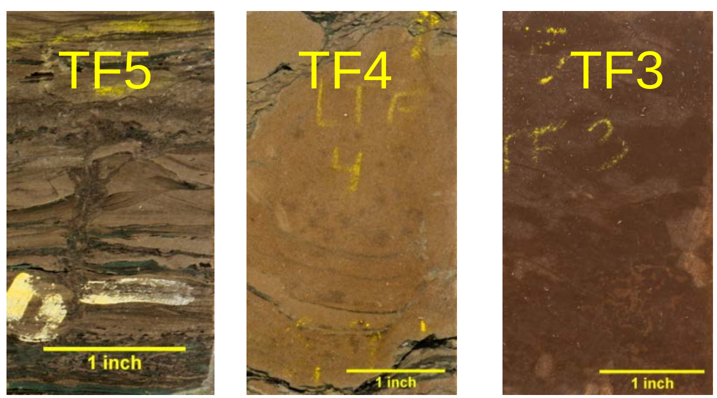
Middle Bakken Lithofacies

Upper Shale

Lower Shale



Three Forks Lithofacies



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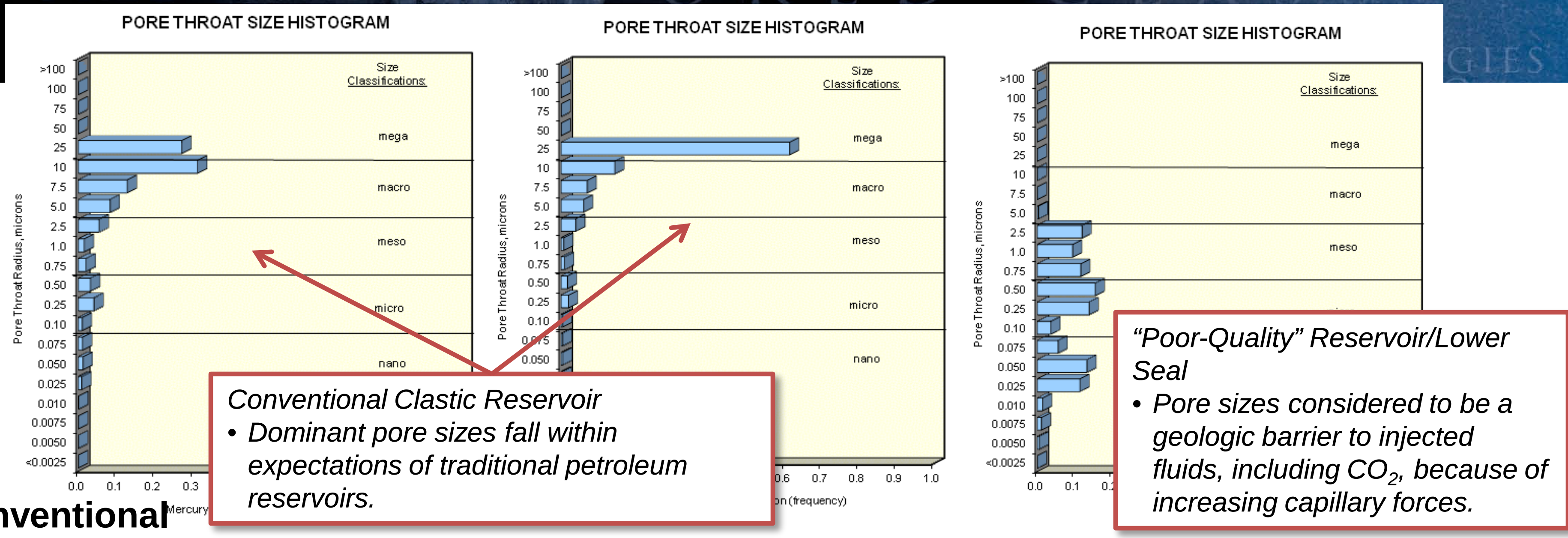
Comparison of Pore Throat Sizes



