Chemically Enabled CO_2-Enhanced Oil Recovery in Multi-Porosity, Hydrothermally Altered Carbonates in the Southern Michigan basin

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Battelle

U.S. Department of Energy

National Energy Technology Laboratory

Carbon Management and Natural Gas & Oil Research Project Review Meeting

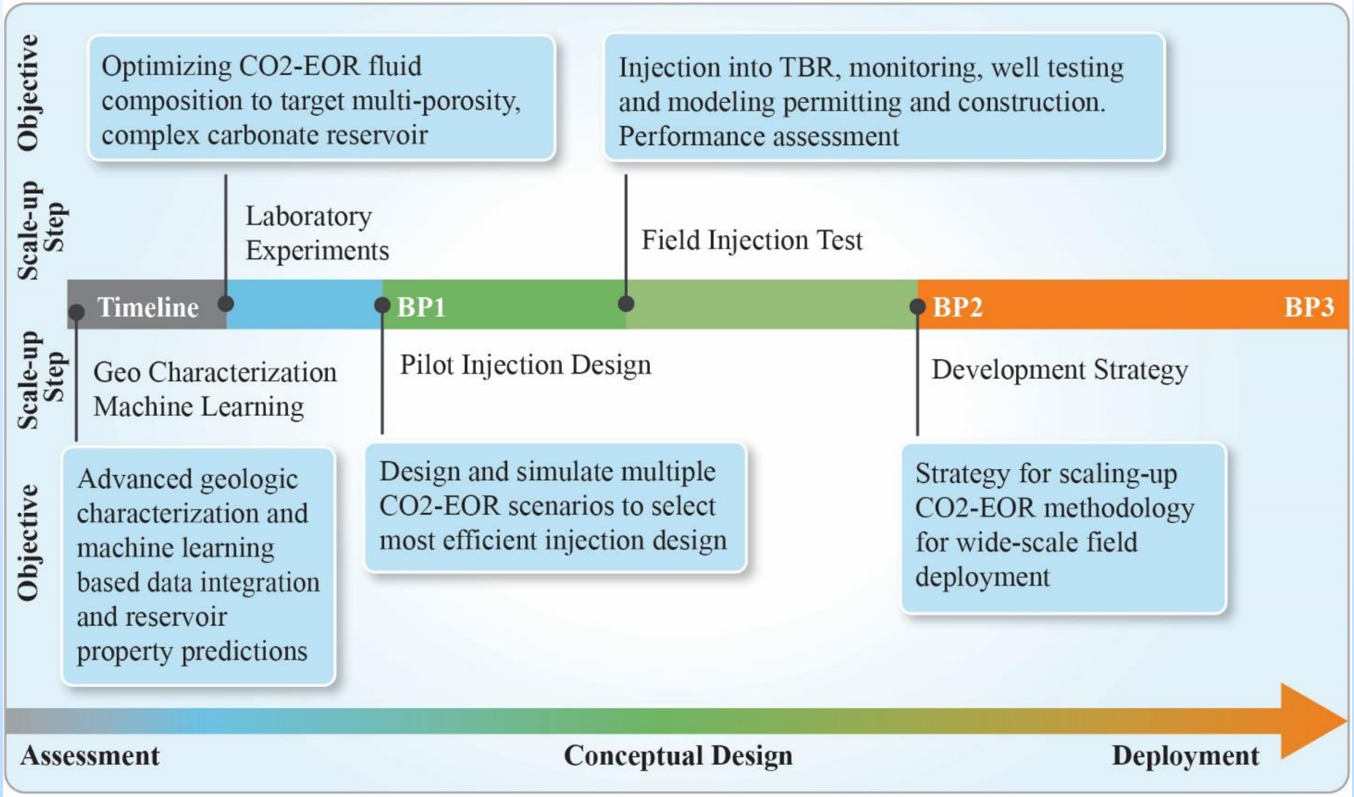
Virtual Meetings August 2 through August 31, 2021

Presentation Outline

- Project Overview
- Technical Status
- Accomplishments to Date
- Lessons Learned
- Project Summary
- Appendix

Project Goals and Objectives

- Carry out a **comprehensive laboratory experiment, computer modeling, and field testing-based evaluation** of **chemically enabled CO_2-EOR** in the **Southern Michigan Basin conventional Trenton/Black River play** to **optimize recovery in a complex, multi-porosity, hydrothermally altered carbonate**



Project Team of Research, Academia, and Industry

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INNOVA EXPLORATION, INC.

CORE ENERGY, LLC

WESTERN MICHIGAN UNIVERSITY

THE UNIVERSITY OF TEXAS AT AUSTIN

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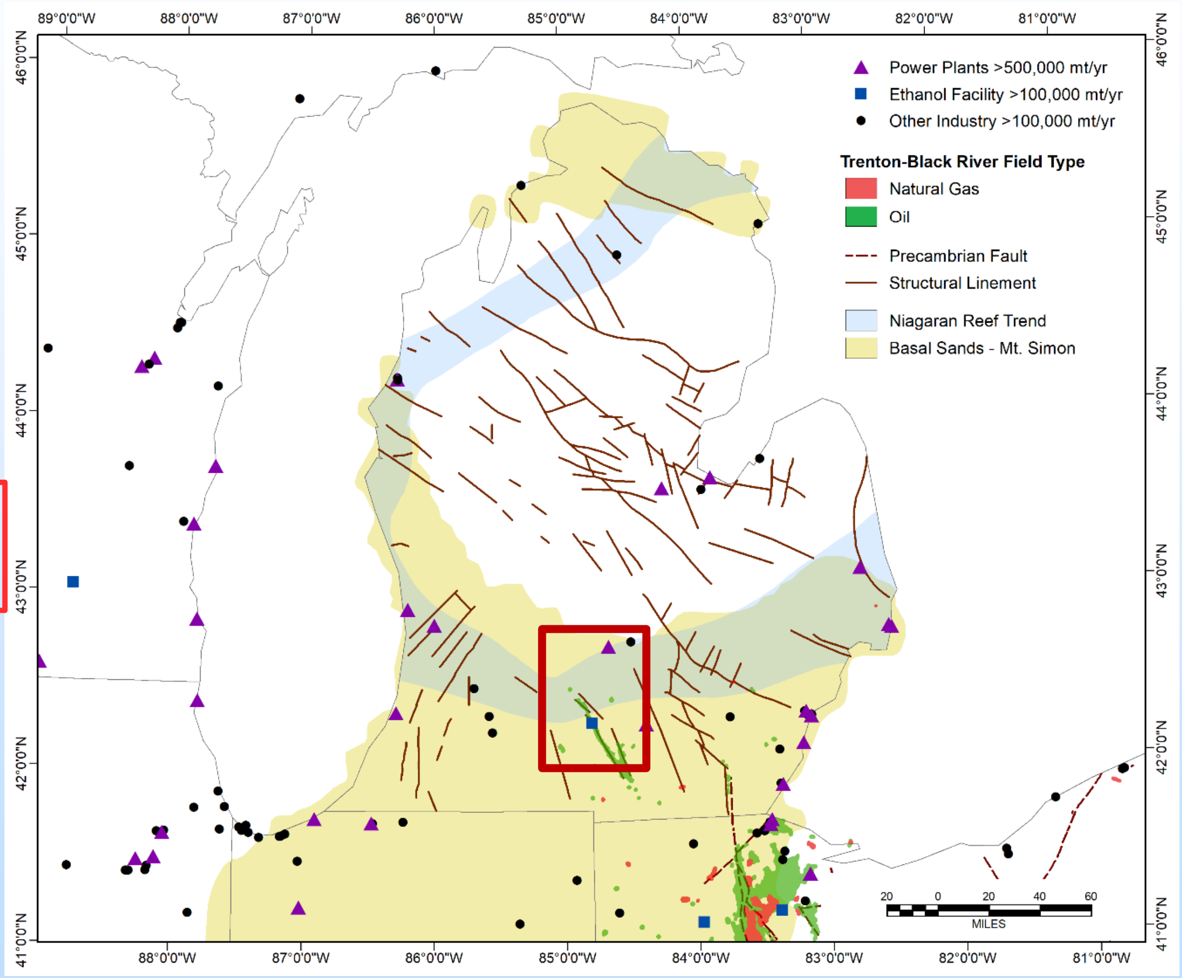
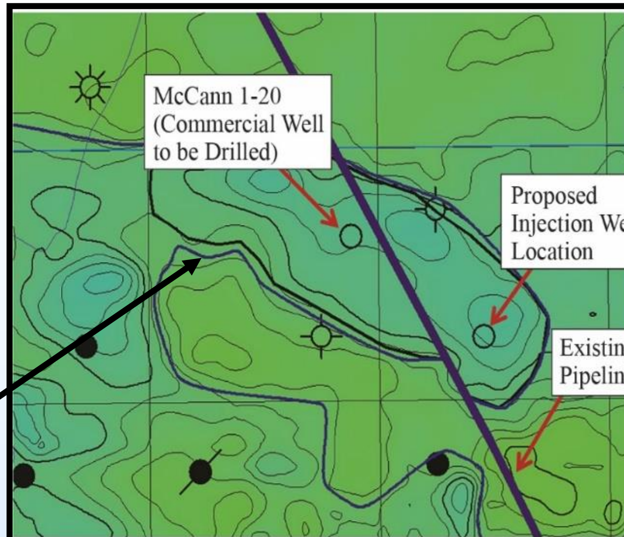
Why the Michigan Basin?

