IMPROVED CHARACTERIZATION AND MODELING OF TIGHT OIL FORMATIONS FOR CO_2 ENHANCED OIL RECOVERY POTENTIAL AND STORAGE CAPACITY ESTIMATION

DE-FE0024454

Mastering the Subsurface Through Technology Innovation & Collaboration: Carbon Storage & Oil & Natural Gas Technologies Review Meeting

August 17, 2016

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Critical Challenges. **Practical Solutions.**

ACKNOWLEDGMENT OF PARTNERS

LIGNITE Energy COUNCIL

Department of Energy – United States of America

NETL

North Dakota oil & gas research program

INGRAIN Digital Rock Physics Lab

Marathon Oil

Great Seal – State of North Dakota

North Dakota DMR – Department of Mineral Resources

PRESENTATION OUTLINE

- Benefits to the program
- Background
- Goals and objectives
- Technical status
- Accomplishments to date
- Synergy opportunities
- Summary

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

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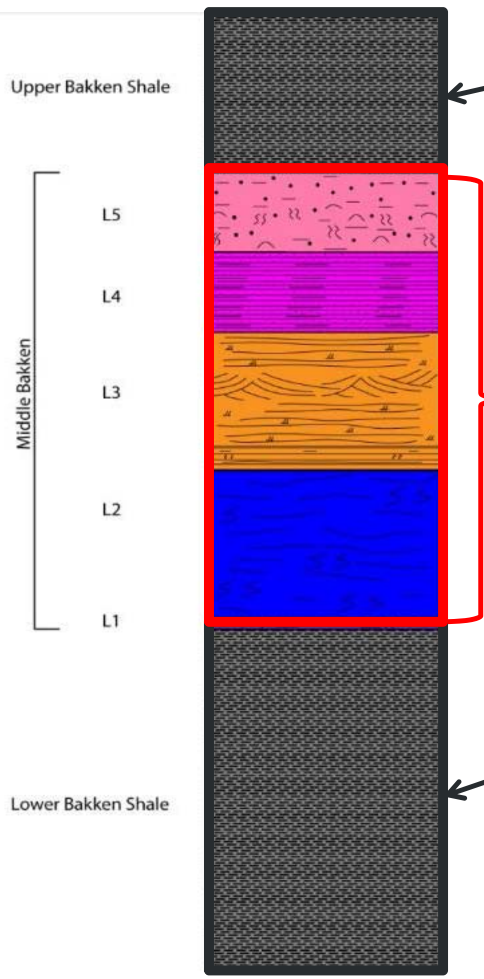
BAKKEN FORMATION LITHOLOGY



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

- **Bakken source rock**
- **1% to 4% porosity**
- **0.0001 to 0.1 mD permeability**

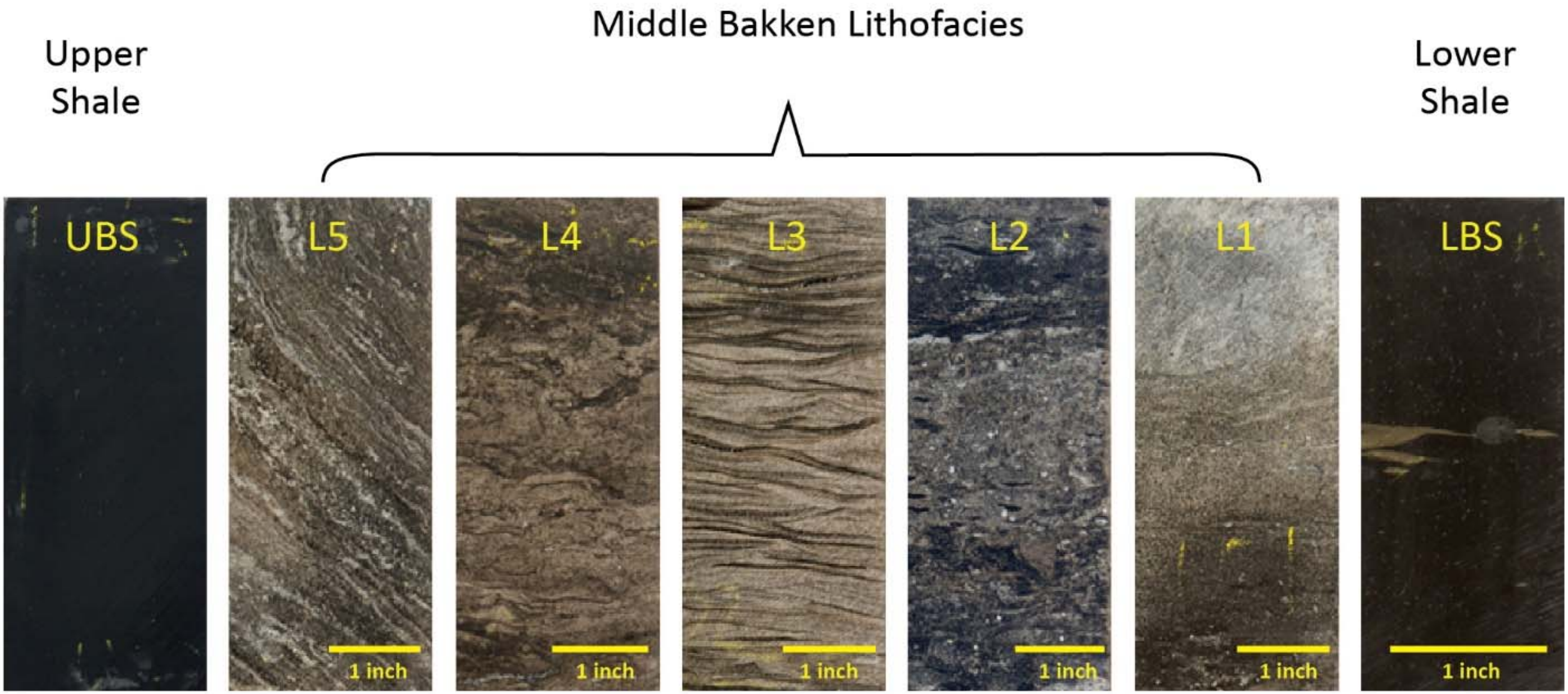
Middle Bakken: Variable lithology (up to nine lithofacies), ranging from silty sands to siltstones and tight carbonates

- **Bakken reservoir rock (horizontal drilling target)**
- **5% to 10% porosity**
- **0.0005 to 50 mD permeability**

Lower Bakken Shale: Brown to black, organic-rich

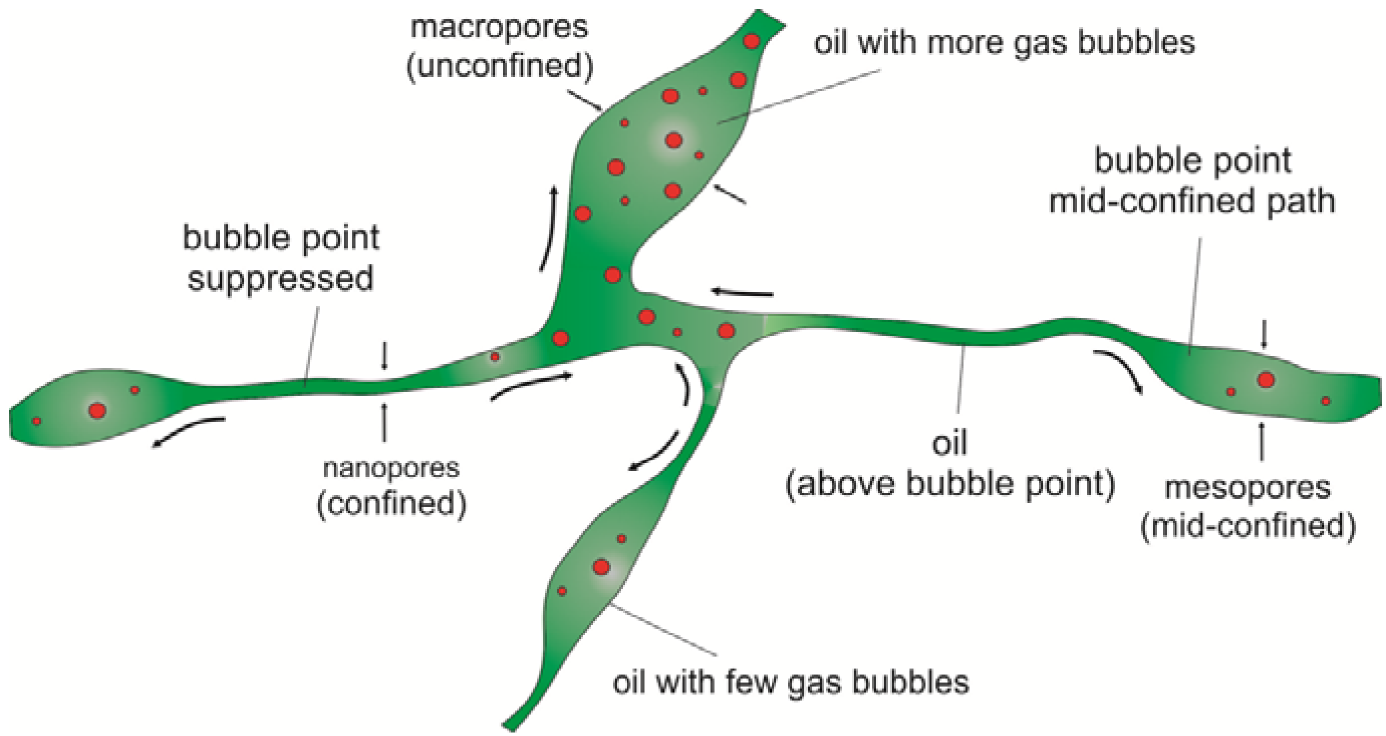
- **Bakken source rock**
- **1% to 4% porosity**
- **0.0001 to 0.1 mD permeability**

THE ROCKS WITHIN THE SYSTEM ARE COMPLEX



CHALLENGES OF CO_2 STORAGE AND ENHANCED OIL RECOVERY (EOR) IN THE BAKKEN

- Fractures acting 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.
- 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?



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 Computer Modelling Group

PROJECT OVERVIEW: GOALS AND OBJECTIVES

- Develop 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.
- 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 (e.g., mineralogy, geomechanical) 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.

TECHNICAL STATUS

COMPLETED

Phase I – November 2014 to April 2016

- Sample selection and detailed baseline characterization
- Development of improved methodologies to identify multiscale fracture networks and pore characteristics

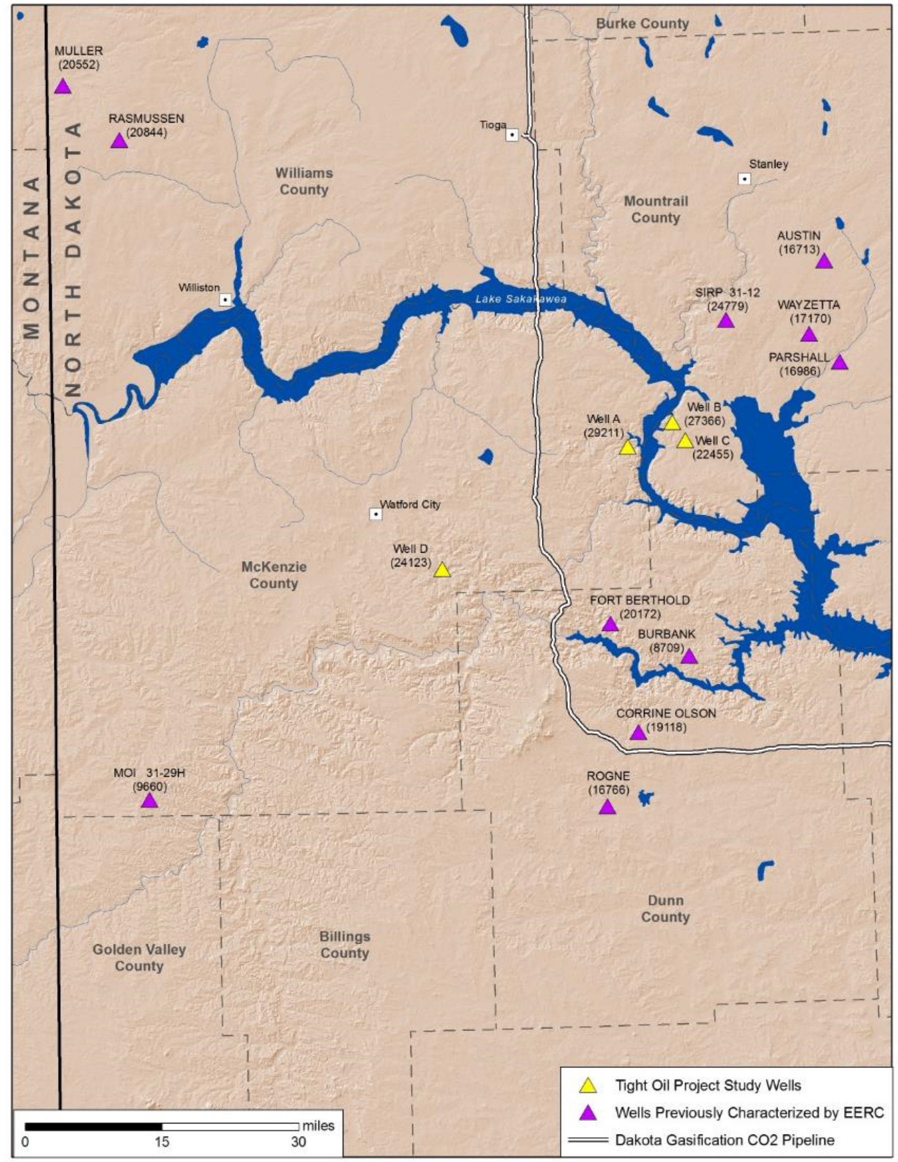
INITIATED

Phase II – May 2016 to October 2017

- CO_2 transport, permeation, and oil extraction testing
- Multimineral petrophysical analysis (MMPA), modeling, and simulation

SAMPLE SELECTION AND BASELINE CHARACTERIZATION

- Cores and well logs come from five well locations (yellow triangles).
- Samples represent:
  - Middle Bakken reservoir lithofacies.
  - Upper and Lower Bakken shale source rocks.
  - Reservoir–shale interface.
- Samples provided by Marathon and North Dakota Geological Survey.