Conventional

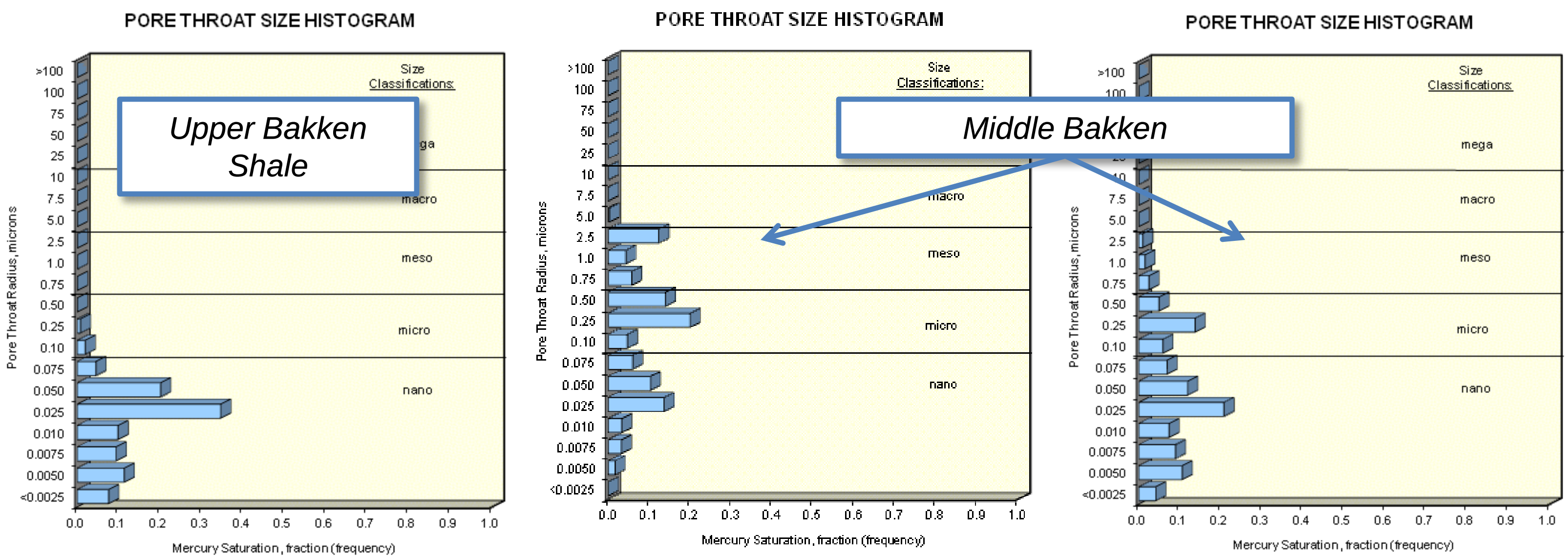
Conventional Clastic Reservoir

- *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

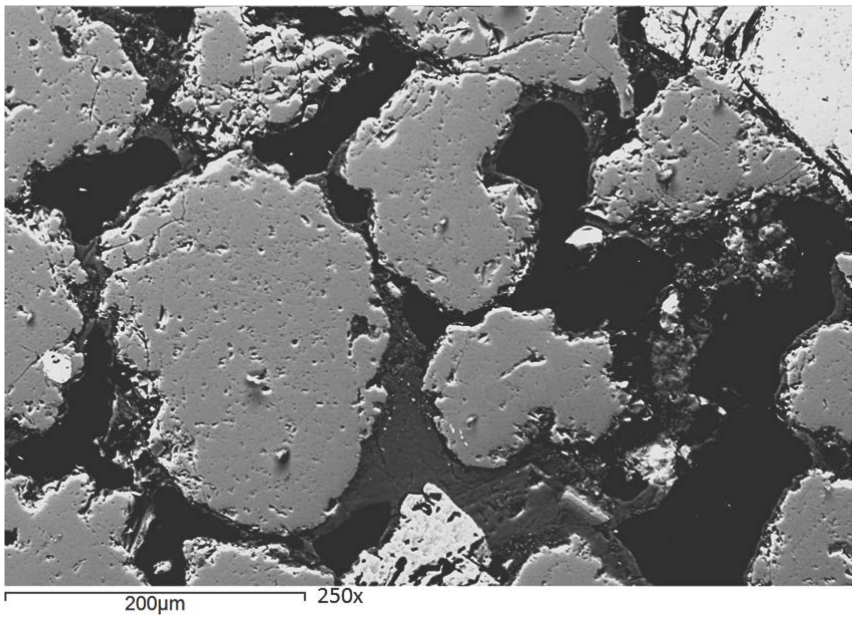


Upper Bakken Shale

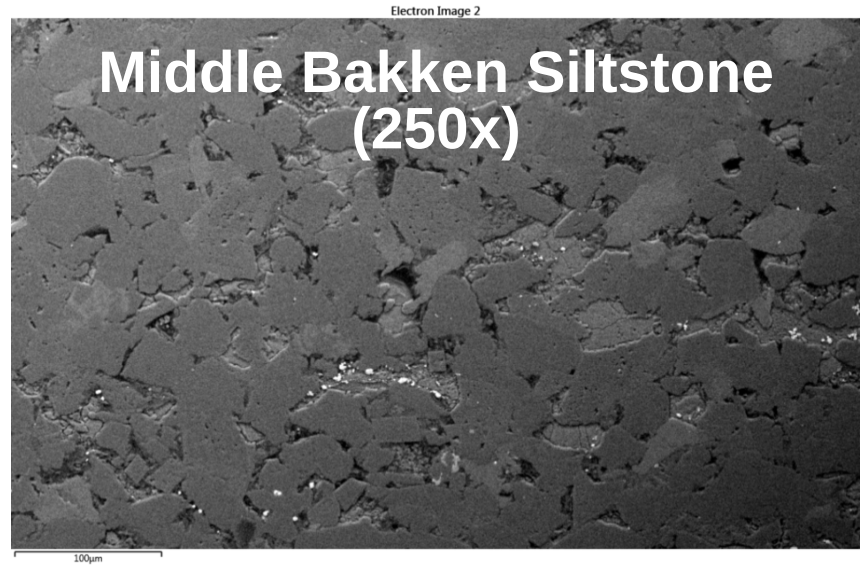
Middle Bakken

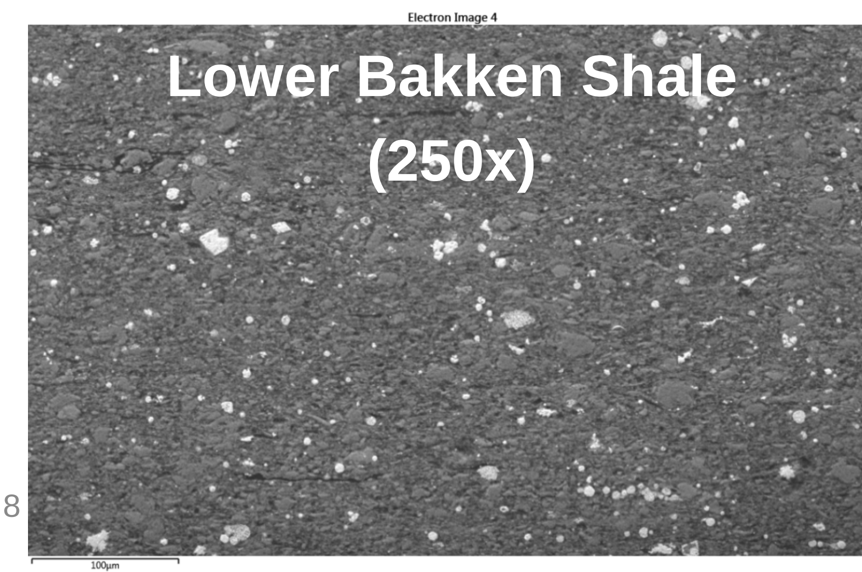
Conventional vs. Tight Oil Reservoir

Muddy Fm Sandstone (Bell Creek) (250x)



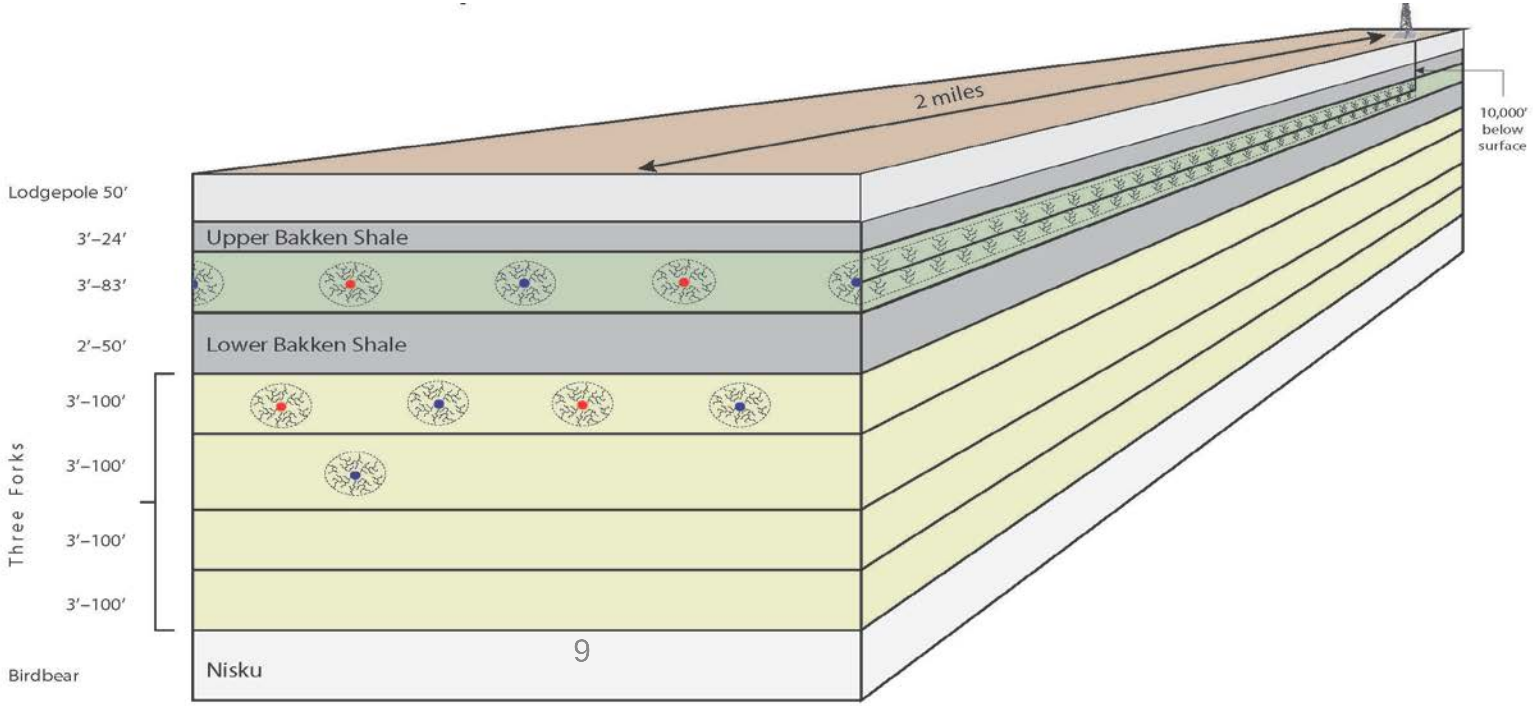
Black represents porosity in these images from a scanning electron microscope (SEM).





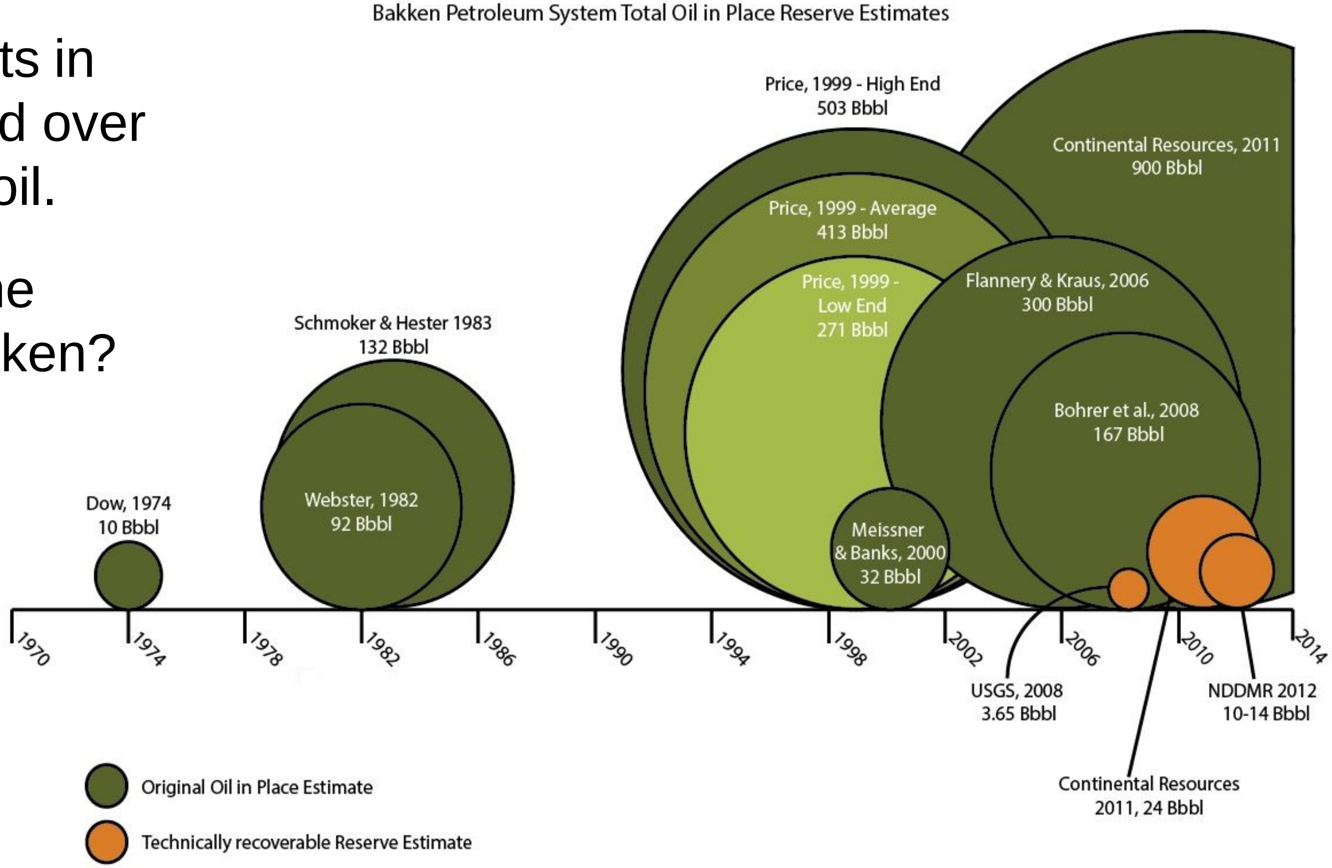
Bakken and Three Forks Production

- **Production (June 2015)**
  - Over 12,800 wells in North Dakota
  - Over 1.2 Mbbl/day of oil
  - Over 1.65 Bcf/day of gas
  - Horizontal wells and hydraulic fracturing



How Much Bigger Can Bakken Get?