- Multiple CO_2 sources
  - Power plants
  - Ethanol
- Multiple storage systems
  - Mt. Simon sandstone saline reservoir
  - Southern Niagaran Pinnacle Reef Trend storage
  - Trenton-Black River oil and gas fields for EOR
  - Stacked storage possibilities
- Established infrastructure
- Michigan announced net zero by 2050



Significant Oil Potential in the TBR

- Trenton/Black River play
  - >170 MMBO produced
  - >170 MMBO remaining
  - >800 MMBO potentially undiscovered
  - ~ 20 fields

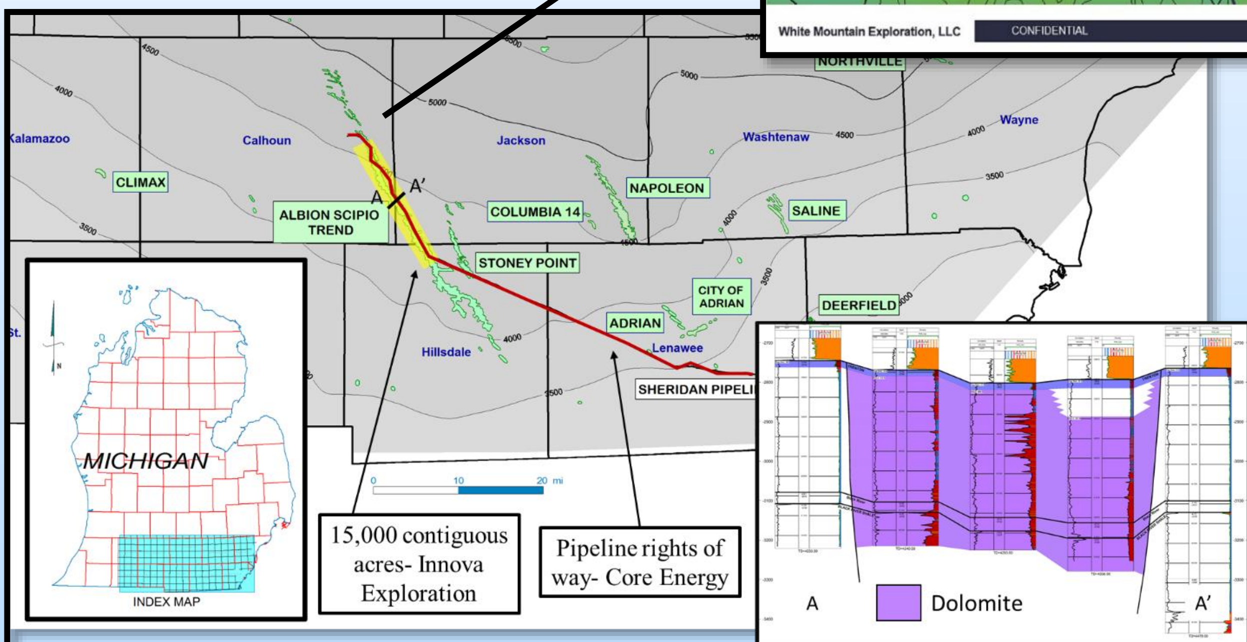


Unit	Formation	Depth	Thickness
Caprock	Ordovician Grouped	3183	516
Gas Column	Trenton-Black River	3699	127
Oil Column		3826	140
OWC		3966	171
TD		4137	