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WELL LOG DATA

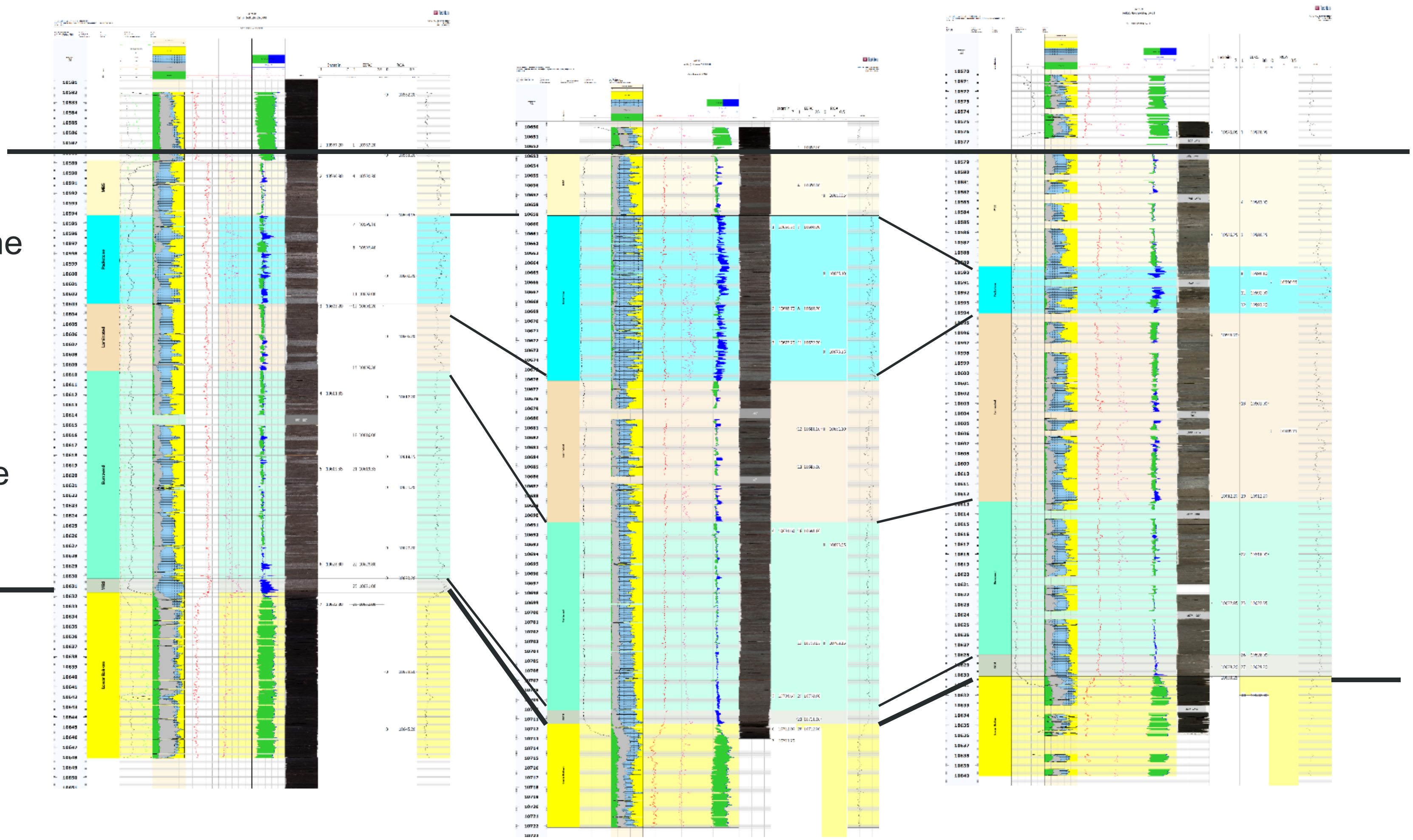
Base of the Upper Bakken Shale

MB4 – Packstone Zone

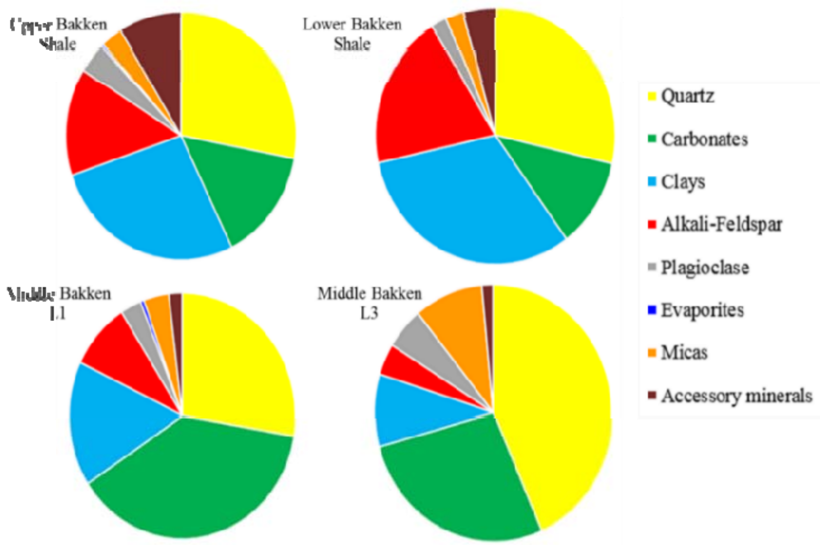
MB3 – Laminated Zone

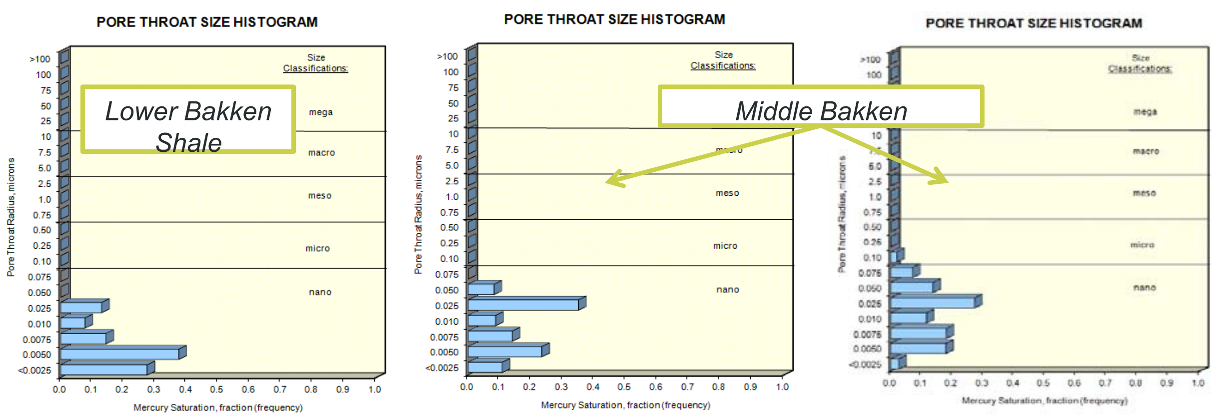
MB2 – Burrowed Zone

Top of the Lower Bakken Shale



ROCK CHARACTERIZATION





X-ray diffraction (XRD) mineralogical analysis was conducted to quantify the bulk mineral composition.

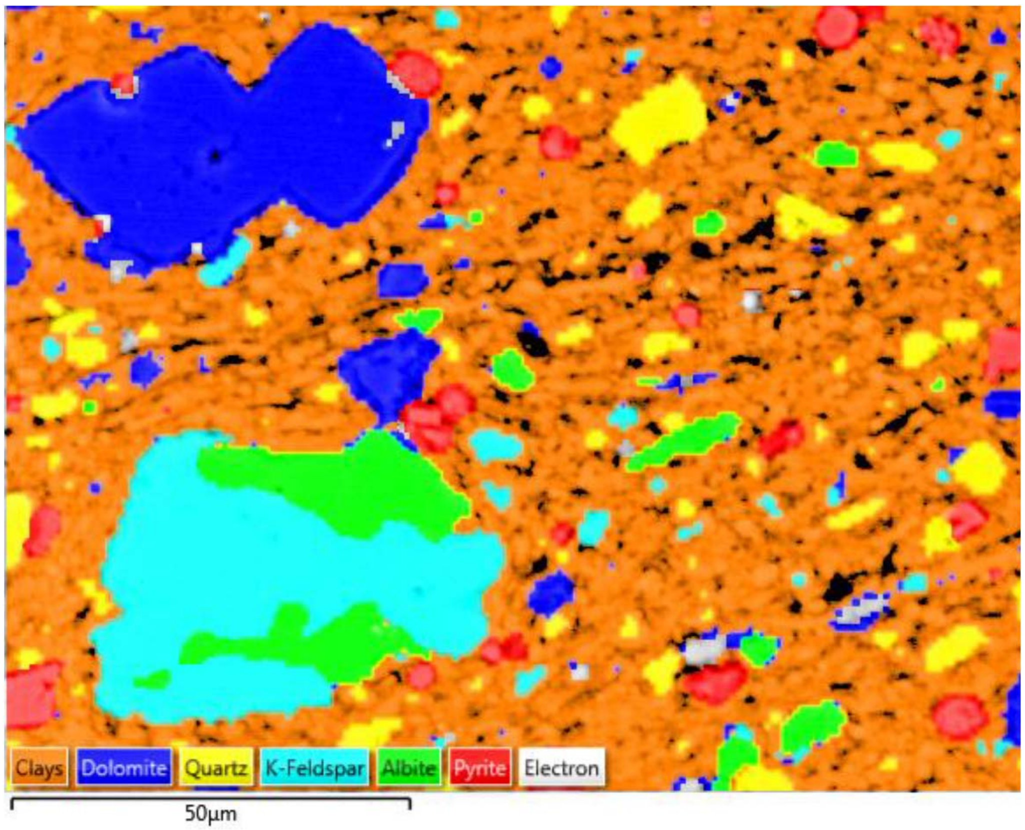
Also used standard techniques to determine rock properties, including:

- Porosity
- Permeability
- Grain density
- Pore throat size distribution through mercury injection capillary pressure analysis

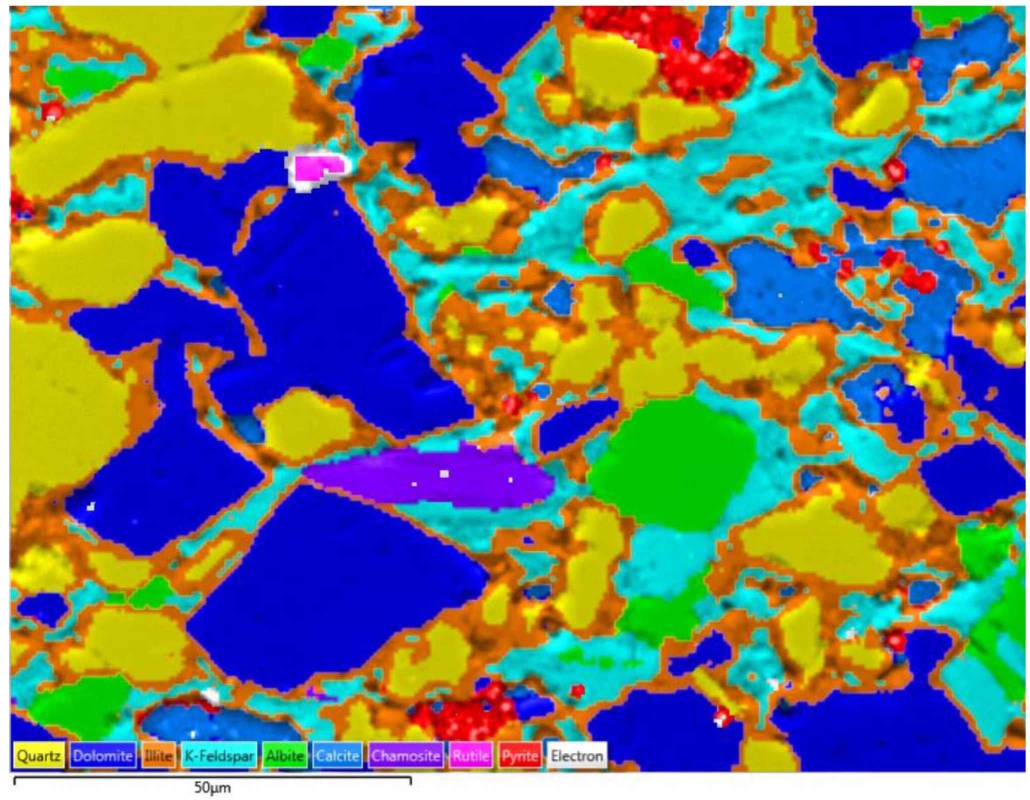
ROCK CHARACTERIZATION

- Scanning electron microscopy (SEM) mineral mapping shows the mineral composition of the rock matrix.