- 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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Estimation of Bakken CO_2 Storage Capacity and EOR Potential

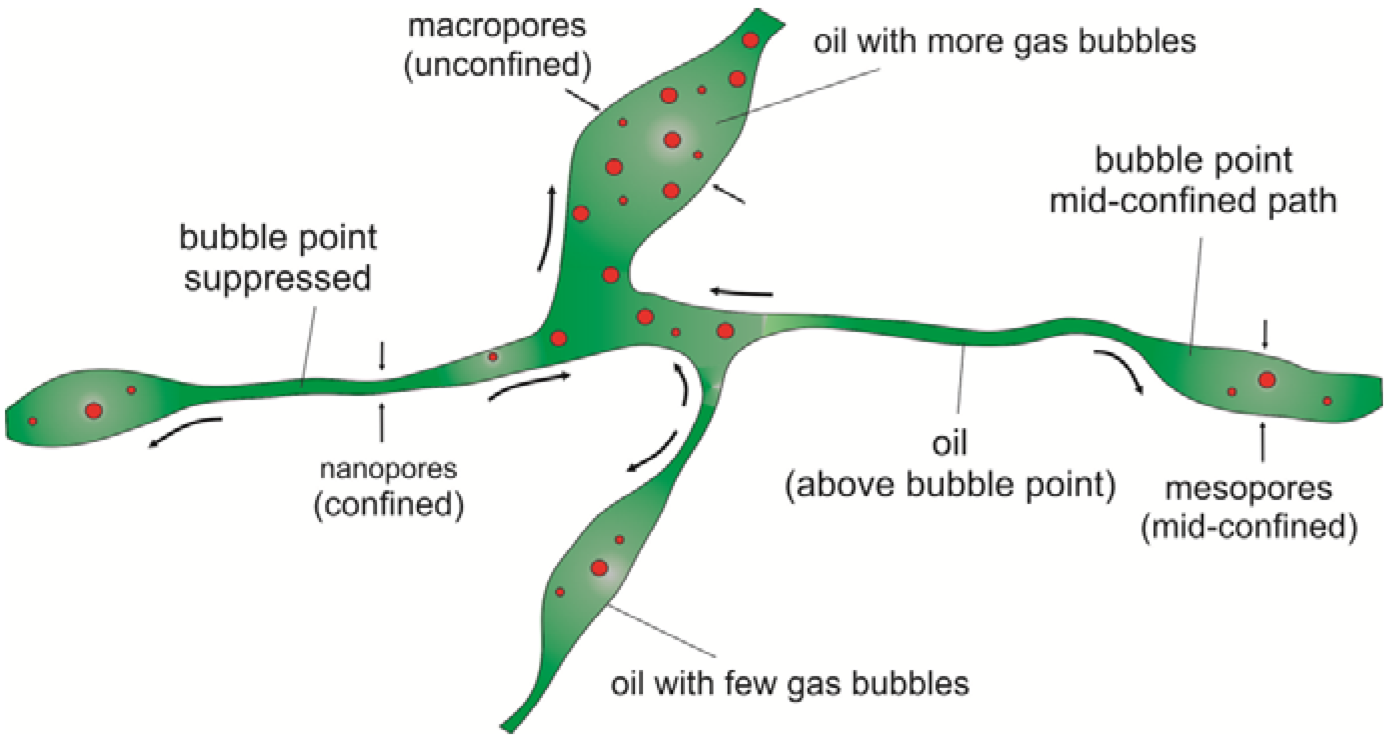
The DOE methodology for estimating CO_2 EOR and storage capacity (Carbon Sequestration Atlas of the United States and Canada, 2007) was applied to the Bakken petroleum system:

- The cumulative production approach yields a storage capacity ranging from 121 to 194 million tons of CO_2.
  – 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_2.
  – This could yield **4 to 7 billion barrels** of incremental oil.

Challenges of EOR in the Bakken

- Fractures may act as “thief zones”, limiting the ability of CO_2 to interact with the matrix.
- Reactivity of clays in the Bakken to CO_2 is not well understood.
- Waterflooding not likely to be effective in oil-wet Bakken reservoirs.
- The role of wettability (oil-wet and mixed-wet) with respect to CO_2 in tight oil reservoirs is not well understood.
- High vertical heterogeneity of the lithofacies complicates our understanding of flow regimes (fractures and matrix).
- Multiphase fluid flow behavior varies substantially depending on the size of the pore throats.
- Fluid viscosity and density are much different in nanoscale pores than in macroscale pores.
- How does the sorptive capacity of the organic carbon materials affect CO_2 mobility, EOR, and storage?

Pore Size Affects Fluid Phase Behavior



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

Source: Alharthy, N.S., Nguyen, T.N., Teklu, T.W., Kazemi, H., and Graves, R.M., 2013, SPE 166306, Colorado School of Mines, and Computer Modelling Group Ltd.

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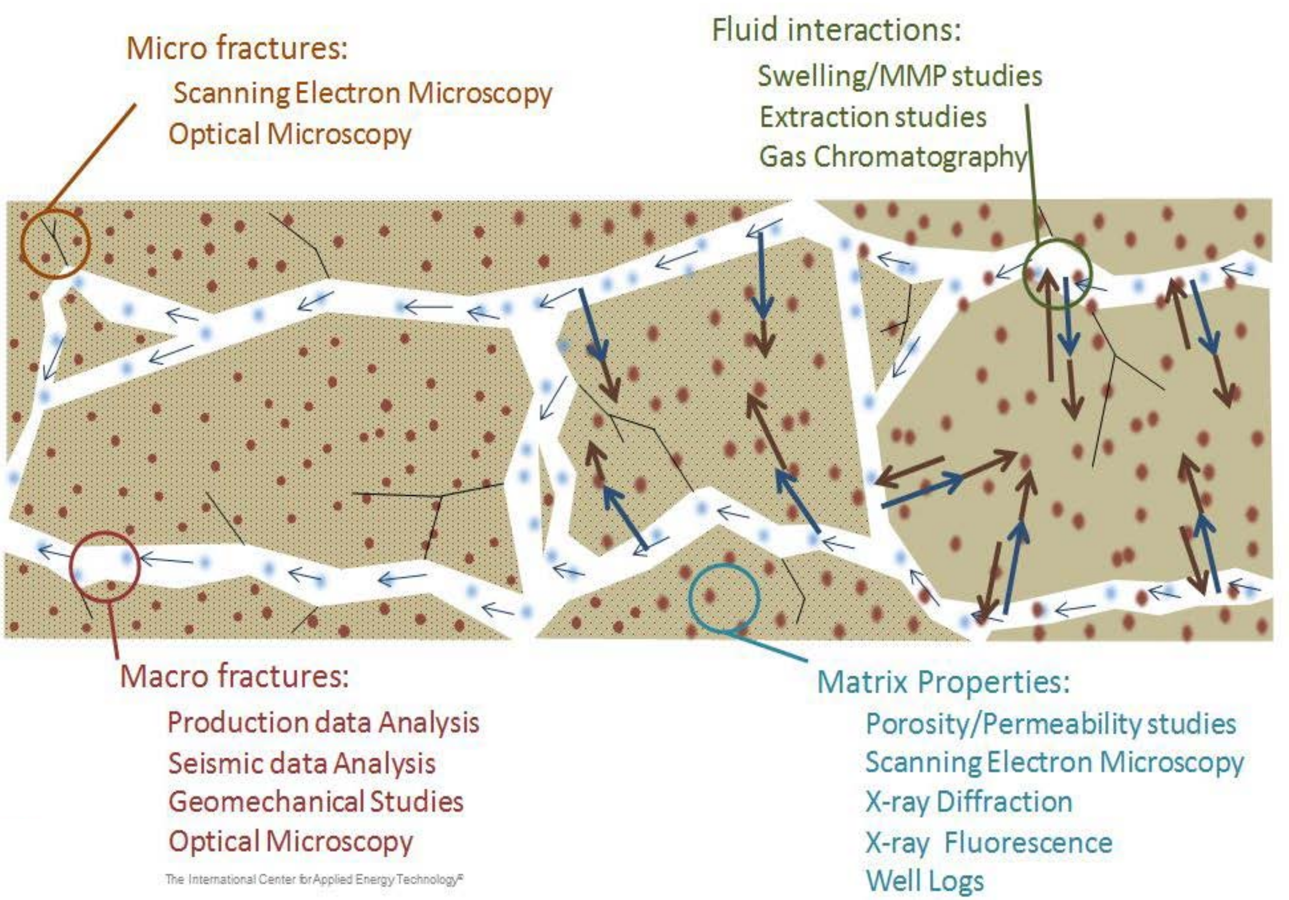
EERC Bakken CO_2 Storage and EOR Research Program (2012 to present)

Laboratory work to evaluate:

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

Static and dynamic modeling

Evaluation of data from pilot field injection tests



Ultimate goal is to apply lessons learned from experiments and modeling to a pilot-scale injection test in at least one well.