FOADOE1988 MI-07

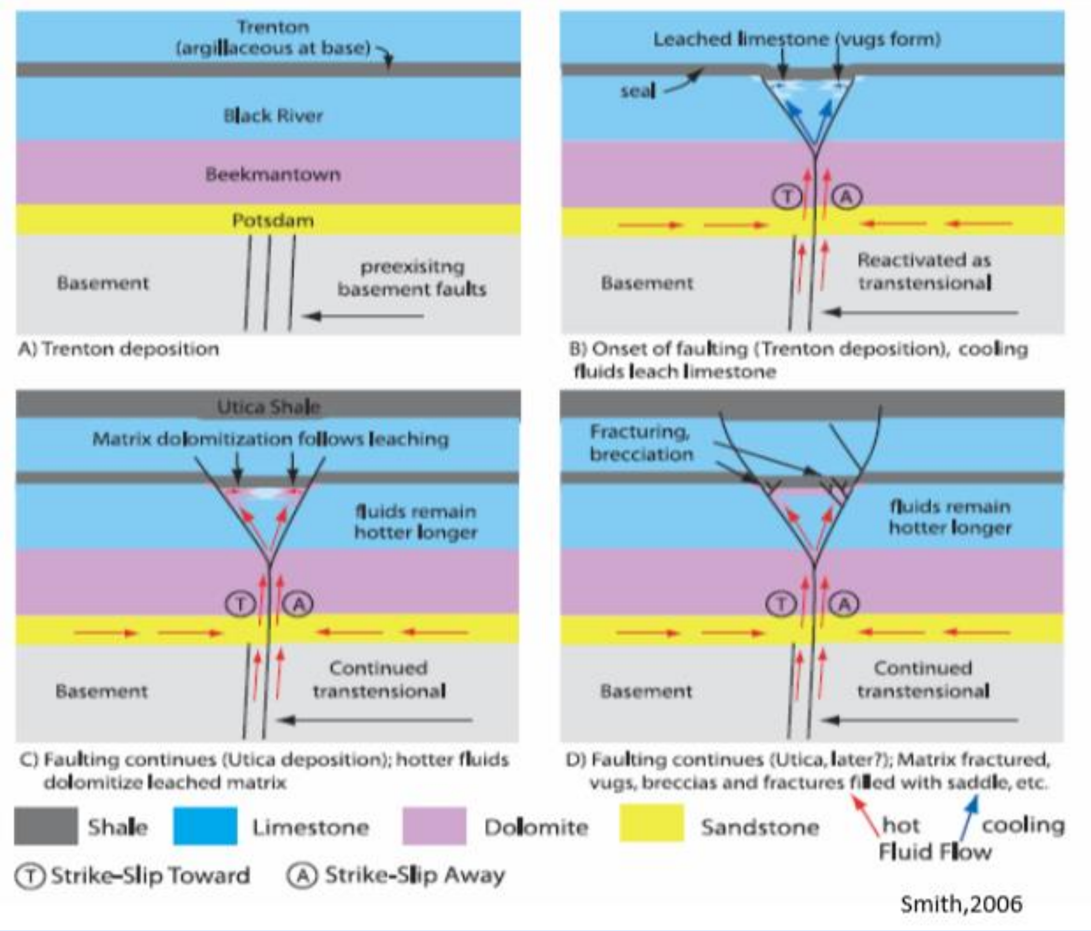
BRS Time Contours
BRS Deformation Outline

White Mountain Exploration, LLC CONFIDENTIAL Innova Exploration, Inc.



Complex Carbonate System

- Facies heterogeneity
- Dolomitization from hydrothermal fluids
- Zones of enhanced porosity and permeability from vugs and fractures
- Developed methods and technology applicable to many, large producing complex carbonate fields globally



Outcomes and Impacts

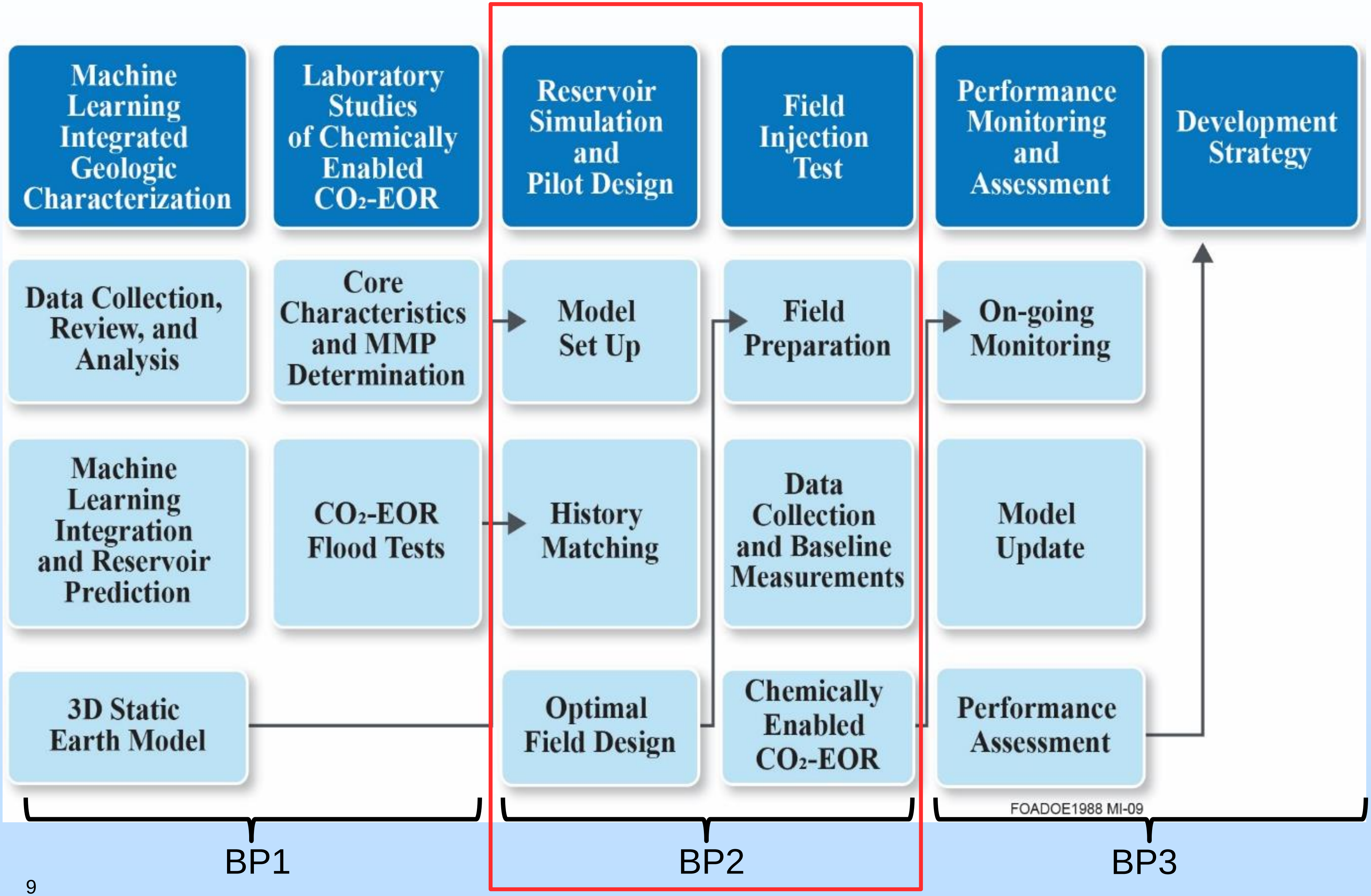
Outcomes and Impacts

- First-of-a kind comprehensive database
- ML based predictive models for electrofacies, vugs, and fractures
- Laboratory designed chemically enhanced CO_2
- Modeling and field-testing CO_2-EOR methods