Upper Bakken Shale



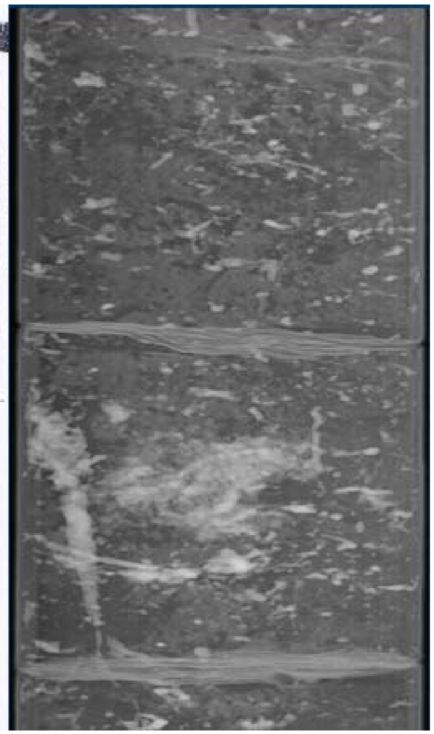
Middle Bakken (laminated lithofacies)



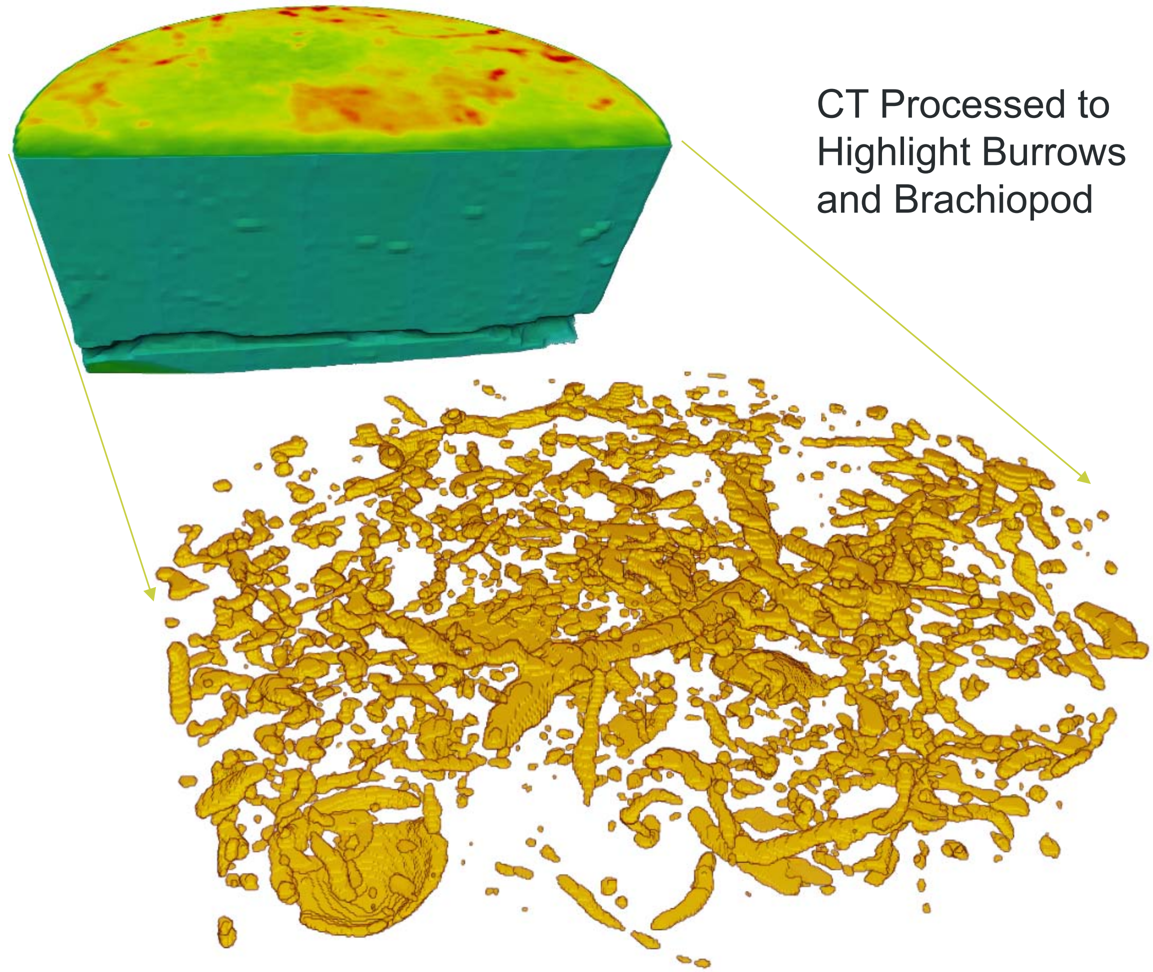
COMPUTER TOMOGRAPHY (CT) SCANNING

Middle Bakken – Burrowed Facies
4-inch Core Sample

Plain Light Photo



CT Image



CT Processed to Highlight Burrows and Brachiopod

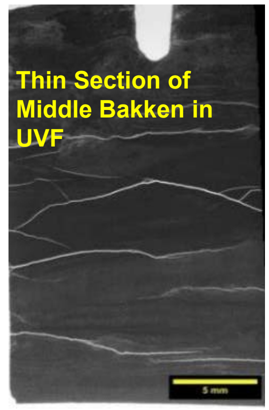
FRACTURE AND PORE ANALYSIS TECHNIQUES

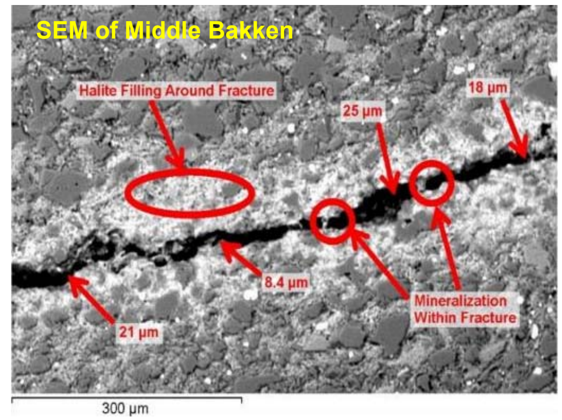
Macrofracture Characterization

- **Ultraviolet fluorescence (UVF)** technique uses dyes that fluoresce under UV light to help to visualize the fractures.
- **Conventional SEM** methods were used for macro- and microscale fracture analysis.

Micro- and Nanoscale Fracture and Pore Analysis

- **Field emission (FE)–SEM**, **micro-CT scanning**, and **focused ion beam (FIB)–SEM** conducted by Ingrain Inc. were used to characterize micro- and nanoscale fractures and pores.





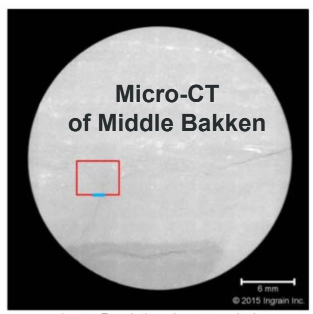
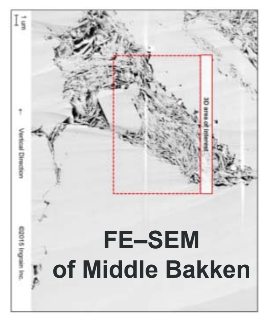
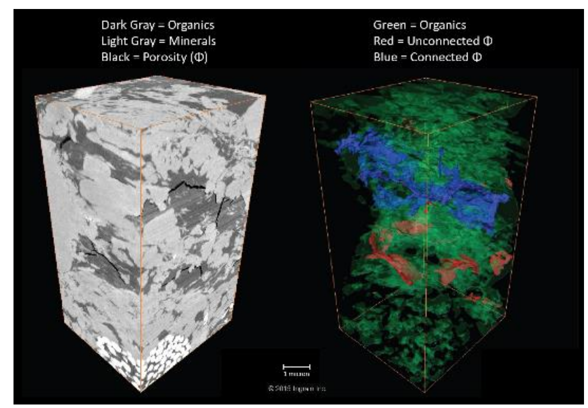