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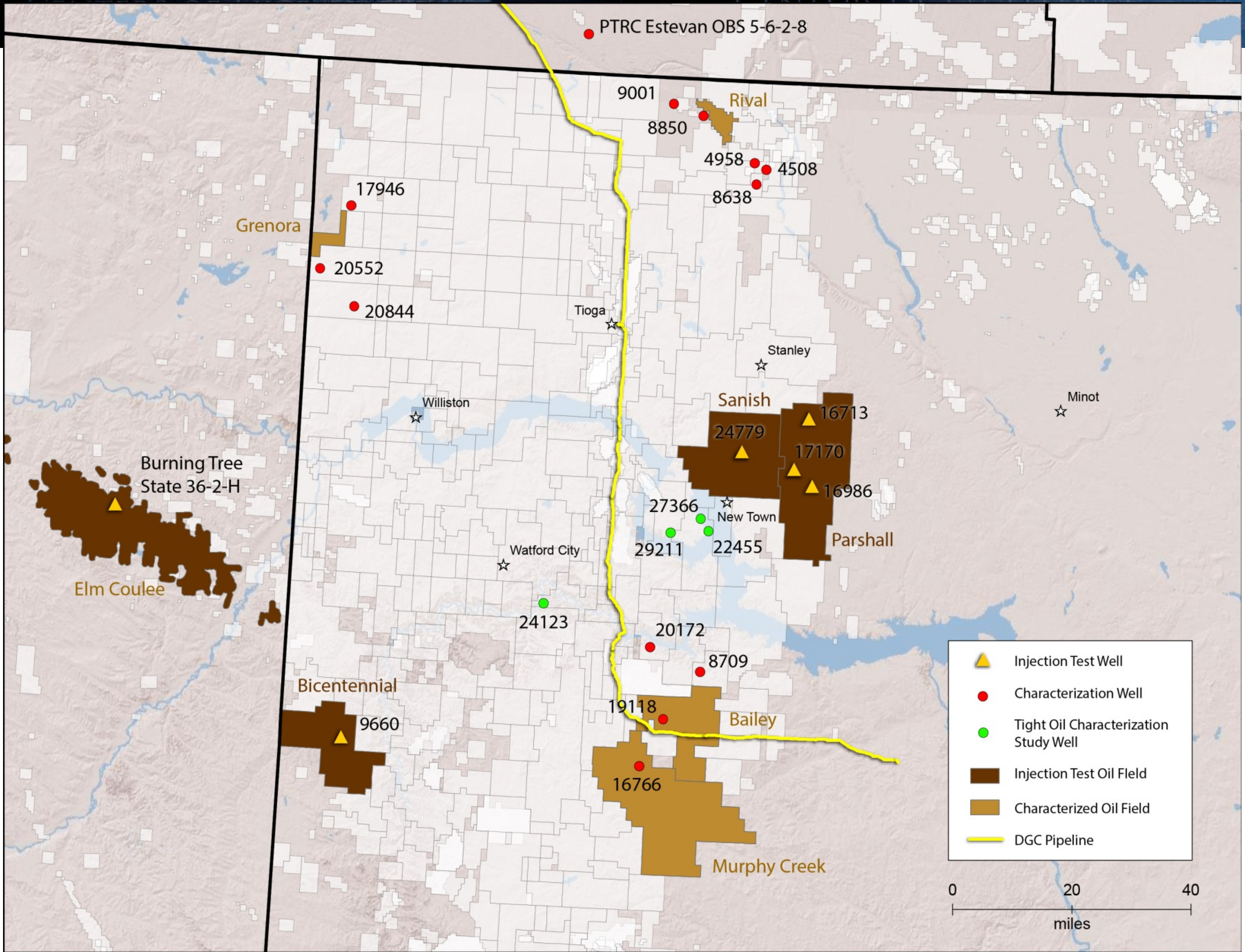
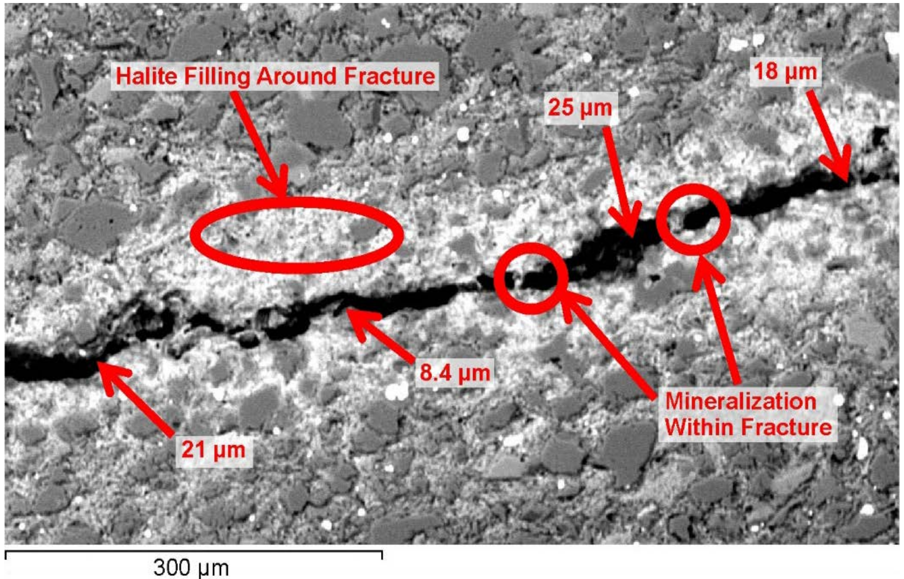
EERC Bakken Study Areas