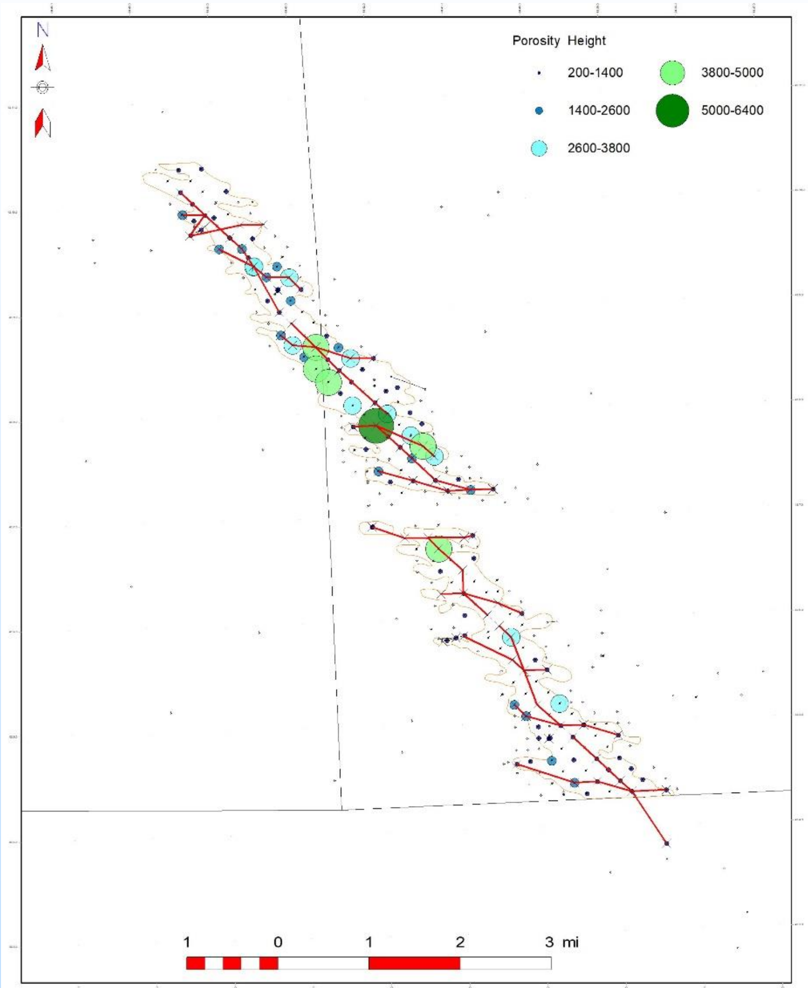
- Improved understanding of geologic heterogeneity
- Improved understanding of property distributions
- EOR methods targeted for multi-porosity, complex carbonates
- Development strategies for similar fields

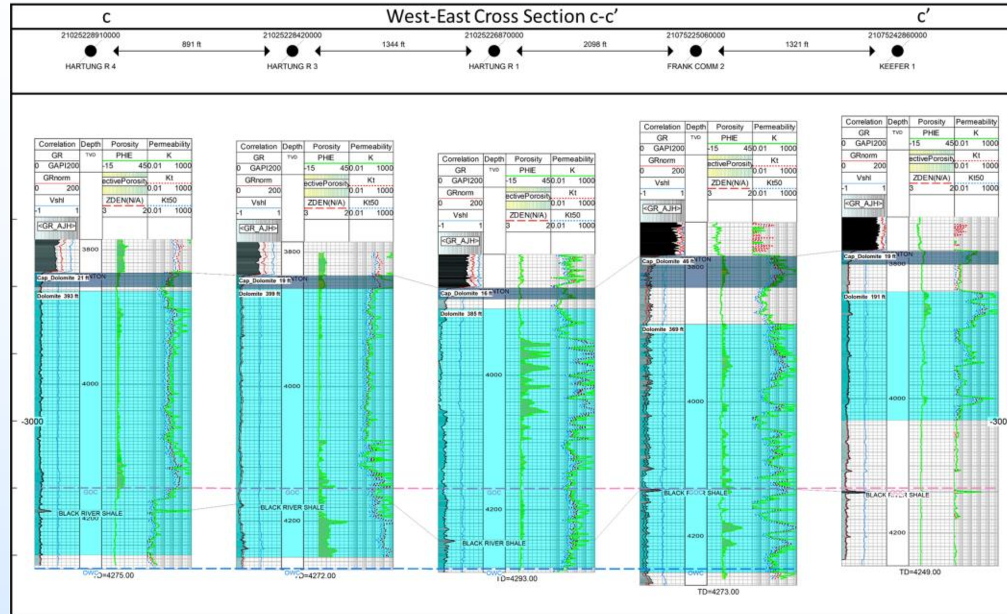
Development of CCUS Complexes in the Michigan Basin