Image Resolution- 4 µm per pixel

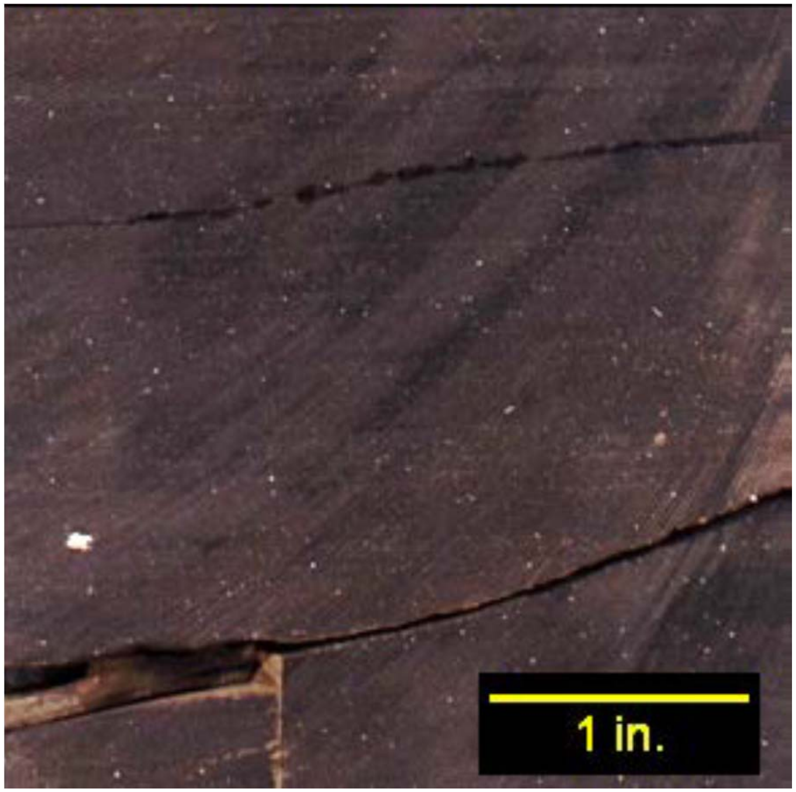


FIB–SEM of Bakken Shale

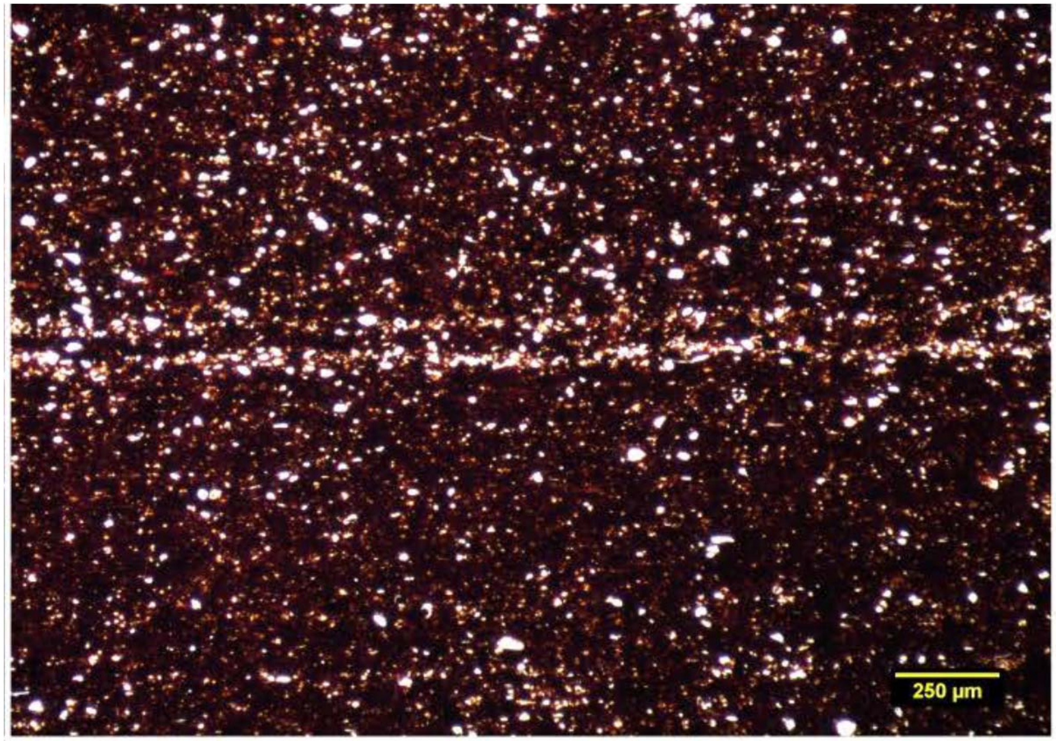


UPPER BAKKEN SHALE

Slabbed Core Photo

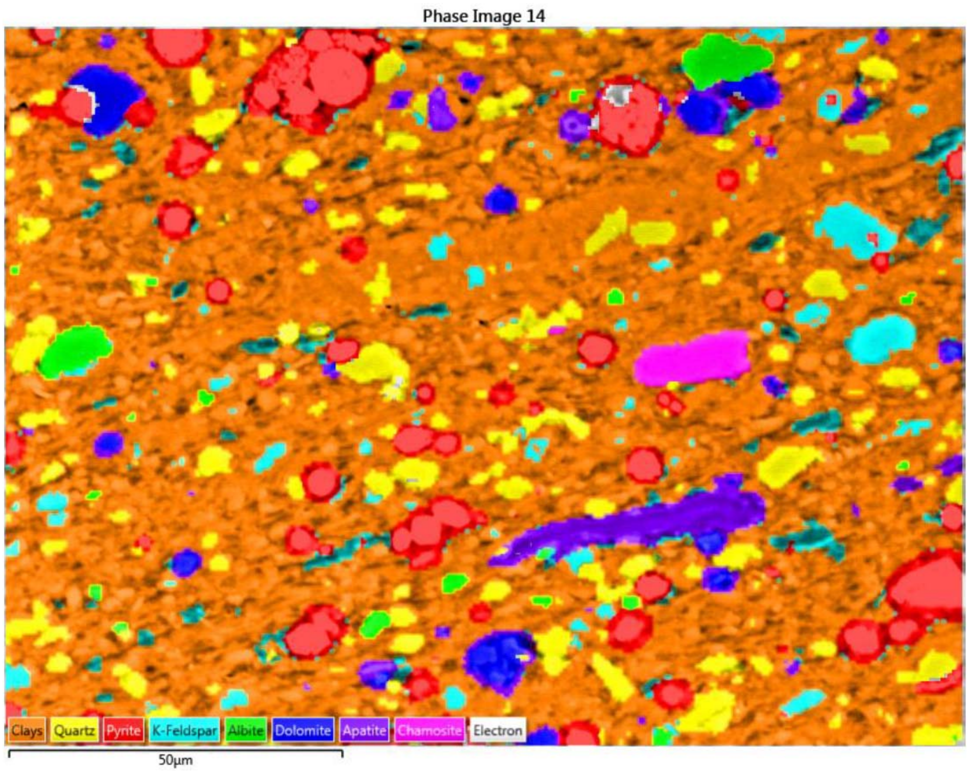


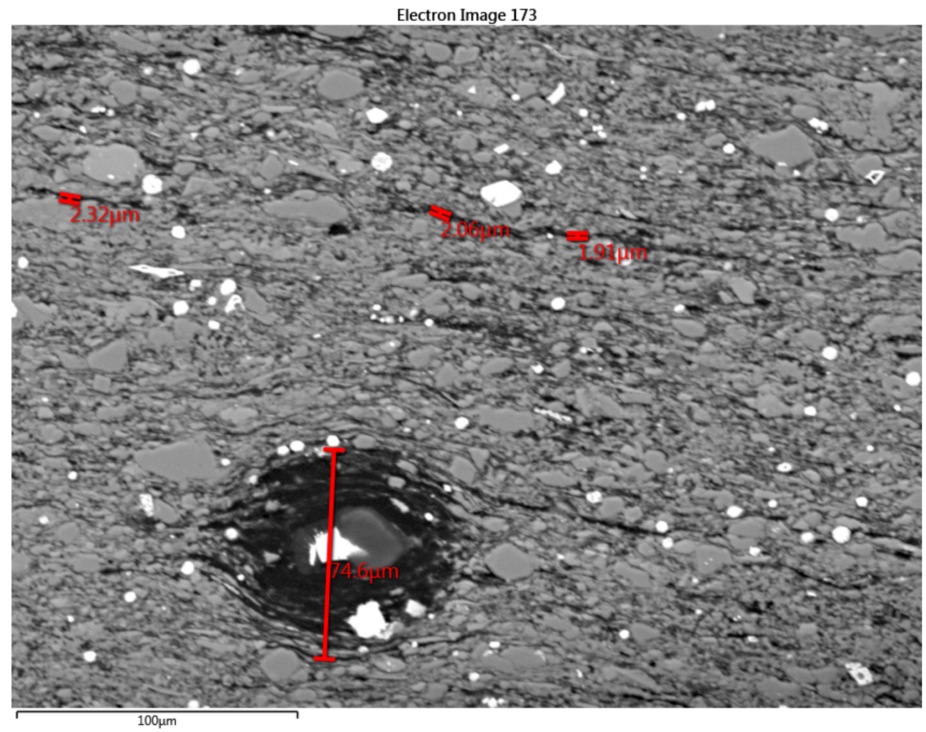
Thin-Section Photo
(5× cross-polarized light)



UPPER BAKKEN SHALE

Composite SEM Mineral Map and Backscatter SEM (BSEM) Image





75-μm Oil-Wet Pore

UPPER BAKKEN SHALE

MACROFRACTURES IMAGED USING CT SCAN DATA

Track 1 is the original CT image.

Track 2 is CT data processed in such a way as to highlight bedding features.

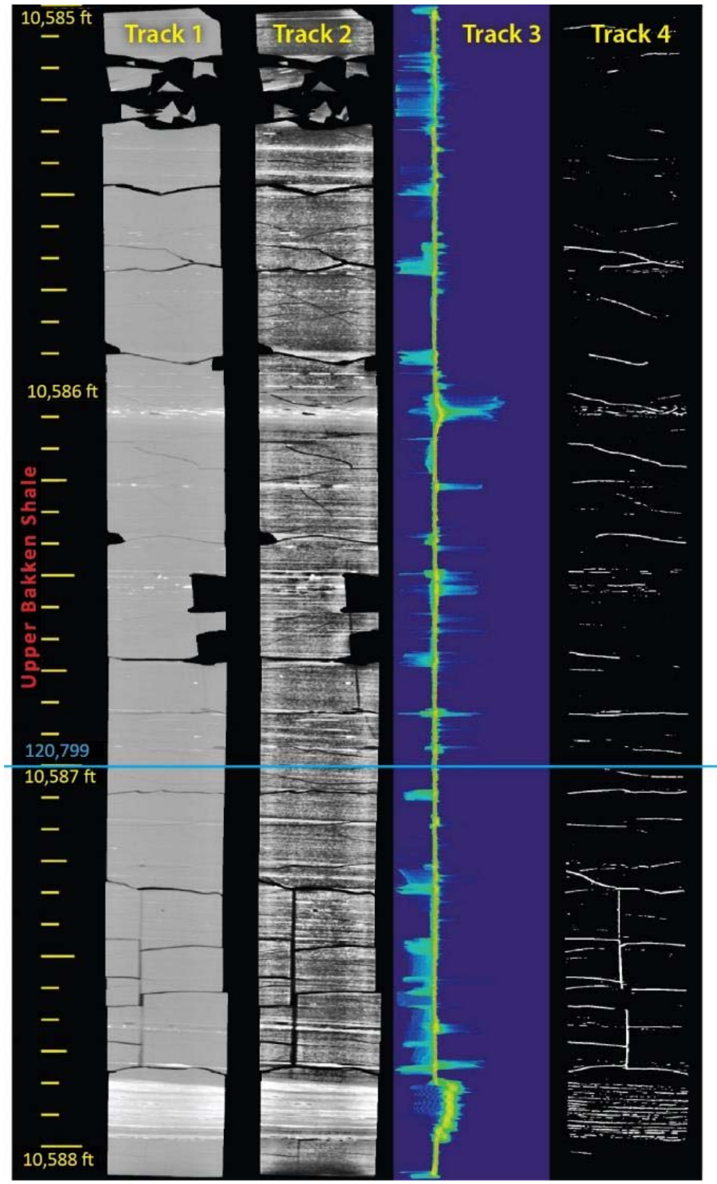
Track 3 is a log histogram of fractures (left peaks) and high-density matrix (right peaks).

Track 4 is CT data processed to show just the fractures.

Macrofractures (vertical and horizontal) observed here are most likely induced by the core collection and handling process.

Occasional bright spots and bright bands in largely similar matrix suggest potential areas of microfractures, although their proximity to induced macrofractures suggests they may also be induced by the core collection and handling process.

Image resolution: 0.24 mm x 0.24 mm x 0.33 mm



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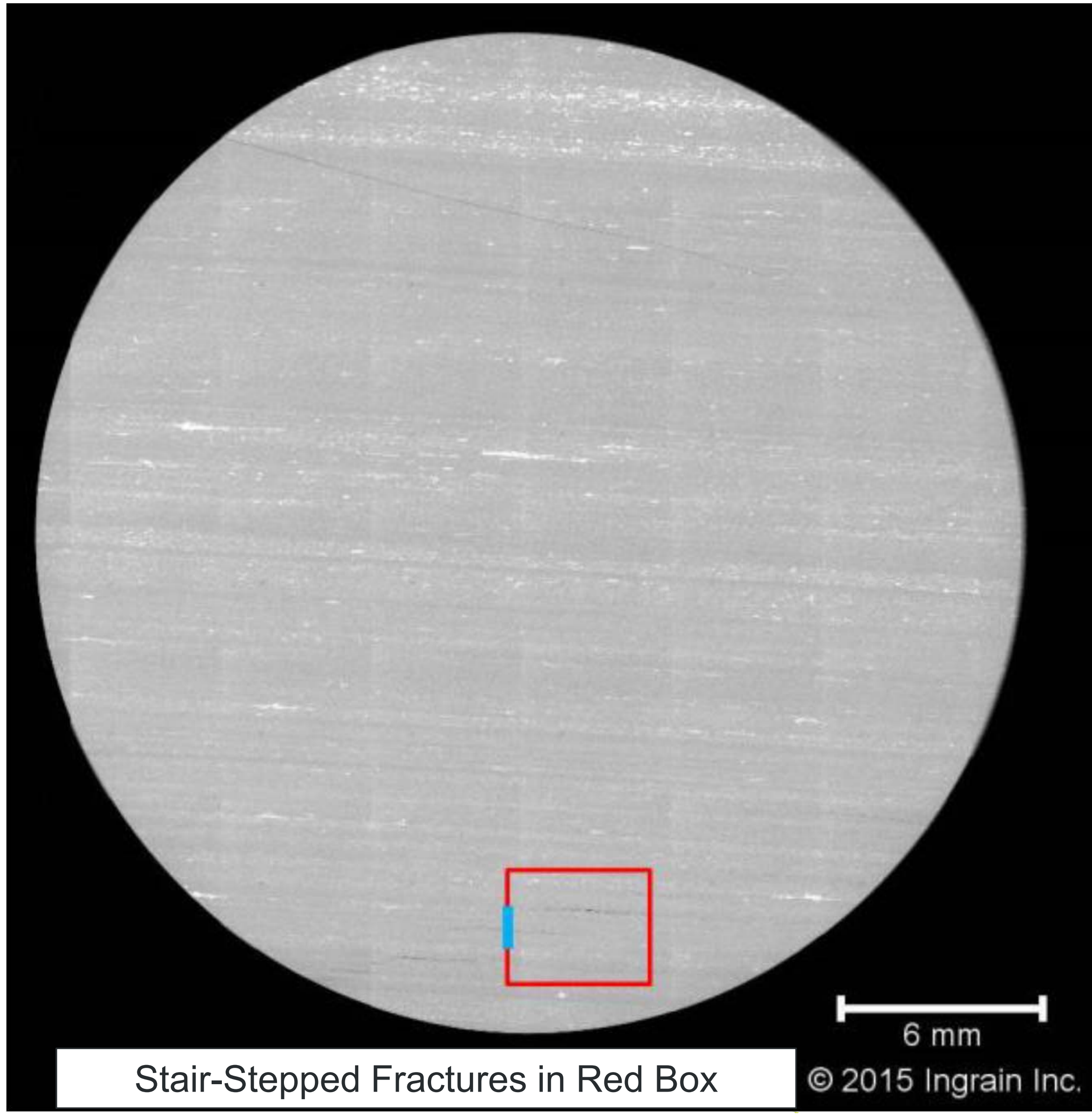
UPPER BAKKEN SHALE

MICRO-CT 1-INCH PLUGS ORIENTED HORIZONTALLY

Extremely thin laminae can be seen. Some microfractures are also apparent.

Red box indicates area sampled for advanced SEM analysis (FIB–SEM and FE–SEM).

Blue line indicates location of FE–SEM analysis.



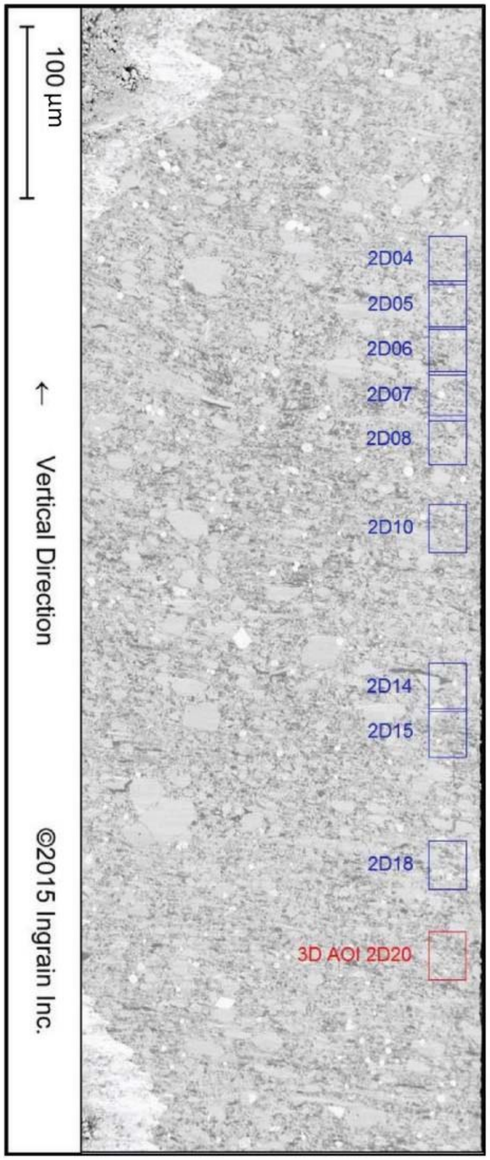
UPPER BAKKEN SHALE

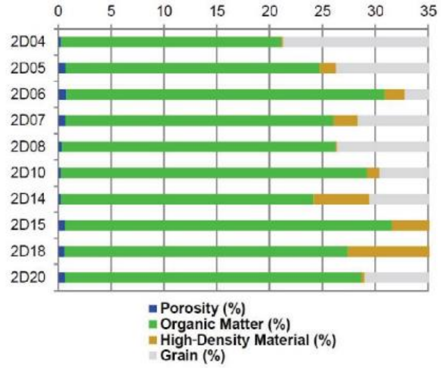
FE–SEM ANALYSIS

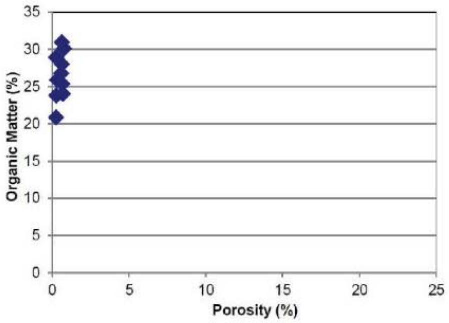
Lighter-colored areas are mineral grains.