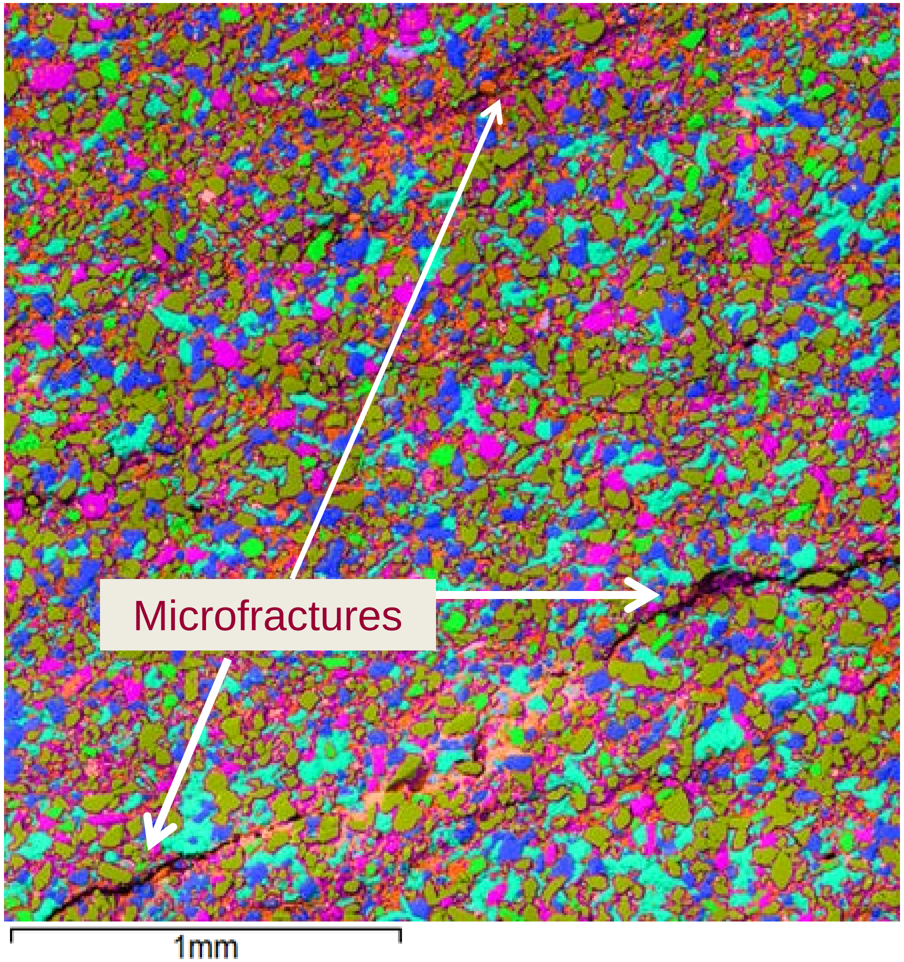


Reservoir Characterization Key Lessons Learned

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

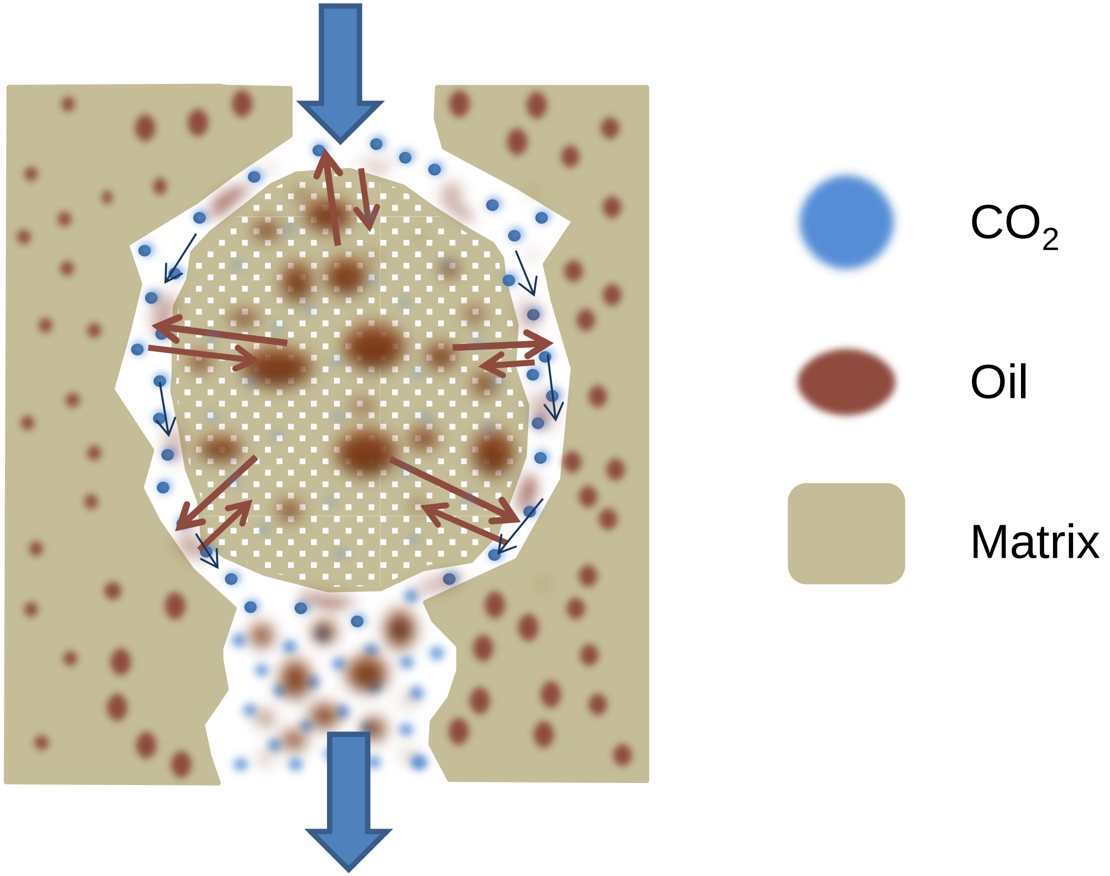


Scanning Electron Microscopy (SEM) Mineral Map of a Middle Bakken Sample (colors represent minerals; black represents porosity)



CO_2 Interactions with Bakken Rocks and Oil

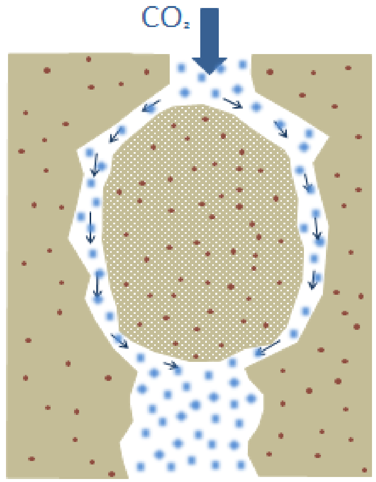
Laboratory Experiments to Examine the Ability of CO_2 to Extract Oil from Lower Bakken Shale and Middle Bakken Silty Packstone



Lab-Scale Experiments
CO_2 Extraction of Oil from Tight Rocks

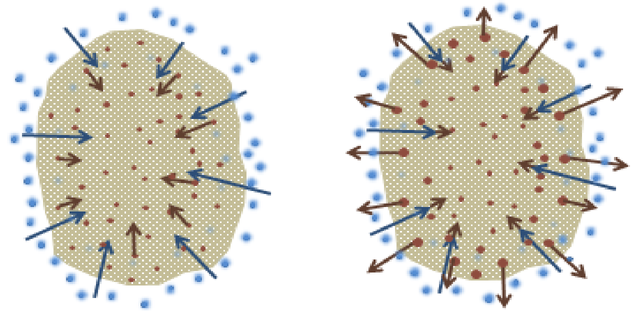
Step 1

Initial injection: CO_2 flows rapidly through fractures.



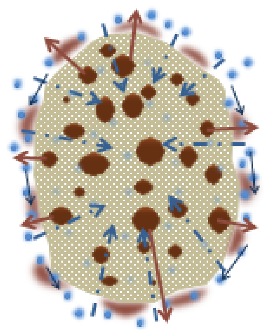
Step 2: CO_2 starts to permeate rock based on pressure gradient.

CO_2 carries oil into the rock (bad). ***and or*** CO_2 swelling pushes oil out of the rock (good).



Step 3

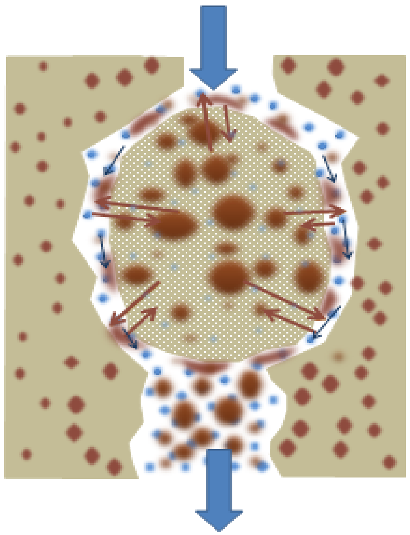
As CO_2 permeates into the rock, oil migrates to bulk CO_2 in fractures based on swelling and lower viscosity.



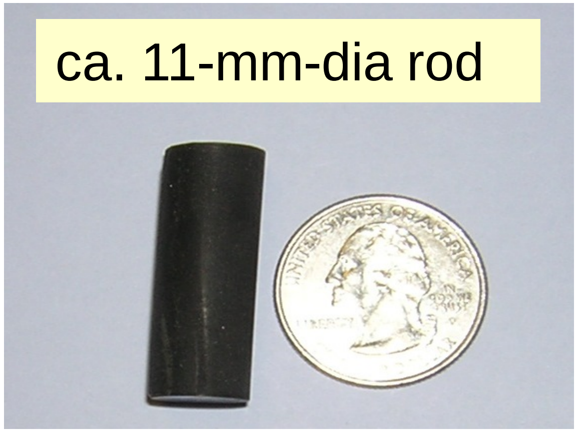
Step 4

CO_2 pressures equalize inside of rock.

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



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



Laboratory exposures include:

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

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

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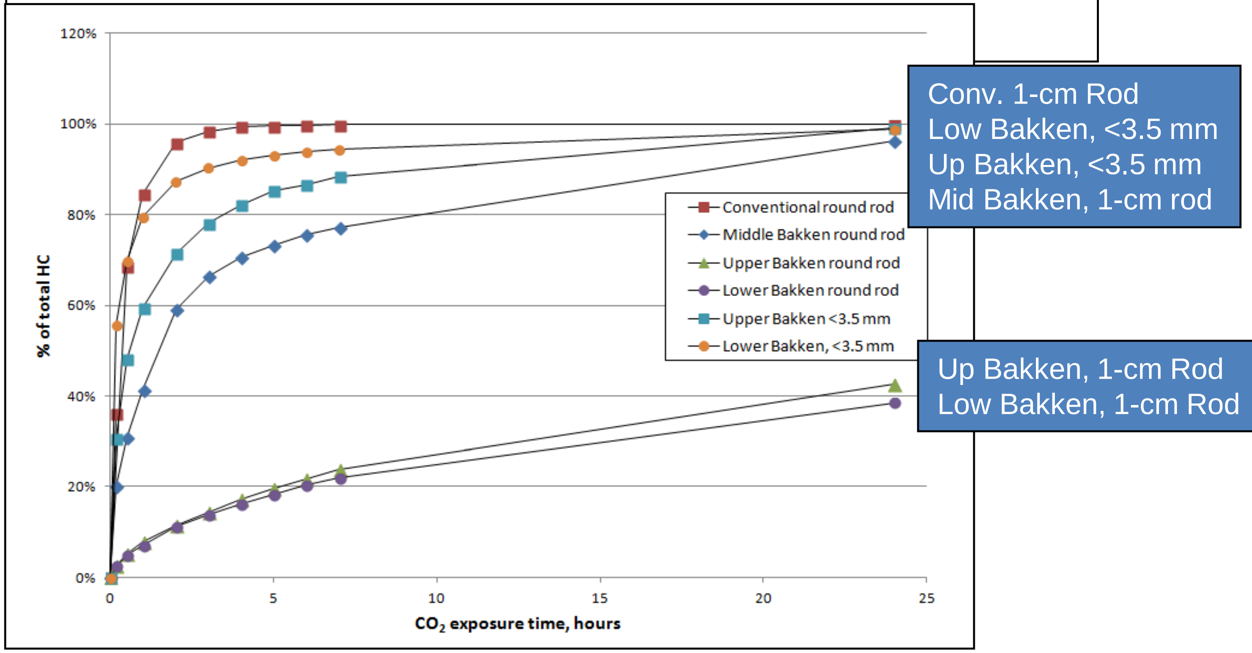
CO_2 Oil Recovery from Upper, Middle, and Lower Bakken from One North Dakota Well

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

- Rates are *highly* dependent on exposed rock surface areas.
- Recoveries are *highly* dependent on long exposure times.
- Diffusion appears to exert much more influence than displacement.

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.