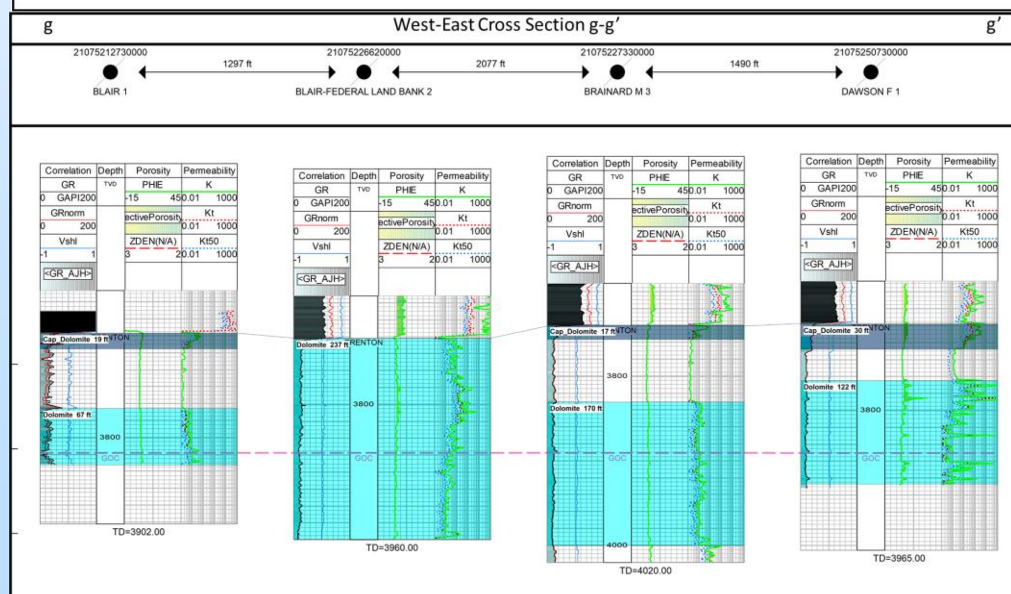
Summary of Tasks to be Performed



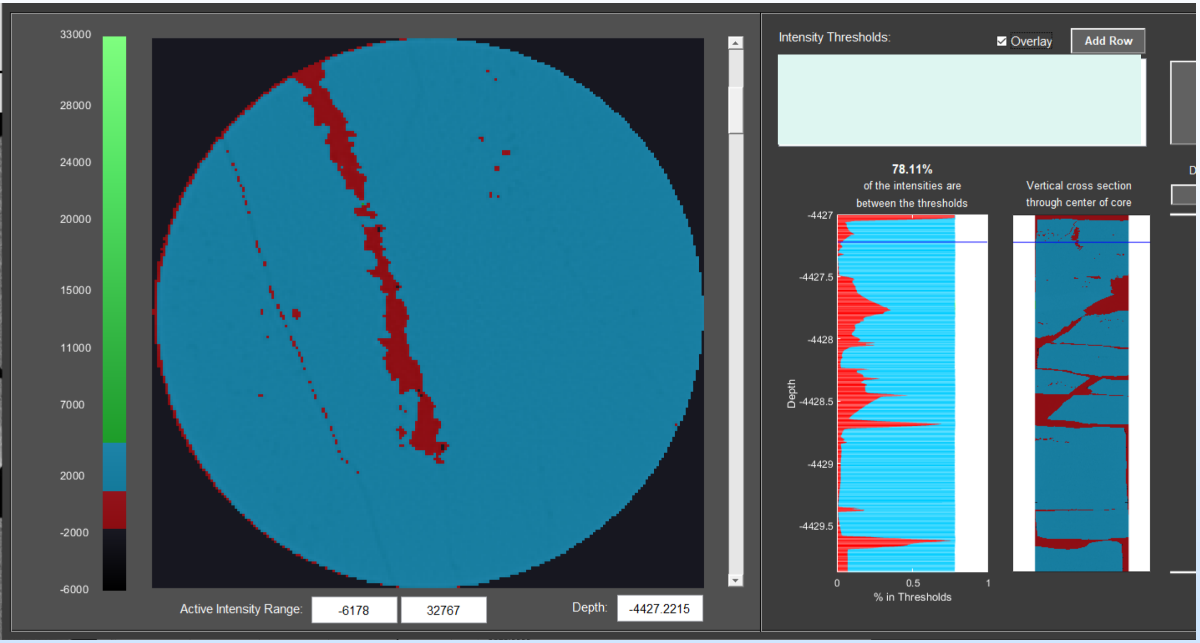
Field Wide Petrophysical Analyses

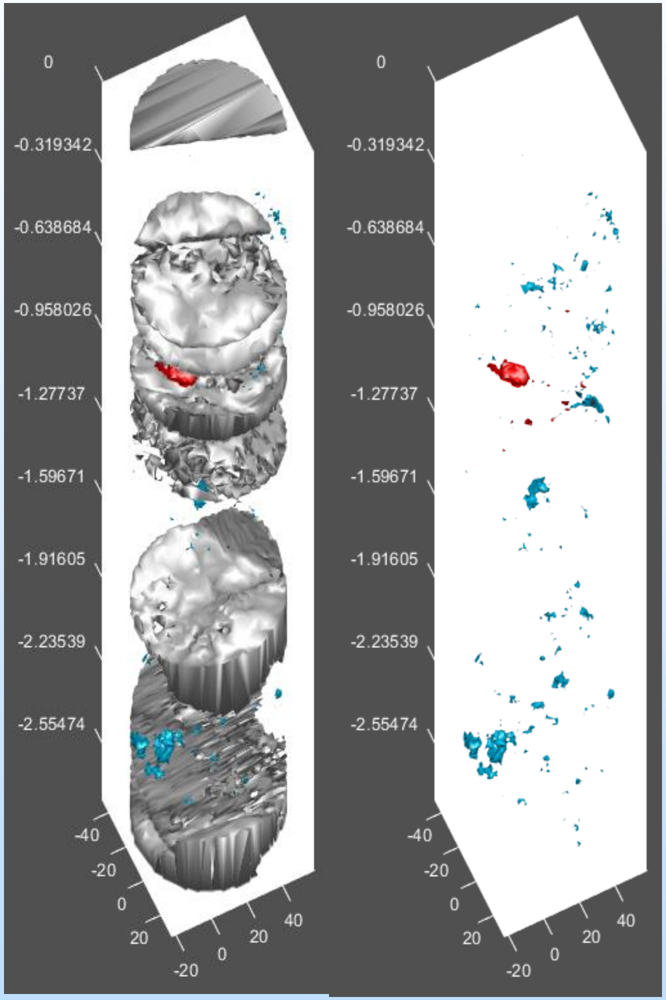






Core Scanning for Advanced Characterization



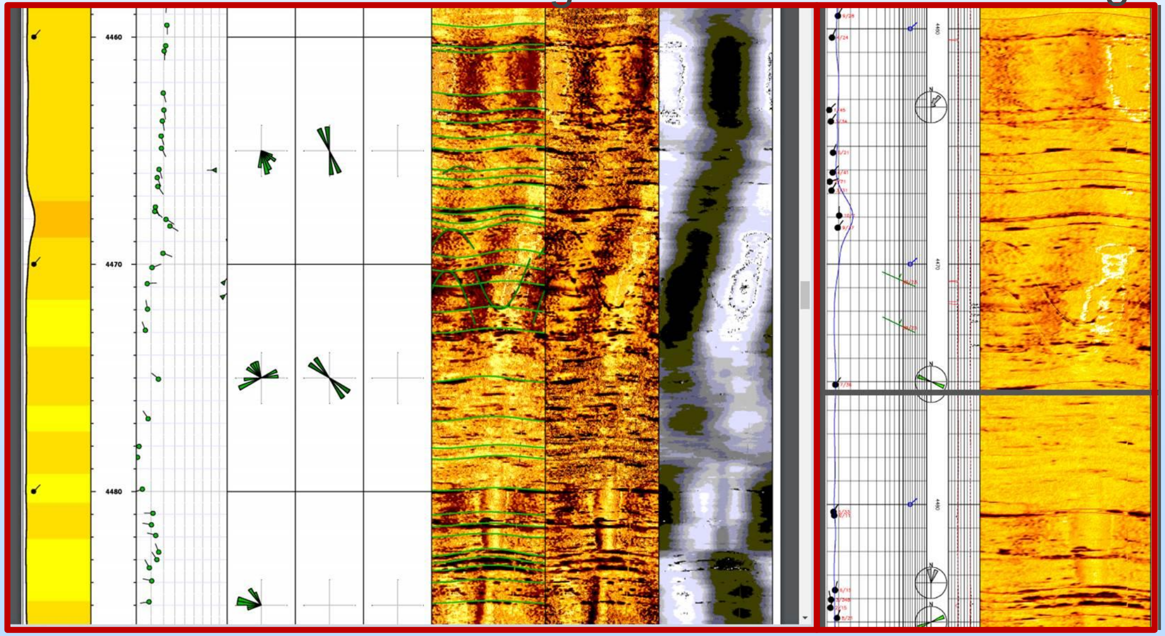


- Collaboration with NETL for data collection
  - CT scans
  - XRF
  - Velocity
  - plugs

Image Log Analysis

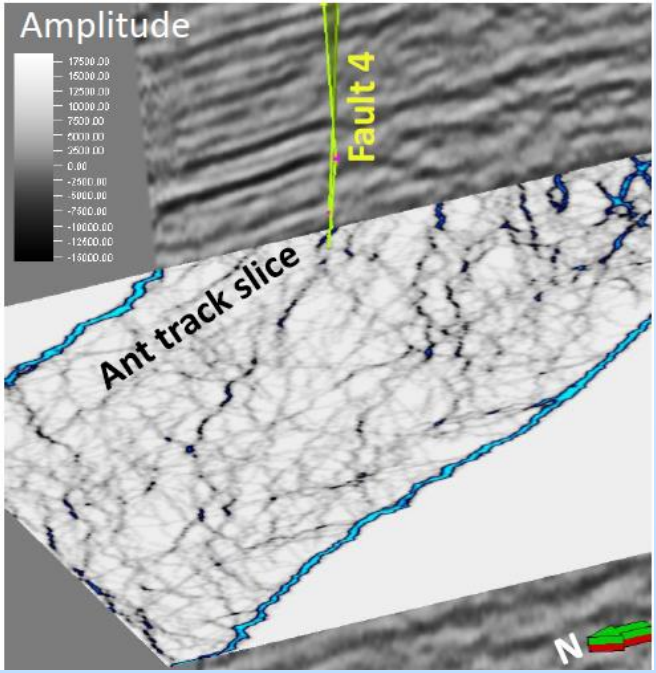
- Napoleon field has >20 wells with image logs available
- Worked with data owners and Baker Hughes to process and analyze for fractures and vugs
- Developed “pseudo” logs of features to predict them from wireline logs and develop vug and fracture distributions