Dark gray areas are organic matter, initially interpreted to be kerogen.

No microfractures are visible in this image, which is consistent with the examinations by other techniques.







Sub-Sample No.	Phi	OM	PAOM	HD	ATR
2D04	0.25	20.87	0.25	0.15	1
2D05	0.70	24.04	0.68	1.52	3
2D06	0.76	30.12	0.75	1.86	2
2D07	0.65	25.36	0.62	2.32	2
2D08	0.32	25.91	0.30	0.12	1
2D10	0.25	28.96	0.24	1.16	1
2D14	0.26	23.85	0.25	5.31	1
2D15	0.62	30.95	0.61	5.90	2
2D18	0.58	26.79	0.56	10.41	2
2D20	0.62	28.02	0.60	0.36	2
AVE	0.50	26.49	0.49	2.91	2

*Percentage by volume.

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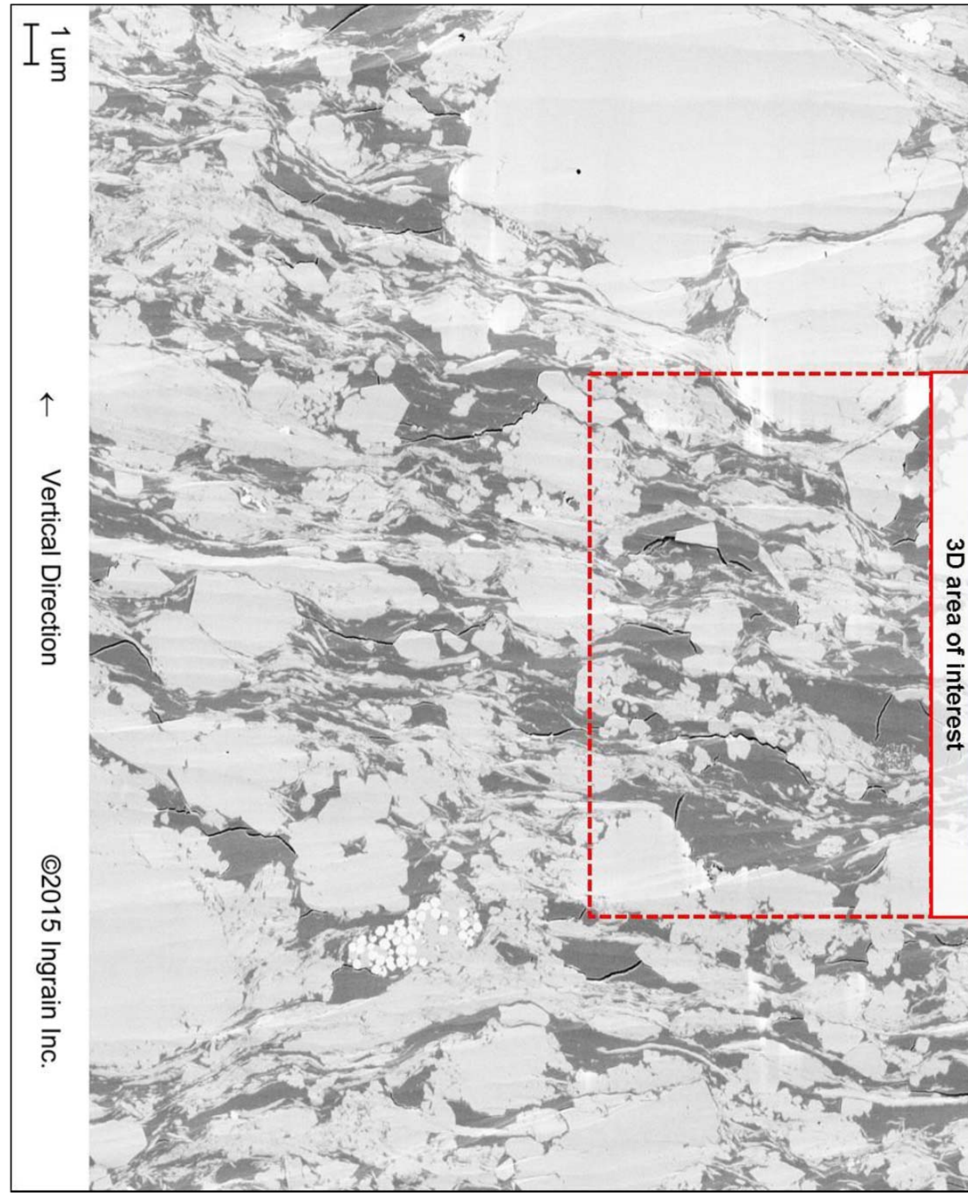
UPPER BAKKEN SHALE

FE–SEM IMAGE

Light-colored areas are mineral grains.

Gray areas are organic matter, initially interpreted to be kerogen.

Black lines are pore spaces. Most occur within the kerogen. Those linear pore spaces are interpreted to be naturally occurring as a result of the conversion of kerogen to oil.



UPPER BAKKEN SHALE

FIB–SEM

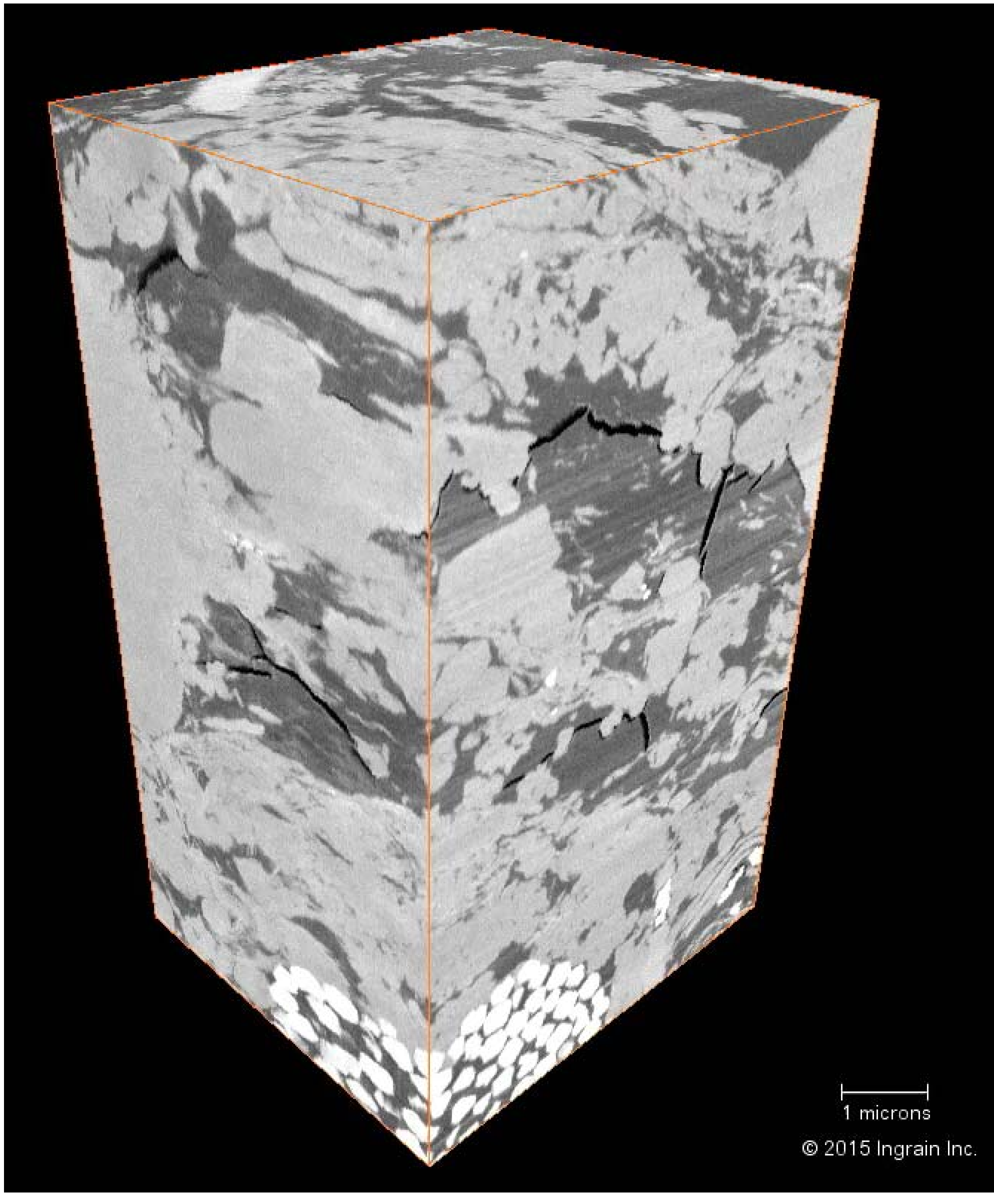
Dark gray = organics
Light gray = minerals
Black = porosity (Φ)

Light-colored areas are mineral grains.

Gray areas are organic matter, initially interpreted to be kerogen.

Black lines are pore spaces. Most occur within the kerogen.

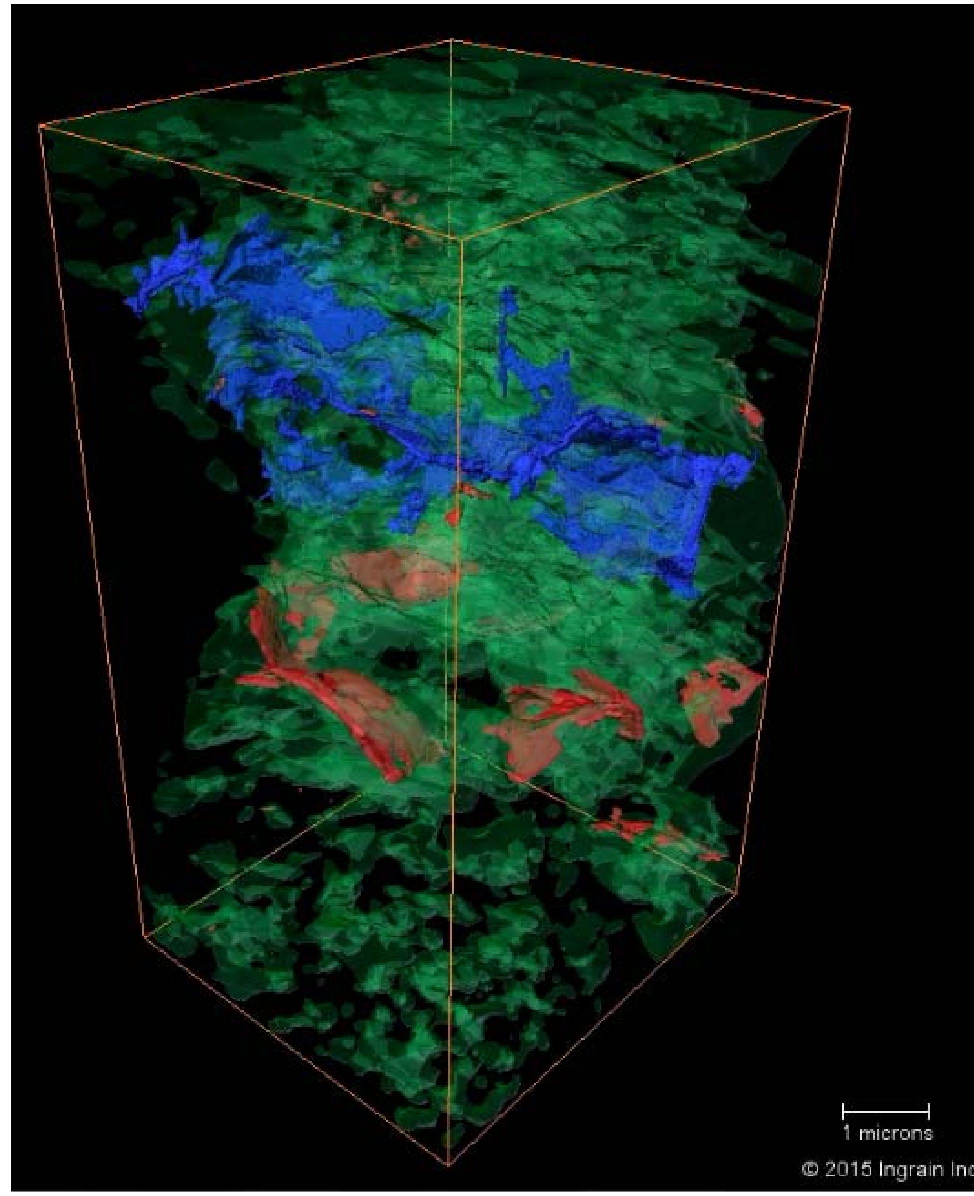
White features are pyrite.



UPPER BAKKEN SHALE

FIB–SEM

Green = organics
Red = unconnected Φ
Blue = connected Φ



Shales are dominated by intergranular distribution of organics, likely kerogen.

The amount of connected and unconnected pore space is roughly equal.

The dominant presence of organics in the shales and the fact that CO_2 can diffuse into organic material such as oil or kerogen suggest that the shales may have an exceptionally high storage capacity.