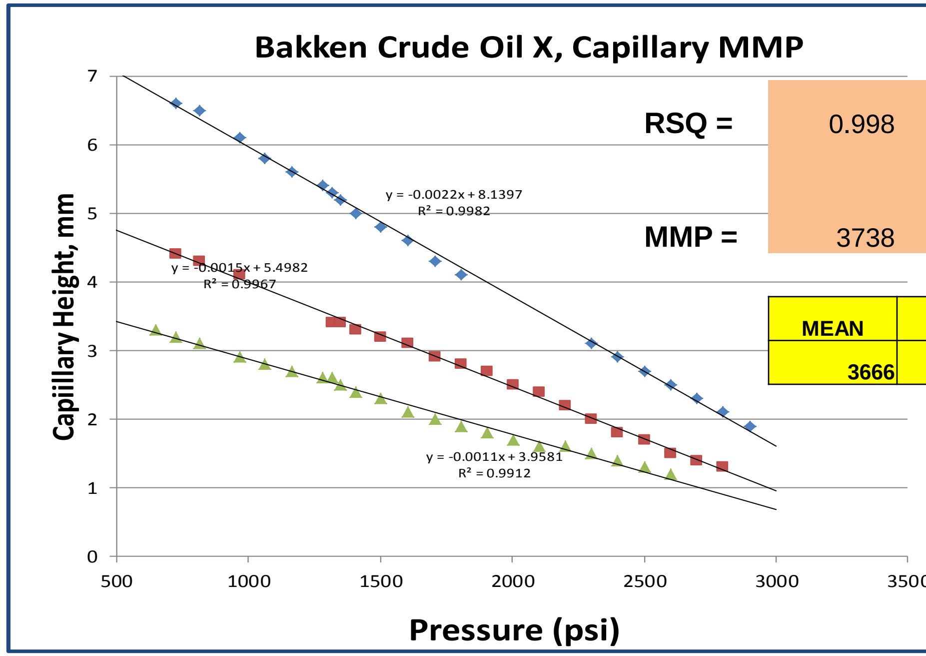
Oil Recovery from Middle Bakken and Bakken Shales



CO_2 and Bakken Oil Miscibility Study

Patent pending

MMP by Capillary Rise



RSQ =	0.998	0.997	0.991
MMP =	3738	3632	3628

MEAN	SD	RSD
3666	62	2%

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

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

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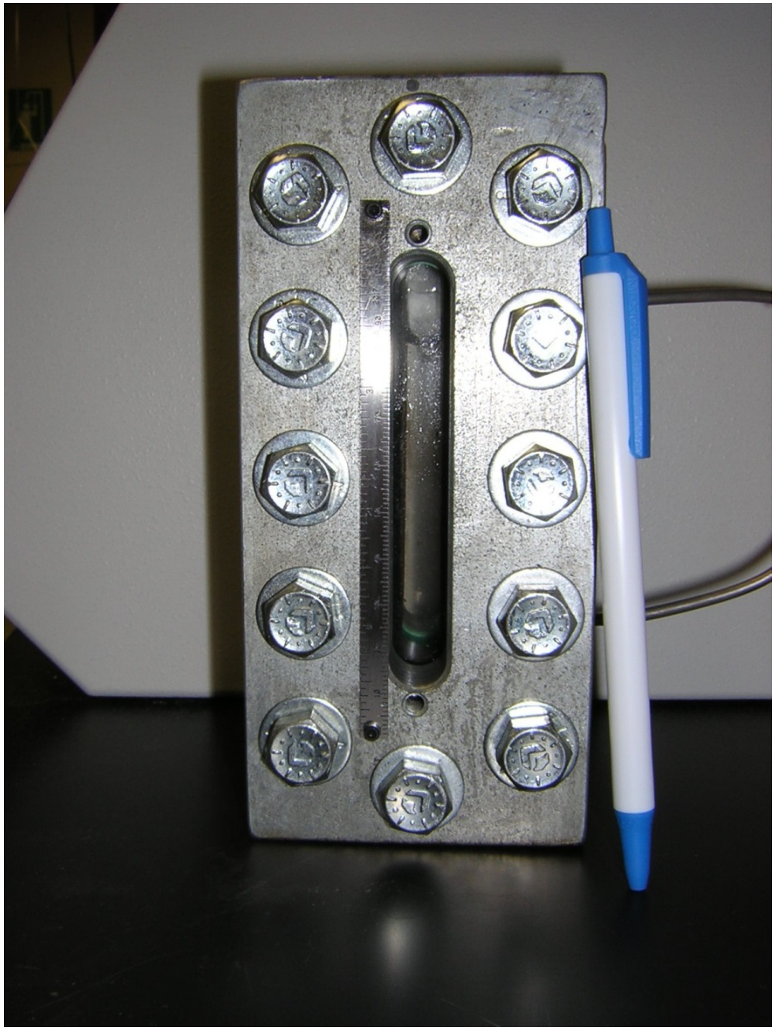
Does anything interesting happen above and below MMP?

Bakken crude/CO_2 behavior, 110 °C

CO_2 pressure increased from ambient to 5000 psi, then reduced back to ambient.



Bakken Crude Oil

110 °C (230 F)

MMP = 2800 psi

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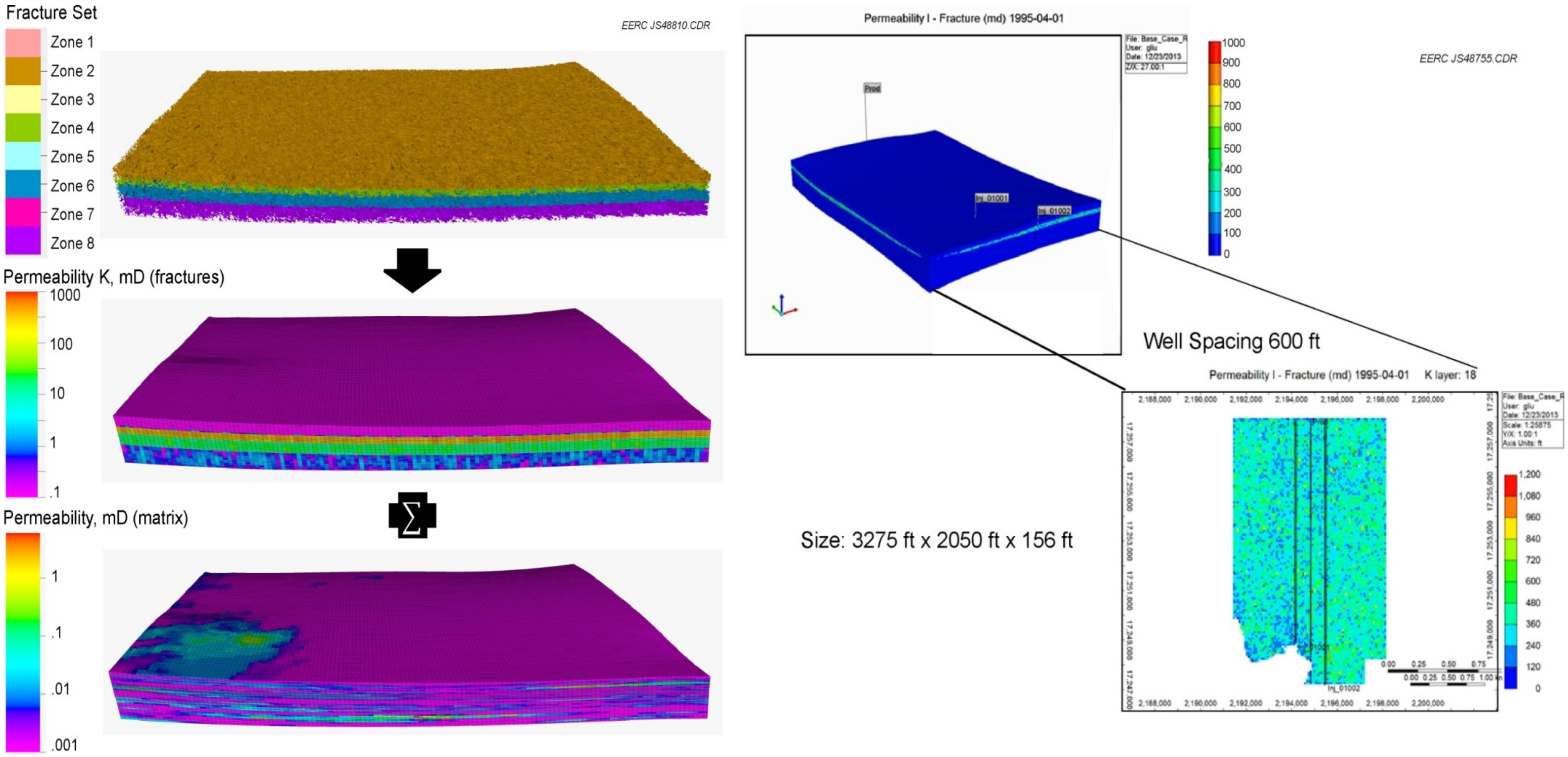
Is there MW selectivity in CO_2-mobilized hydrocarbons—both as the pressure is rising, and then falling below injection pressure?

15 mL oil pressurized for ca. 1 h between each sample collection (ca. 5X at each condition).

Each pressure was tested with new oil.


T= 0:00:00.00 Log=true Capture Rate= 15fpm
Ambient
's' slows capture; 'f' captures faster; 'Q' is for Quit;
'l' toggles logging; UP/DOWN/LEFT/RIGHT adjusts yellow box

Characterization Informs Static Model to Support Simulations of EOR Scenarios



Initial modeling conducted at drill spacing unit (DSU) scale.