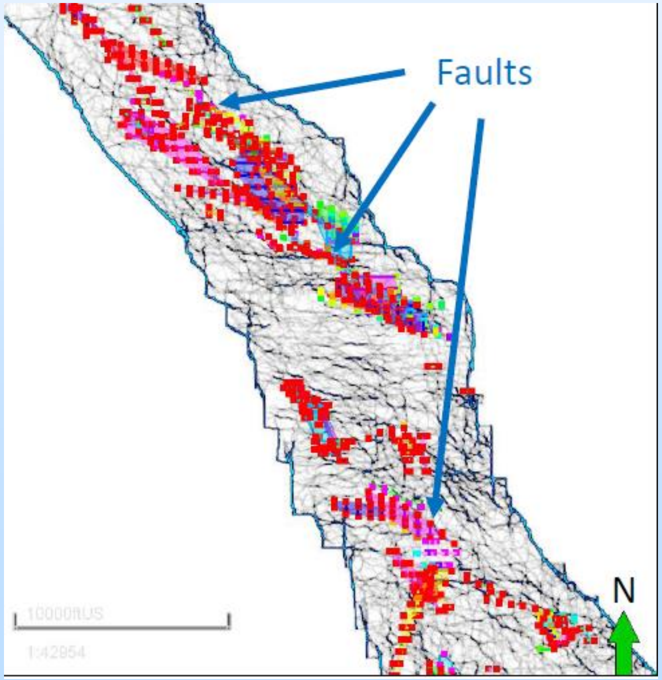
After Processing
Before Processing



Seismic Analysis

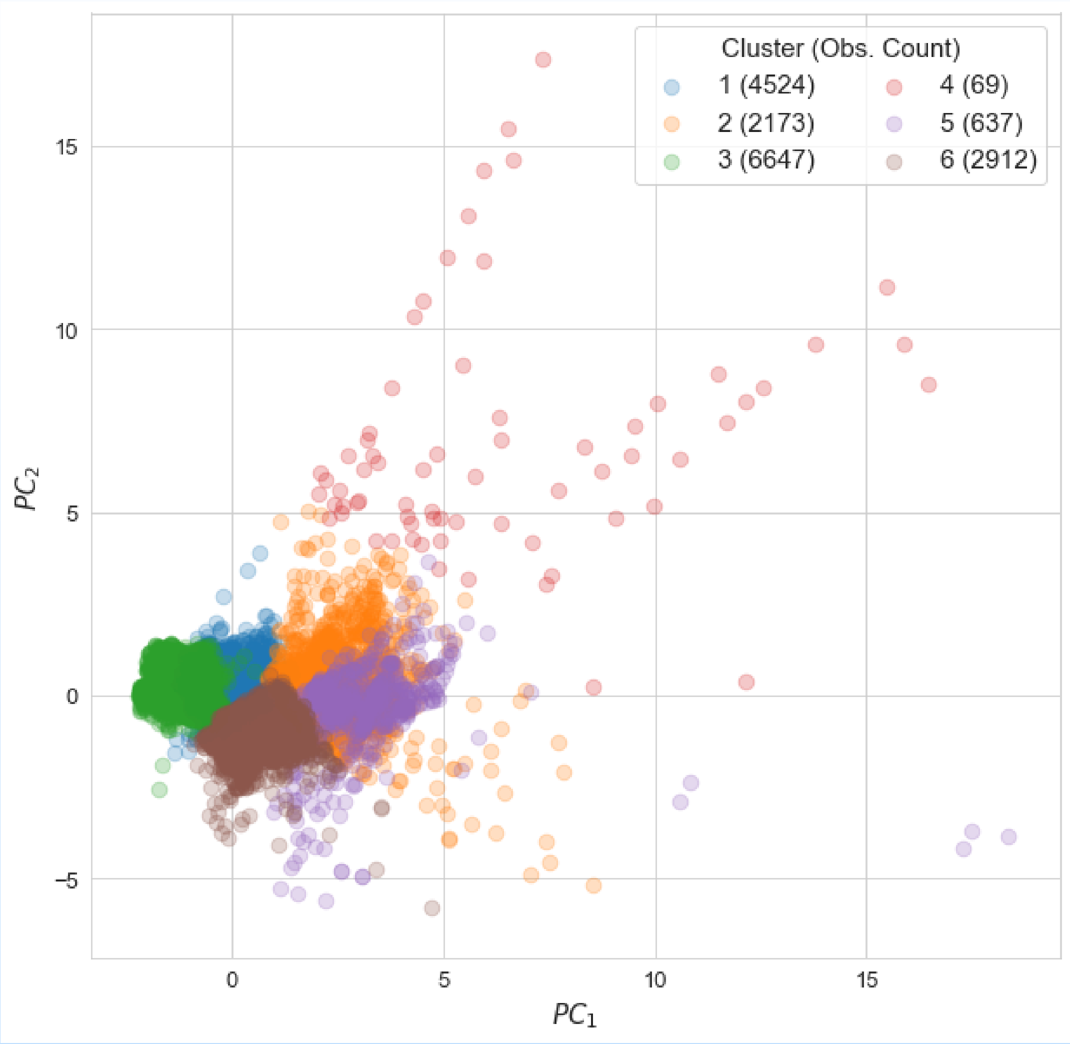
- Well ties and horizon mapping
- Attribute analysis
- >50 faults interpreted in the volume
  - Few large faults with several smaller faults





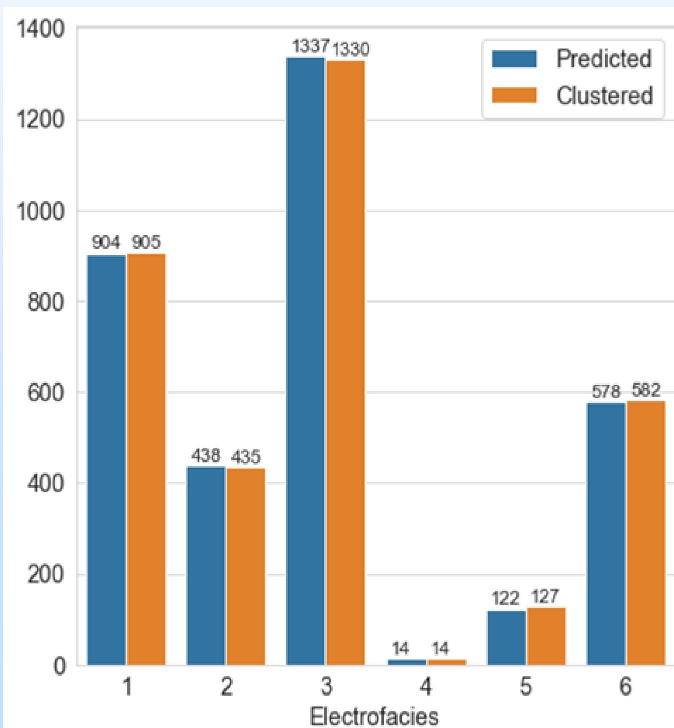
Cluster Analysis to Identify Electrofacies