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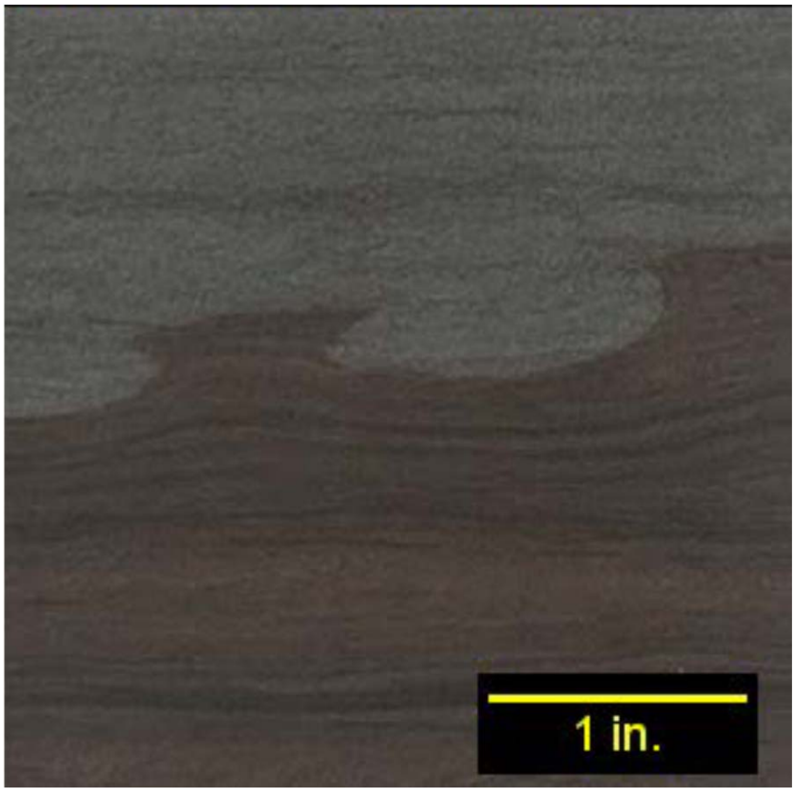
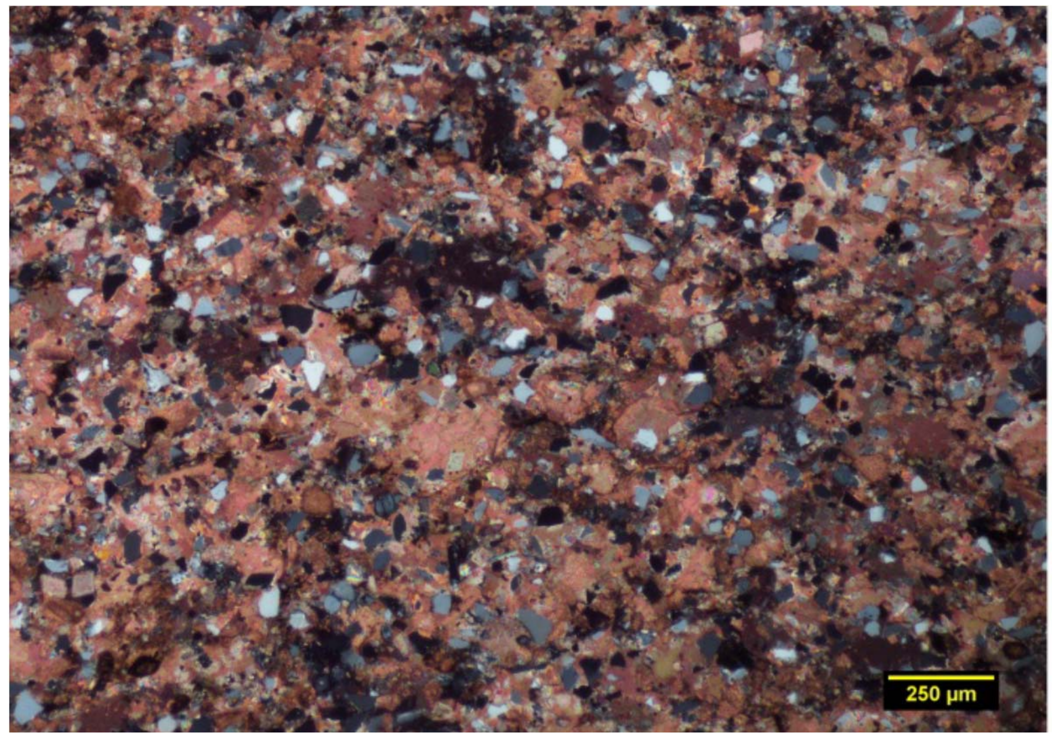
MIDDLE BAKKEN RESERVOIR LAMINATED FACIES

Slabbed Core Photo



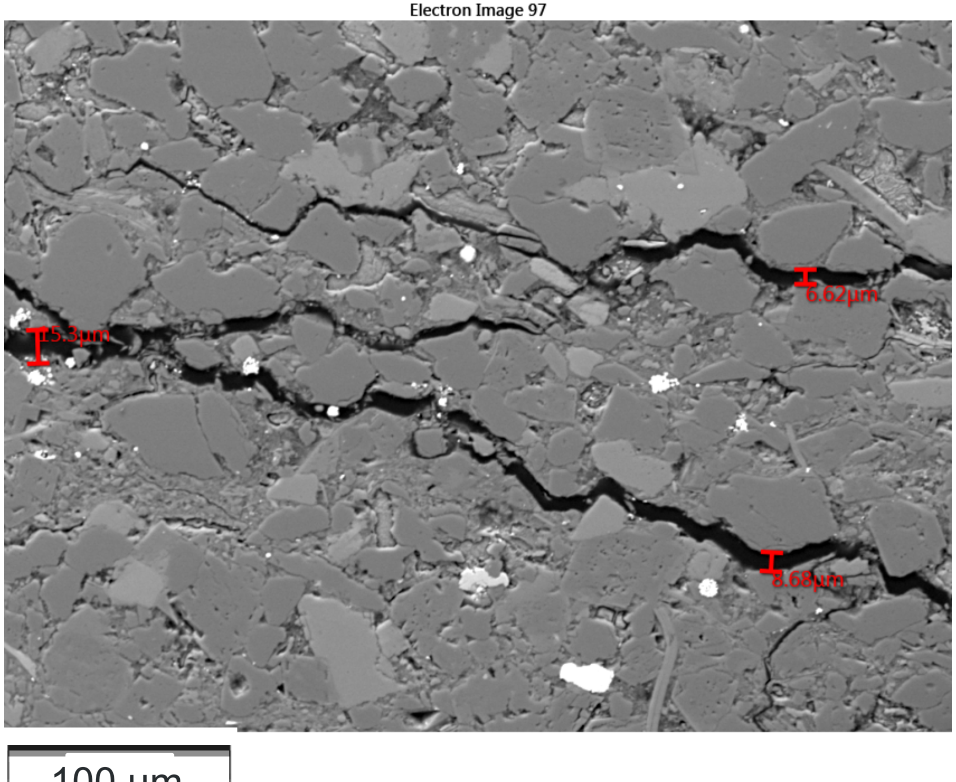
Thin-Section Photo
(5× cross-polarized light)



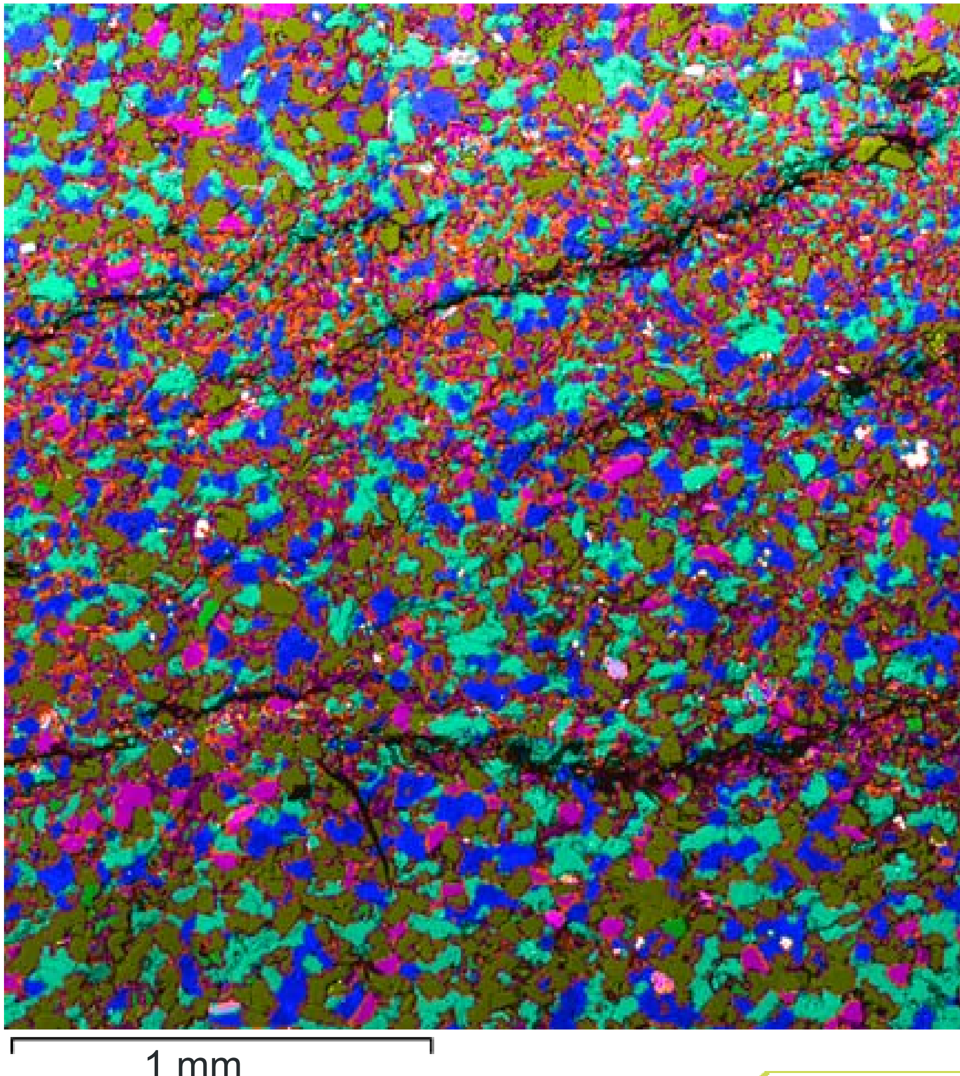
MIDDLE BAKKEN RESERVOIR

BSEM

Electron Image 97



BSEM yields aperture data.



Mineral map combined with BSEM image.

MIDDLE BAKKEN RESERVOIR

MACROFRACTURES IMAGED USING CT SCAN DATA

Laminated Lithofacies

Track 1 is the original CT image.

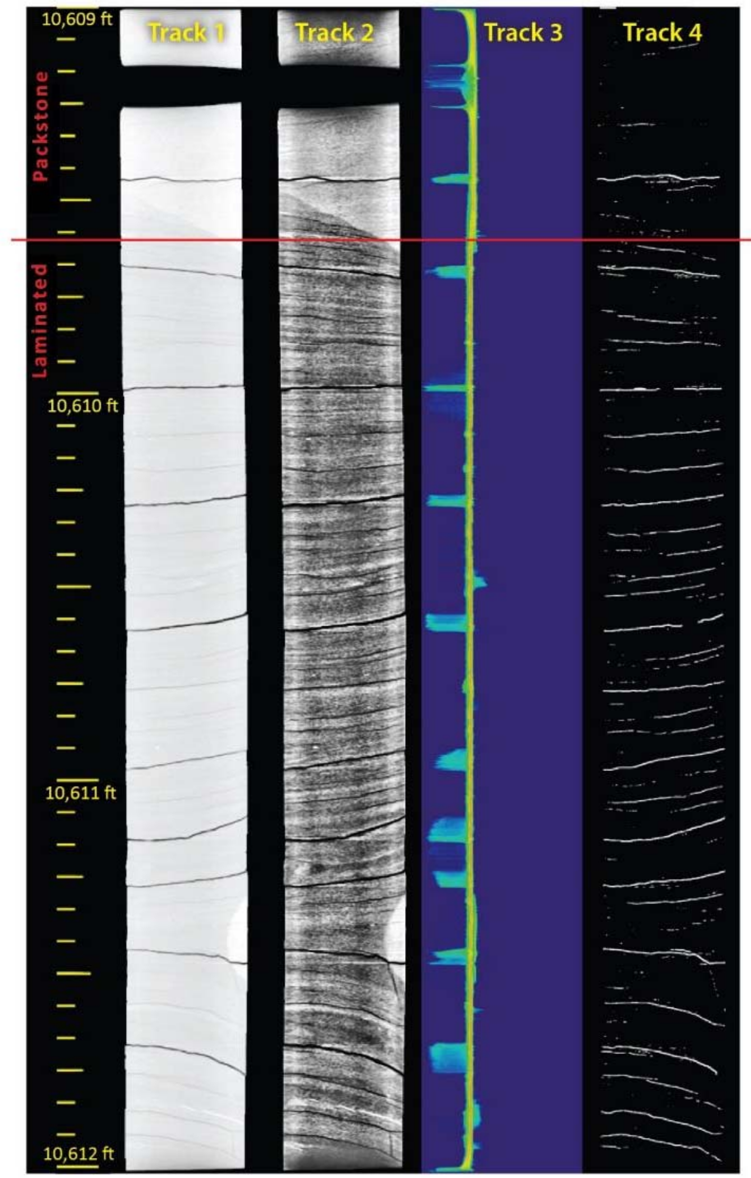
Track 2 shows highly laminated bedding.

Track 3 shows a log histogram of fractures (left peaks) and high-density matrix (right peaks).

Track 4 shows just the fractures.