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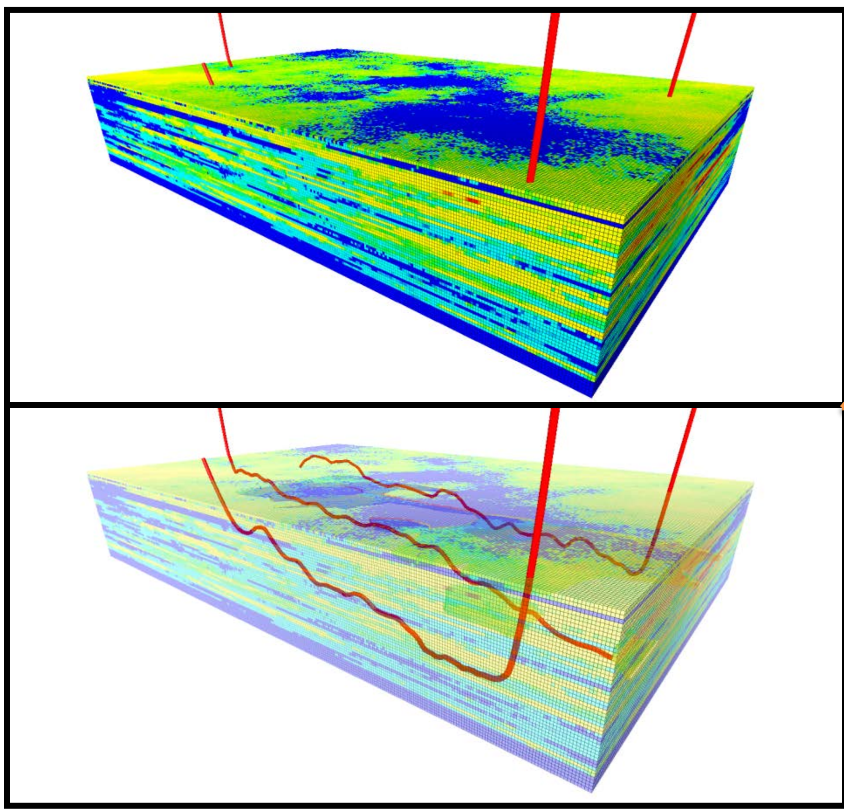
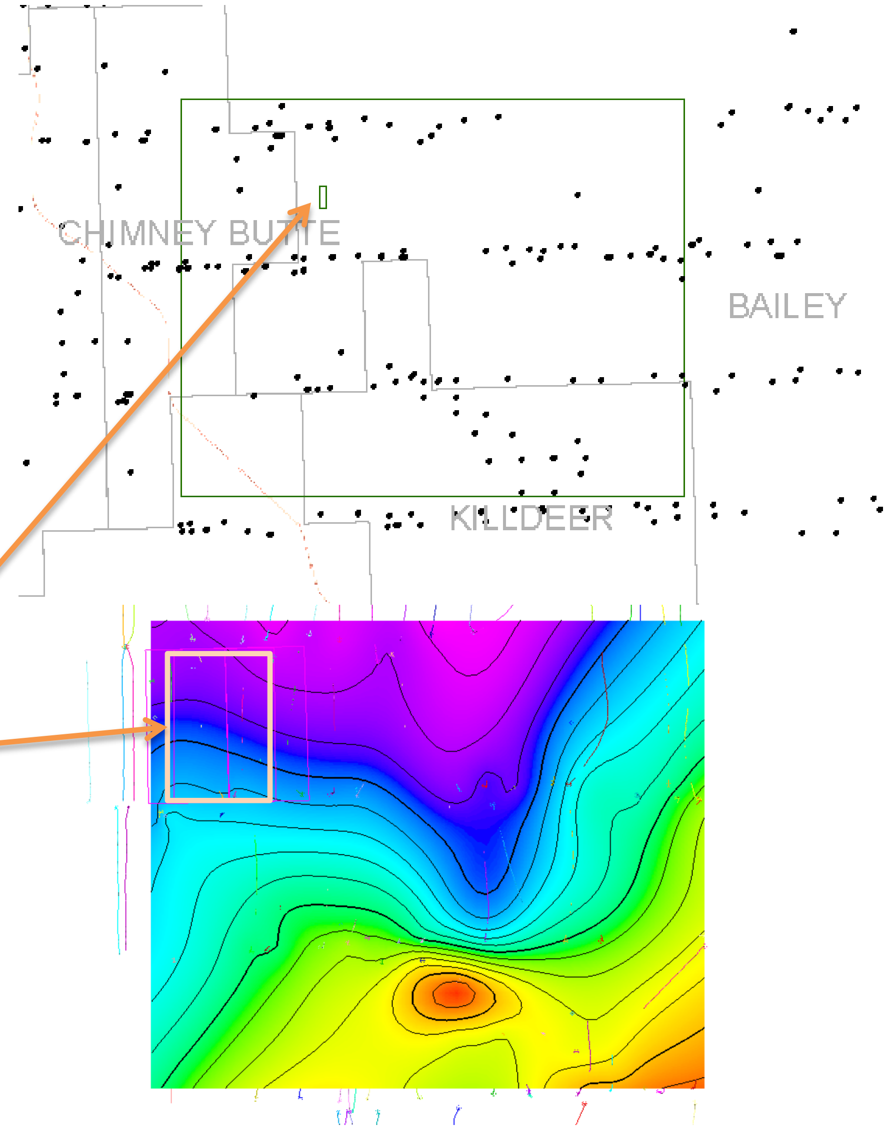
DSU Scale Model – 3 Wells in the Unit

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



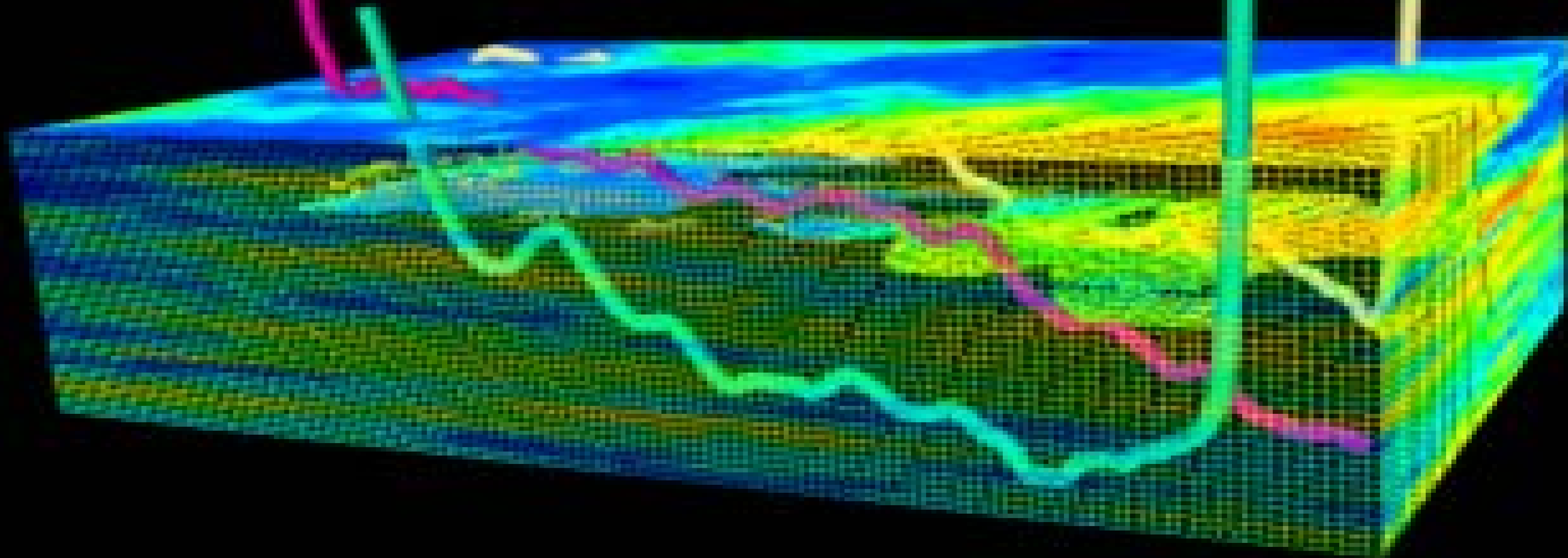


Initial EERC Modeling Highlights

Simulated a variety of huff 'n puff and injector–producer EOR schemes.

Best cases showed reasonable improvement in oil production (some over 100%).

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



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

Bakken Field Injection Tests to Date

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

www.bakkendispatch.com

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 reality in the field.**

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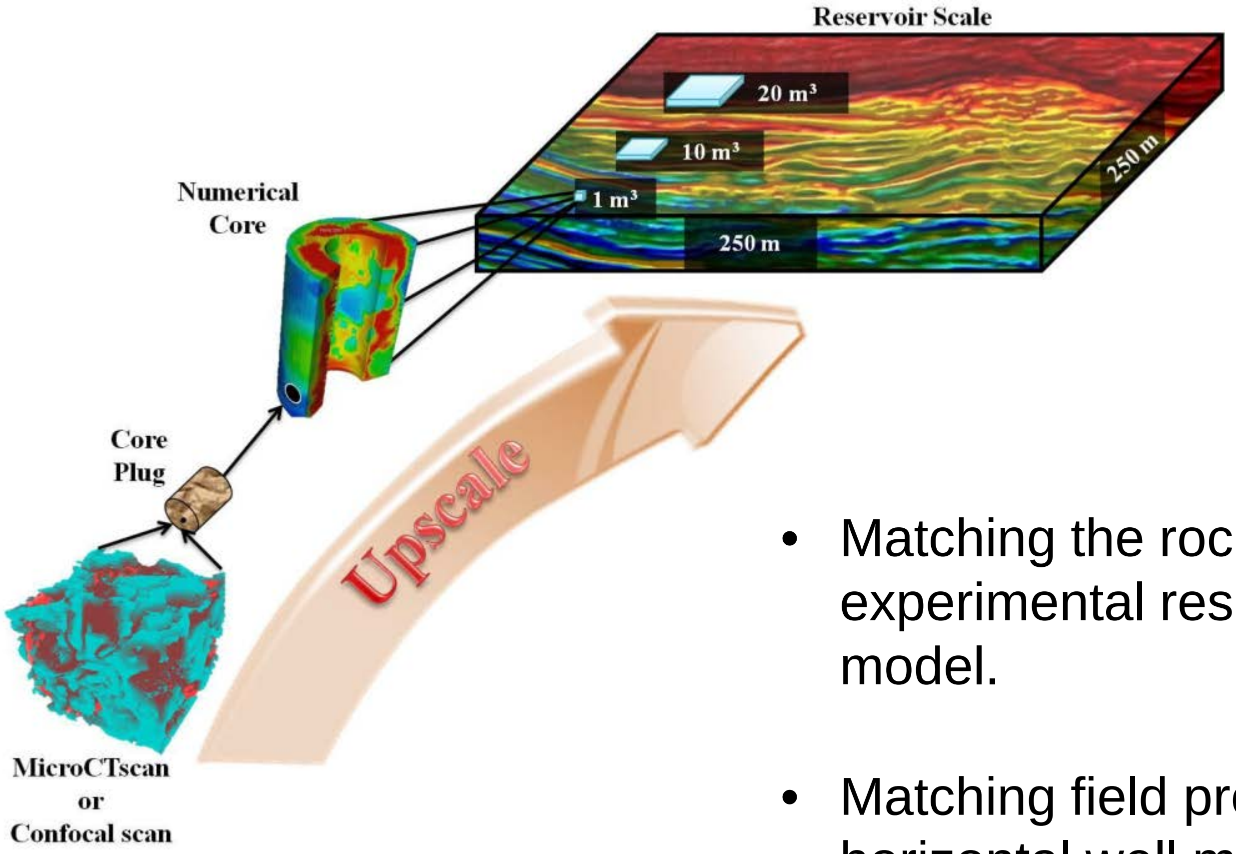
Current Modeling Efforts