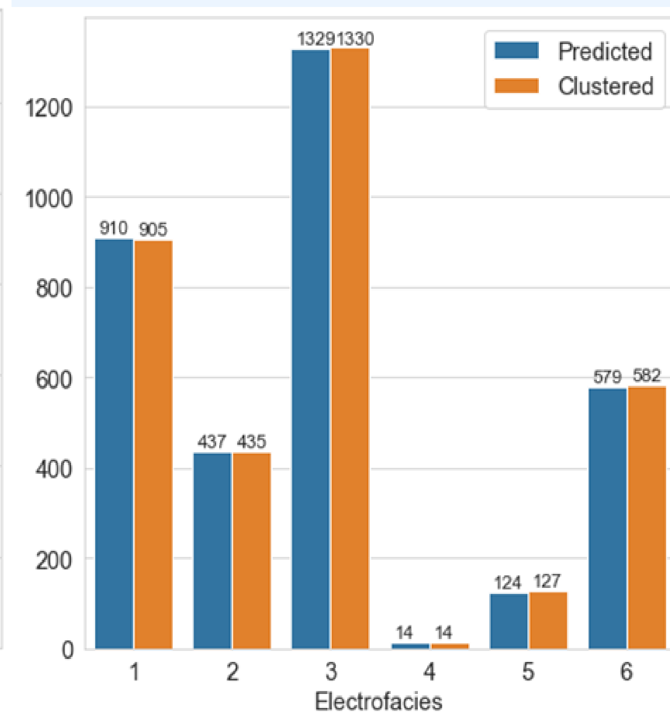
- Branch of multi-variate statistics
- Different methods explored to find how the data naturally clusters
- Results compared to determine which method best represents distinct groups of data
- **Geologic validation**



Predict Electrofacies for All Wells

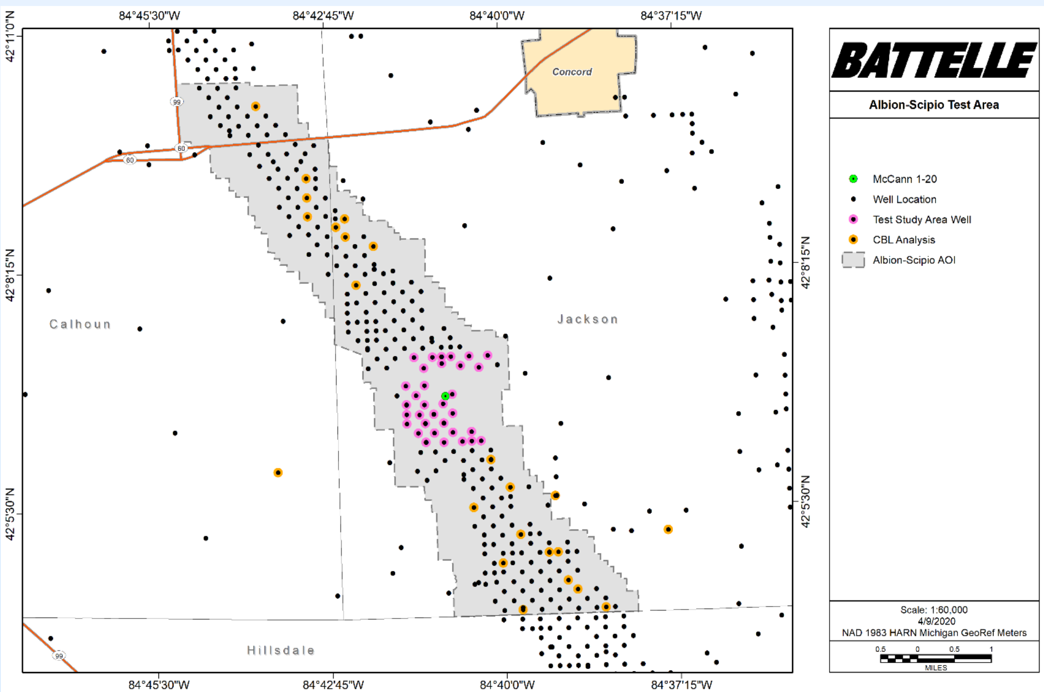
- After data is imputed to fill in missing information, a **machine learning** predictive model is built to predict electrofacies for all wells