Macrofractures (vertical and horizontal) that physically separate parts of the core are most likely induced by the core collection and handling process. The high number of these indicates MB3 is brittle and prone to fracturing, both naturally and hydraulically.

Image resolution: 0.24 mm x 0.24 mm x 0.33 mm



MIDDLE BAKKEN RESERVOIR

MICRO–CT
1-INCH PLUGS ORIENTED HORIZONTALLY

Laminated Lithofacies

- Micro-CT shows faint lamination with a few apparent microfractures.
- Horizontal, vertical, and angled microfractures are apparent.
- Red box indicates area sampled for advanced SEM (FIB–SEM and FE–SEM) analysis.
- Blue line indicates location of 2-D SEM analysis.

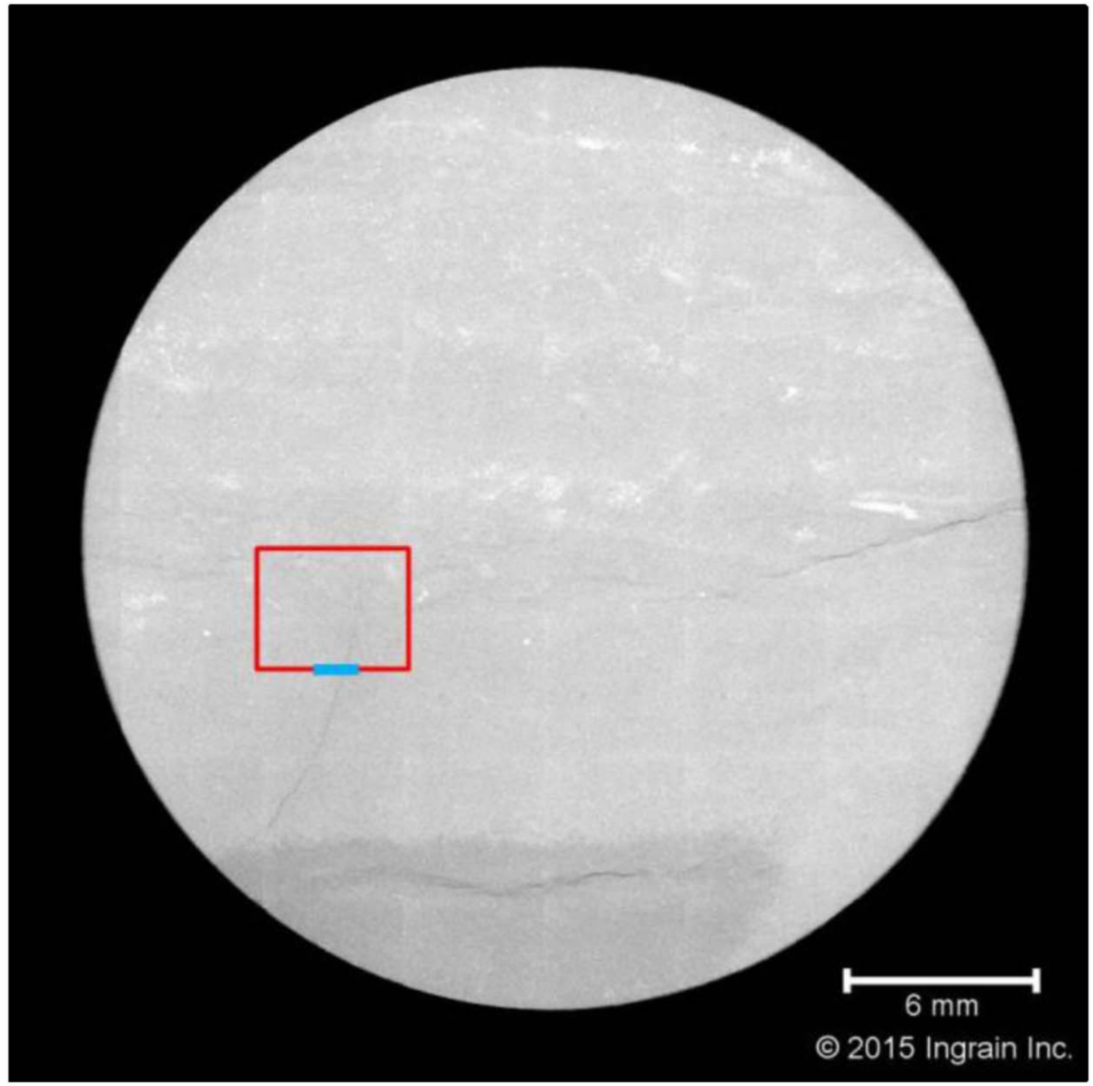


Image Resolution- 4 μm per pixel

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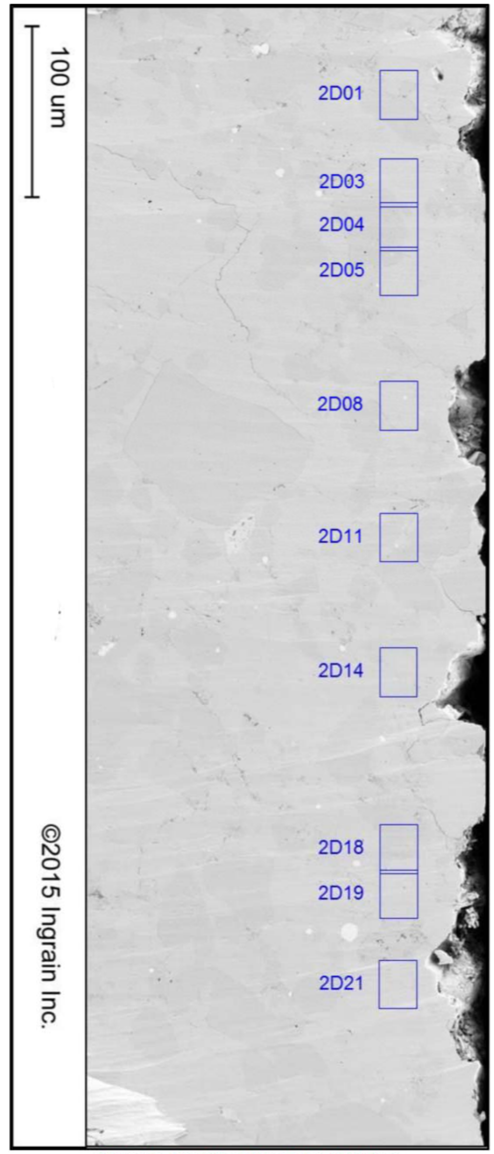
MIDDLE BAKKEN RESERVOIR

FE–SEM ANALYSIS

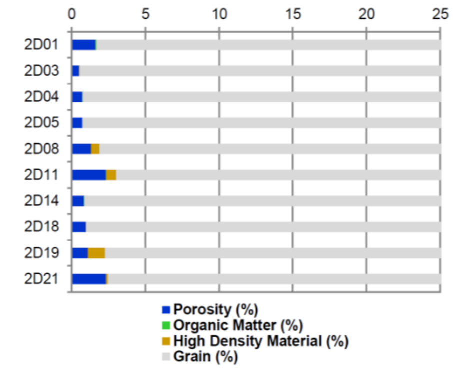
Some apparent micro- to nanoscale fracture networks.

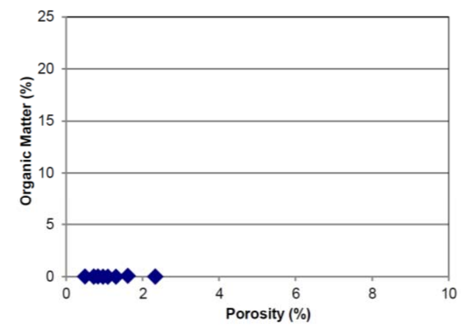
No organic material present.

Porosity is associated with both microfractures and intergranular matrix porosity, although matrix porosity appears to be dominant in these samples.



*Sample Ion-Milled Parallel to Bedding



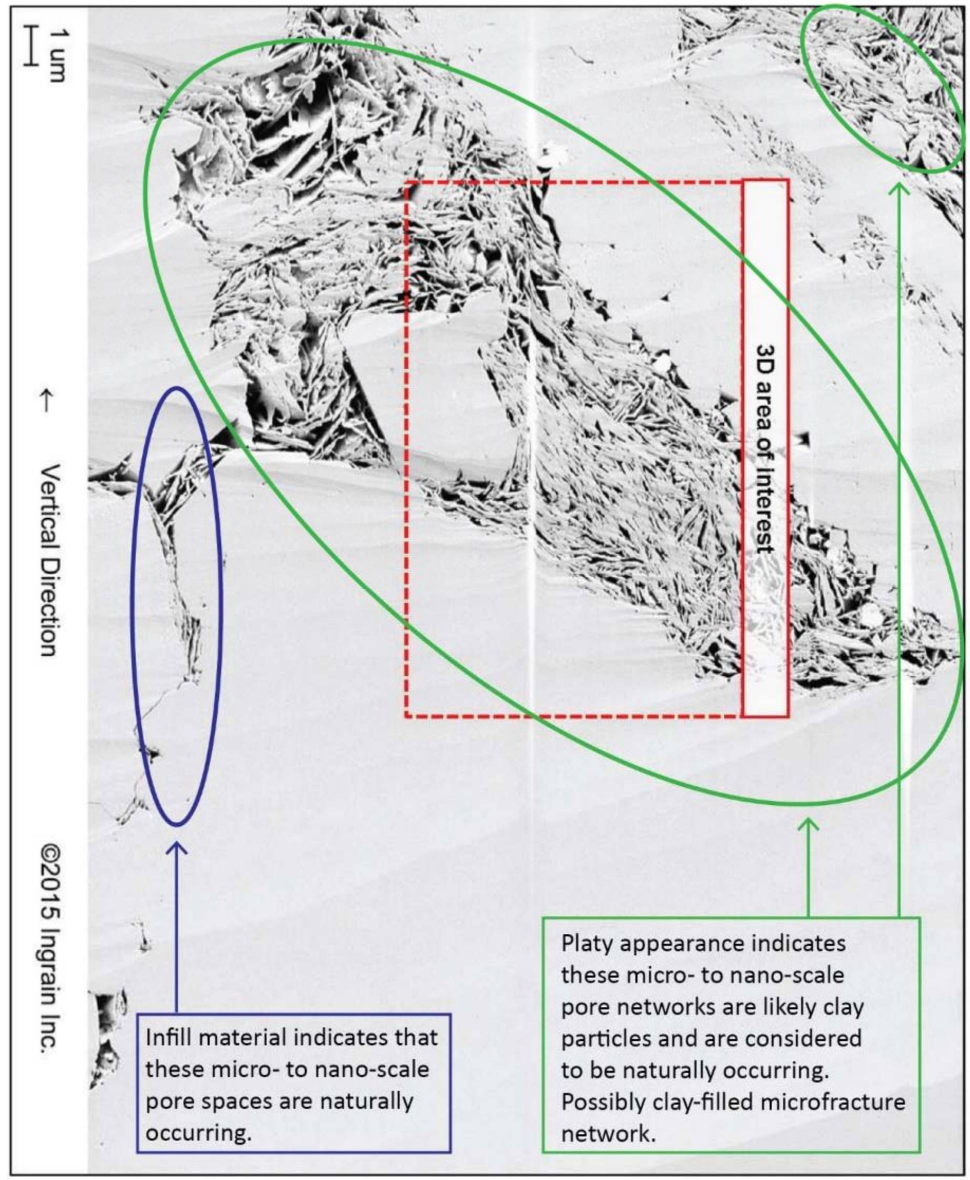


Sub-Sample #	Phi	OM	PAOM	HD	ATR
2D01	1.61	0.07	0.01	0.00	13
2D03	0.49	0.01	0.00	0.02	0
2D04	0.72	0.01	0.00	0.00	0
2D05	0.72	0.00	0.00	0.00	0
2D08	1.30	0.00	0.00	0.58	0
2D11	2.33	0.02	0.00	0.66	0
2D14	0.83	0.02	0.00	0.00	0
2D18	0.96	0.00	0.00	0.02	0
2D19	1.09	0.00	0.00	1.16	0
2D21	2.33	0.00	0.00	0.12	0
AVE	1.24	0.01	0.00	0.26	7