Hurley et. al. 2012

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

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

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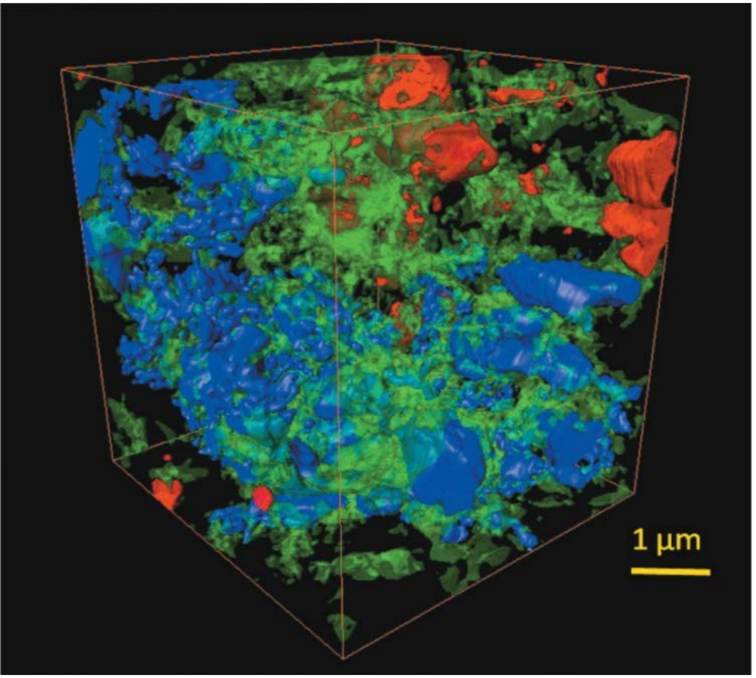
Pore- and Core-Scale Simulations



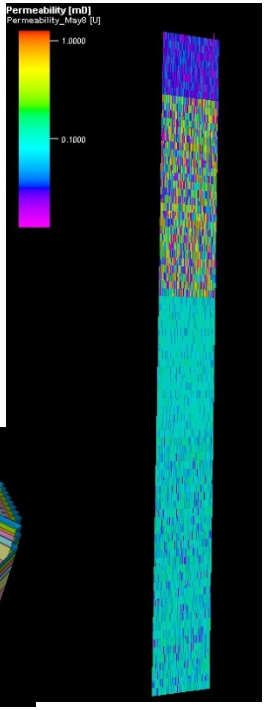
Enables us to history-match laboratory-based CO_2 permeation and oil extraction results to better understand the relative influence of various mechanisms on EOR in the Bakken.

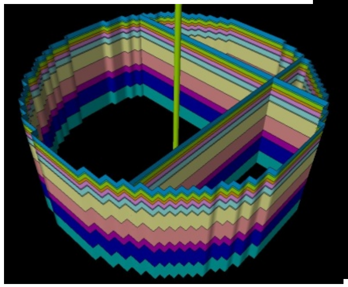
Then the relative influence of those mechanisms can be applied with greater confidence to larger-scale models.

This, in turn, will enable us to develop EOR schemes that are more likely to be effective in the Bakken.

Project Accomplishments Thus Far

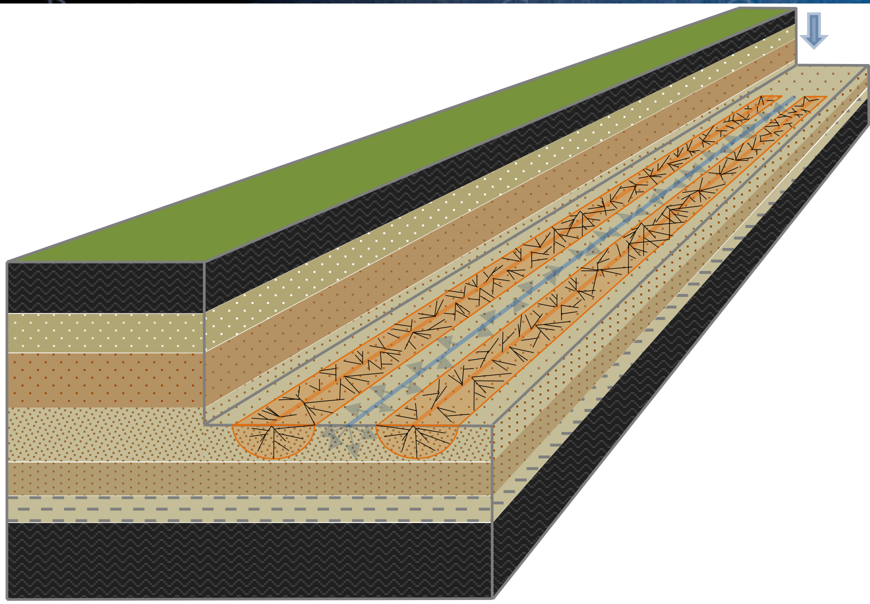
- **We have developed a new method for measuring MMP of an oil sample.**
- **We have demonstrated that CO_2 can effectively permeate and remove oil from both Middle Bakken and Bakken Shale rocks.**
- **Bakken core from 13 wells have been characterized.**
- **Data from 5 field-based injection tests have been evaluated with respect to lessons learned.**
- **Models have been constructed at the DSU, near-wellbore, and core plug scales.**
- **A dozen injection-production scenarios have been simulated using the Bailey DSU model.**
  - **Sequential multi-well injection/production looks promising.**

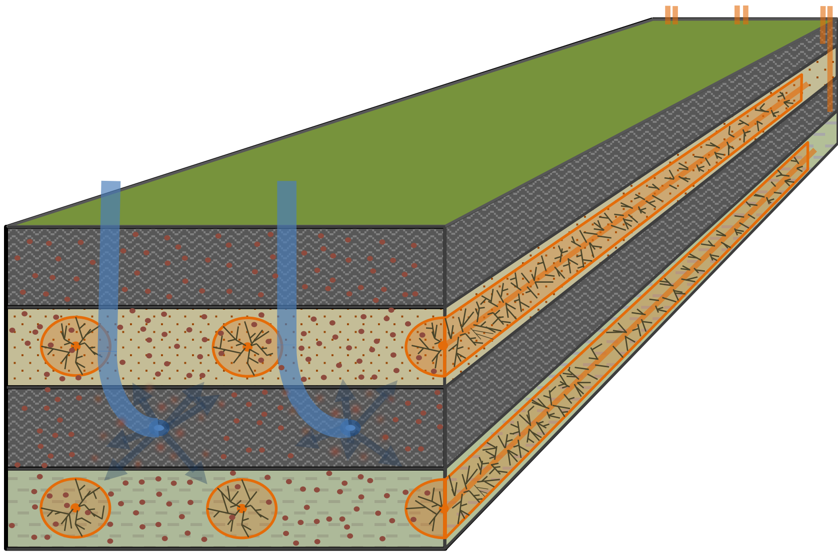




“Take Home” Thoughts

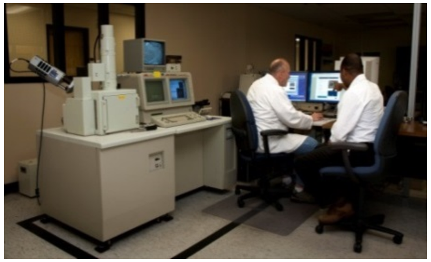
- Unconventional resource will take unconventional approach to EOR.
  - Diffusion is more important than displacement.
  - Patience required, but reward may be substantial.
- Innovative injection and production schemes.
  - Use unfractured wells as injectors; rely on natural fracture system for slower movement of CO_2 through the reservoir and improved matrix contact time.
  - Injectors in the shale paired with producers in the Middle Bakken and/or Three Forks.

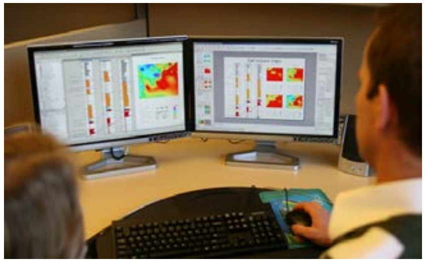




Applying Lessons to the Field

- Detailed reservoir characterization will be key.
  - Microfracture characterization to improve the accuracy of dual-porosity–dual-permeability reservoir models.
  - 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





Field Test of CO_2 Injection into a Bakken Reservoir

- EERC activities will include:
  - Conducting 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.

Thank You!

Andrew Burton/Getty Images

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