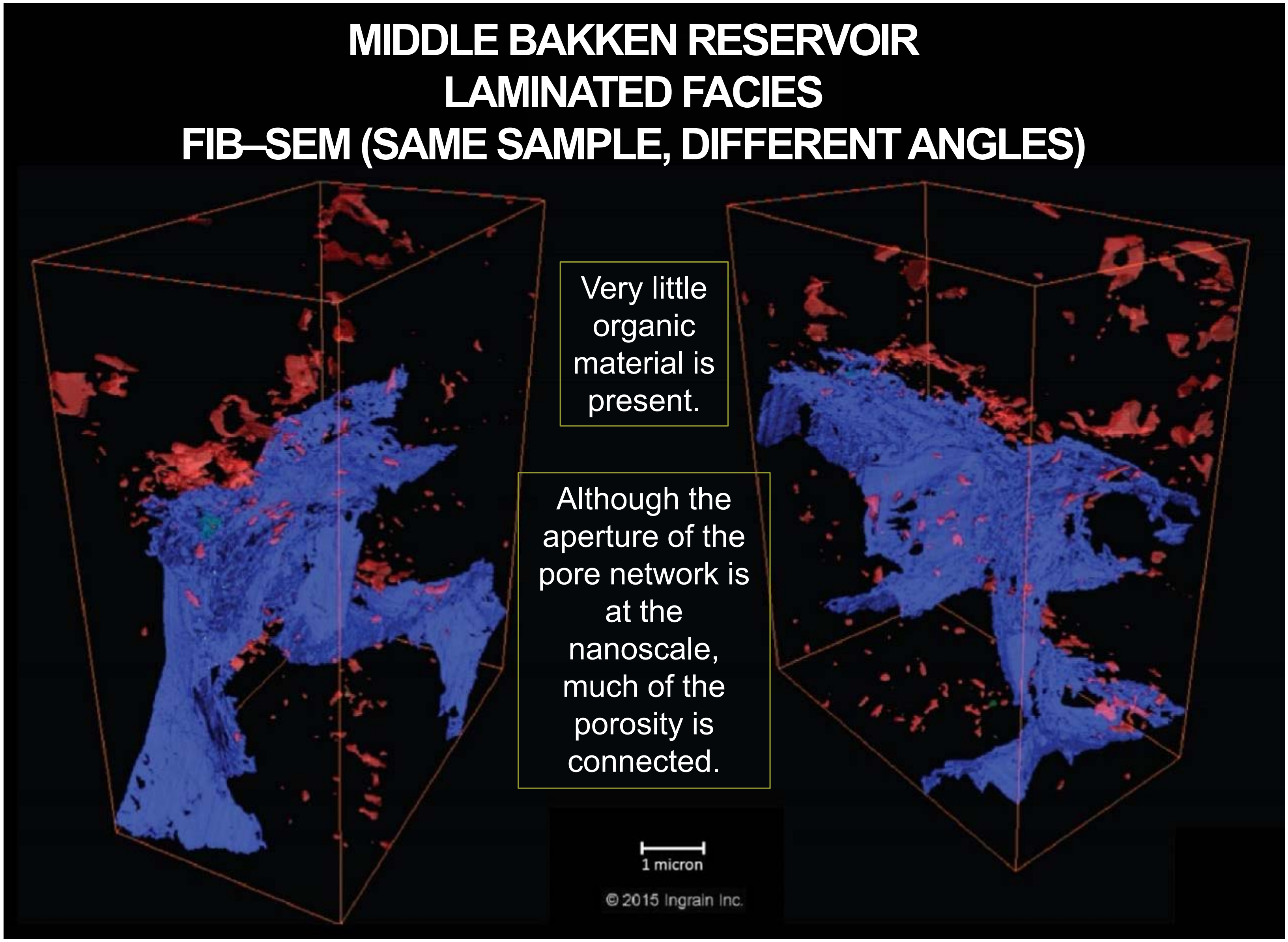
*Percentage by volume

MIDDLE BAKKEN RESERVOIR

FE–SEM
LAMINATED FACIES



Green = Organics
Red = Unconnected Φ
Blue = Connected Φ



ACCOMPLISHMENTS TO DATE

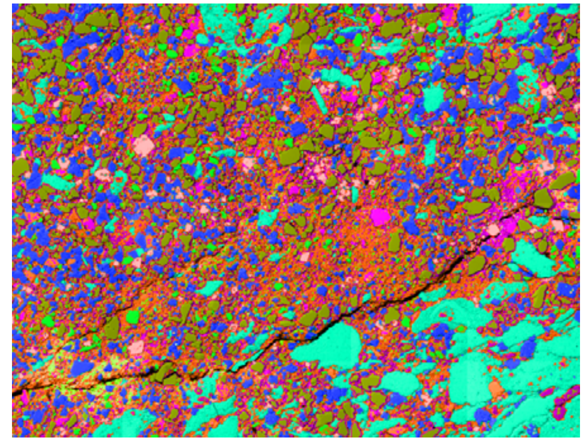
COMPLETED

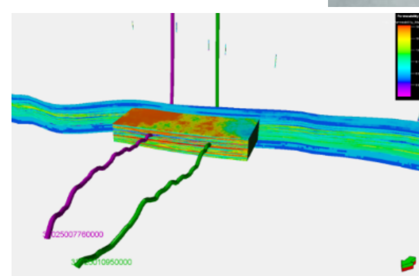
Phase I

- Comprehensive suite of “standard” reservoir properties for key lithofacies from five Bakken cores.
  - Porosity, permeability, bulk density, total organic carbon, RockEval-based maturity data, high-pressure mercury injection, pore throat size distribution, XRD mineralogy, x-ray fluorescence (XRF) bulk chemistry composition.
- Comprehensive suite of advanced analyses for three Bakken cores.
  - Whole-core CT scans, micro-CT scans, FE–SEM, FIB–SEM
  - Multiscale fracture characterization (macro-, micro-, nano-)
- Geomechanical properties data from one Bakken core.
  - Compressive strength, Young’s modulus, Poisson’s ratio
- Lab studies on the ability of Bakken kerogen to sorb CO_2.

SYNERGY OPPORTUNITIES

- Methods and insights developed by this project can be directly applicable to projects in many North American tight oil formations.
  - Micro- and nanoscale analysis techniques.
  - Novel approaches to rock CO_2 permeation and hydrocarbon extraction studies.
  - Improved modeling workflows and enhancements to existing software packages.
  - Support the development of CO_2 storage estimation methodologies that are specific to organic-rich, oil-saturated shales.





SUMMARY

Key Findings

- CT scans provide valuable data related to rock matrix and fracture properties and distribution and can be readily applied to the building of static geomodels.

- Advanced SEM results show that although porosity values are low, it appears that much of the microscale porosity is connected, even in the shales.

Lessons Learned

- **The dominant presence of organics in the shales and the fact that CO_2 can diffuse into organic material such as oil or kerogen suggest that the shales may have an exceptionally high storage capacity.**

Future Plans

- **Laboratory and modeling efforts will investigate:**
  - **Rates at which CO_2 permeates Bakken reservoir and shale and mobilizes oil.**
  - **Mechanisms controlling those interactions.**

ACKNOWLEDGMENT

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Disclaimer

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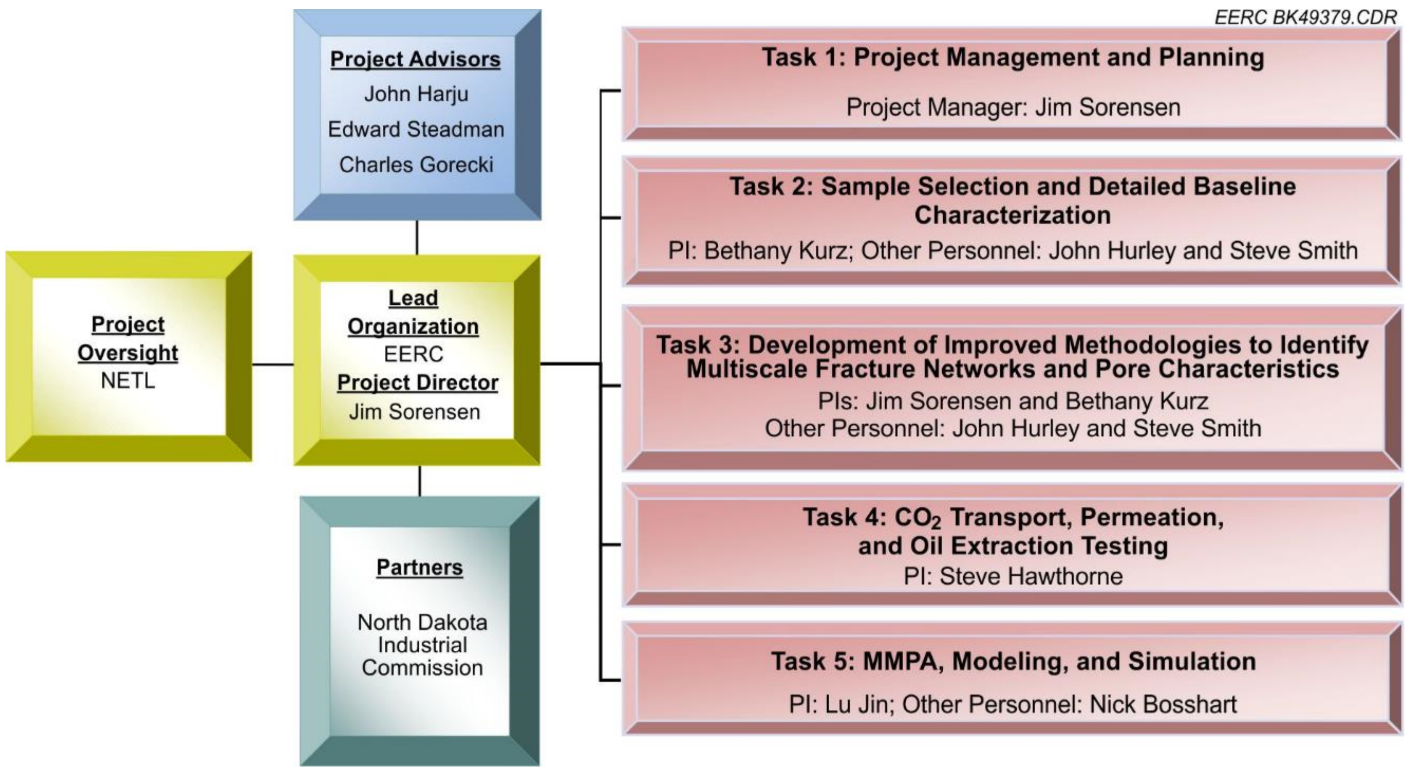
THANK YOU!

Critical Challenges. **Practical Solutions.**

APPENDIX

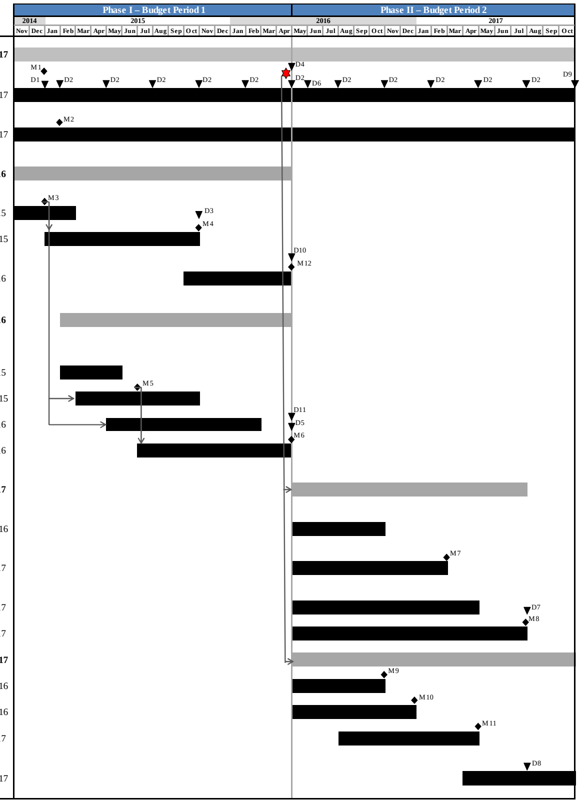
- Organization chart
- Gantt chart
- Bibliography

ORGANIZATION CHART



GANTT CHART

	Start Date	End Date
Task 1 – Project Management and Planning	**11/1/2014**	**10/31/2017**
1.1 – Reporting Requirements	11/1/2014	10/31/2017
1.2 – Information Dissemination and Input from Stakeholders	11/1/2014	10/31/2017
Task 2 – Sample Selection and Detailed Baseline Characterization	**11/1/2014**	**4/30/2016**
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
2.3 – Laboratory Evaluation of the Effects of CO_2 on Kerogen and Bitumen in Bakken Shale	10/1/2015	4/30/2016
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 Shale 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	4/30/2017
5.4 – Best Practices Manual for CO_2 Storage and EOR Potential Estimation of Tight Oil Formations	4/1/2017	10/31/2017



Summary Task
Activity Bar
Milestone (M) ◆
Critical Path
Deliverable (D) ▼
Decision Point

Key for Deliverables (D) ▼
D1 – Updated Project Management Plan (PMP)
D2 – Quarterly Progress Report
D3 – Sample Characterization Data Sheets
D4 – Project Fact Sheet Information
D5 – Manuscript – Use of Advanced Analytical Techniques to Identify and Characterize Multiscale Fracture Networks in Tight Oil Formations
D6 – Phase I Interim Report
D7 – Manuscript – Laboratory-Measured CO_2 Permeation and Oil Extraction Rates in Tight Oil Formations
D8 – Best Practices Manual – Estimation of CO_2 Storage Resource of Fractured Reservoirs
D9 – Final Report
D10 – Manuscript – Effects of Kerogen-bitumen content on CO_2 Storage and EOR in Tight Oil Formations
D11 – Manuscript – Development and Application of Multiscale Pore and Fracture Models to CO_2 Storage and EOR in Tight Oil Formations

Key for Milestones (M) ◆
M1 – Updated Project Management Plan Submitted to DOE
M2 – Project Kickoff Meeting Held
M3 – First Samples Collected for Characterization
M4 – Completion of Baseline Sample Characterization
M5 – First Macroscale Fracture Data Sets Generated
M6 – Completion of Fracture Network Characterization
M7 – Completion of CO_2 Permeation Testing
M8 – Completion of Hydrocarbon Extraction Testing
M9 – MMPA Analysis Completed
M10 – Completion of Geocellular Models
M11 – Completion of Simulations
M12 – Completion of Kerogen and Bitumen Studies

Revised 11/4/15

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- Sorensen, J., Kurz, B., Smith, S., Walls, J., Foster, M., and Aylsworth, B., 2016, The use of advanced analytical techniques to characterize micro- and nanoscale pores and fractures in the Bakken: Paper presented at the Unconventional Resources Technology Conference (URTeC), San Antonio, Texas, USA, August 1–3, 2016, URTeC: 2447958, 13 p.

- Sorensen, J.A., Kurz, B.A., and Smith, S.A., 2016, Improved characterization and modeling of tight oil formations for CO_2 enhanced oil recovery potential and storage capacity estimation: Research Performance Phase I Interim Report – Overview of key learnings from Phase I fracture analysis activities, May 30, 2016, 33 p.

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