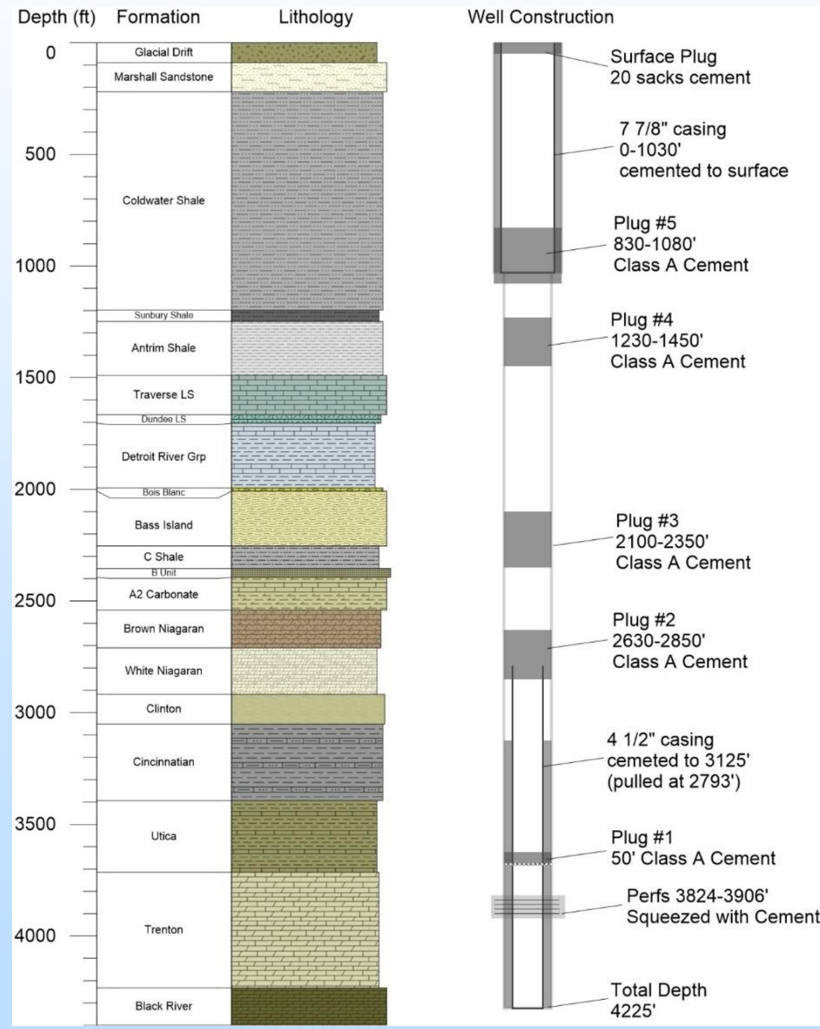




Risk Assessment- Wellbore Integrity

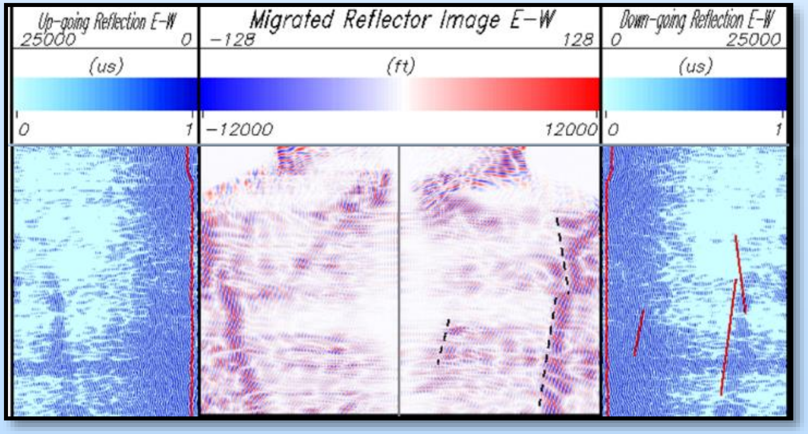
- Review of well records and cement bond logs to screen wells for potential WBI issues





Production/Monitoring Well Drilled Late 2020

- Drilling of the McCann 1-20 well for production/monitoring
- New data collection and analysis
  - Vuggy and fractured zones
  - Oil shows

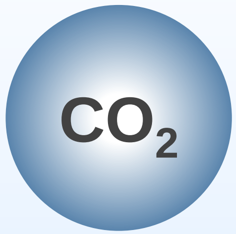


Injection Well Planning

- McCann #2-20 Injection well to be drilled directionally from McCann #1-20 drill pad.
- Bottom hole location will be located about 700 ft. SE of the McCann #1-20 well.

Proposed Mc Cann 2-20 deviated well path with the 2-20 SHL on the 1-20 pad and the revised 2-20 BHL

Laboratory Testing Two-Fold EOR Strategy



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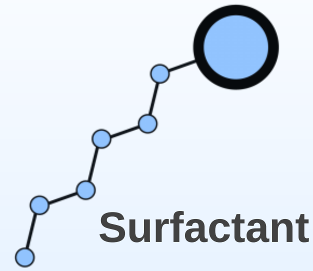


Improve Reservoir Oil Flowability

- Reducing viscosity of in-situ fluid by solubilizing CO_2
- Contacting oil trapped in tight spaces with CO_2

Aid CO_2 Injection

- Altering injectant mobility within the reservoir to target bypassed regions
- Stabilizing foam lamella between CO_2 bubbles

Mobility Control Using Foams

- Foam injection could help manage mobility of CO_2 in the reservoir to contact tight pores in order to extract additional oil

- Sasol's Soloterra 843 produced stable foam
  - ✓ Foam stability increased with salinity
  - ✓ Half-life was higher at higher salinities
  - ✓ Addition of oil didn't impact foam stability vs. salinity

Core Characterization

➢ **Air Porosity and Permeability**

ROWE A-2, 3721 ft

#	Φ (%)	kg,avg (mD)
R11	8.0	0.10
R12	7.0	0.09
R14		0.10

ROWE A-2, 3867 ft

#	Φ (%)	kg,avg (mD)
R21	7.9	0.14
R22		0.11
R24		6.99

NERRETER, 4432 ft

#	Φ (%)	kg,avg (mD)
N11	10.1	0.15
N12	10.0	3.07
N13	8.2	0.31
N14		0.23

NERRETER, 4446.5 ft

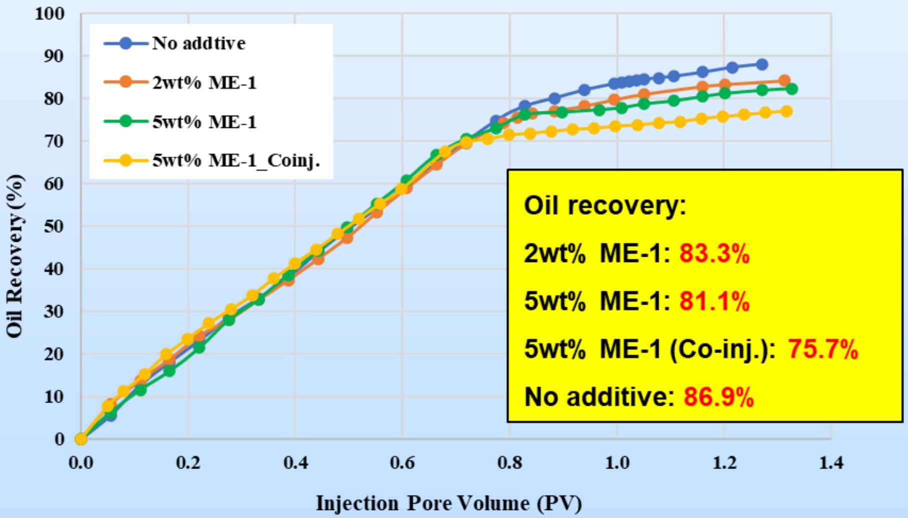
#	Φ (%)	kg,avg (mD)
N21	10.3	0.18
N22	7.6	0.17
N23	8.7	0.15
N24		0.23

Porosity: 7-10%; Permeability: 0.1-0.3 mD mostly

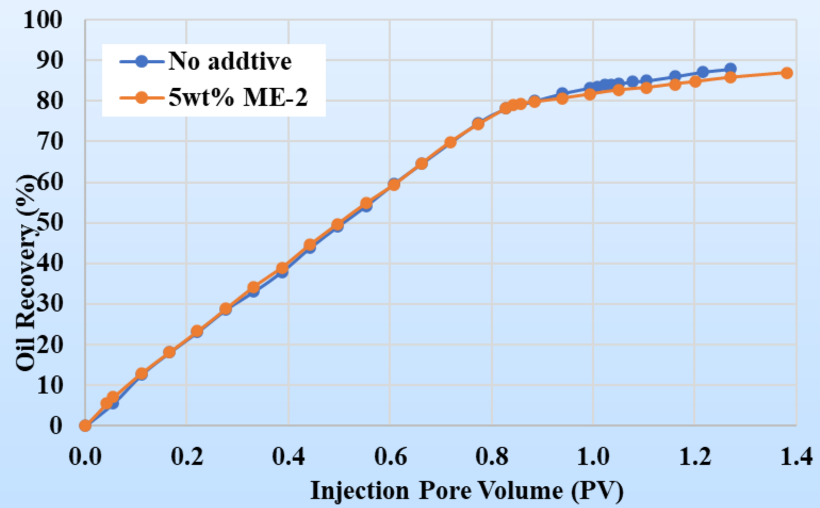
MMP Determination: Effect of Additives

	Flash Point (°C)	Density @ 20ºC (g/cm3)	Viscosity @ 20ºC (mPa · s)
SOLOTERRA ME-1	133	0.958	12
SOLOTERRA ME-2	145	0.915	32

ME-1 (2wt%, 5wt%, 1750 psi)



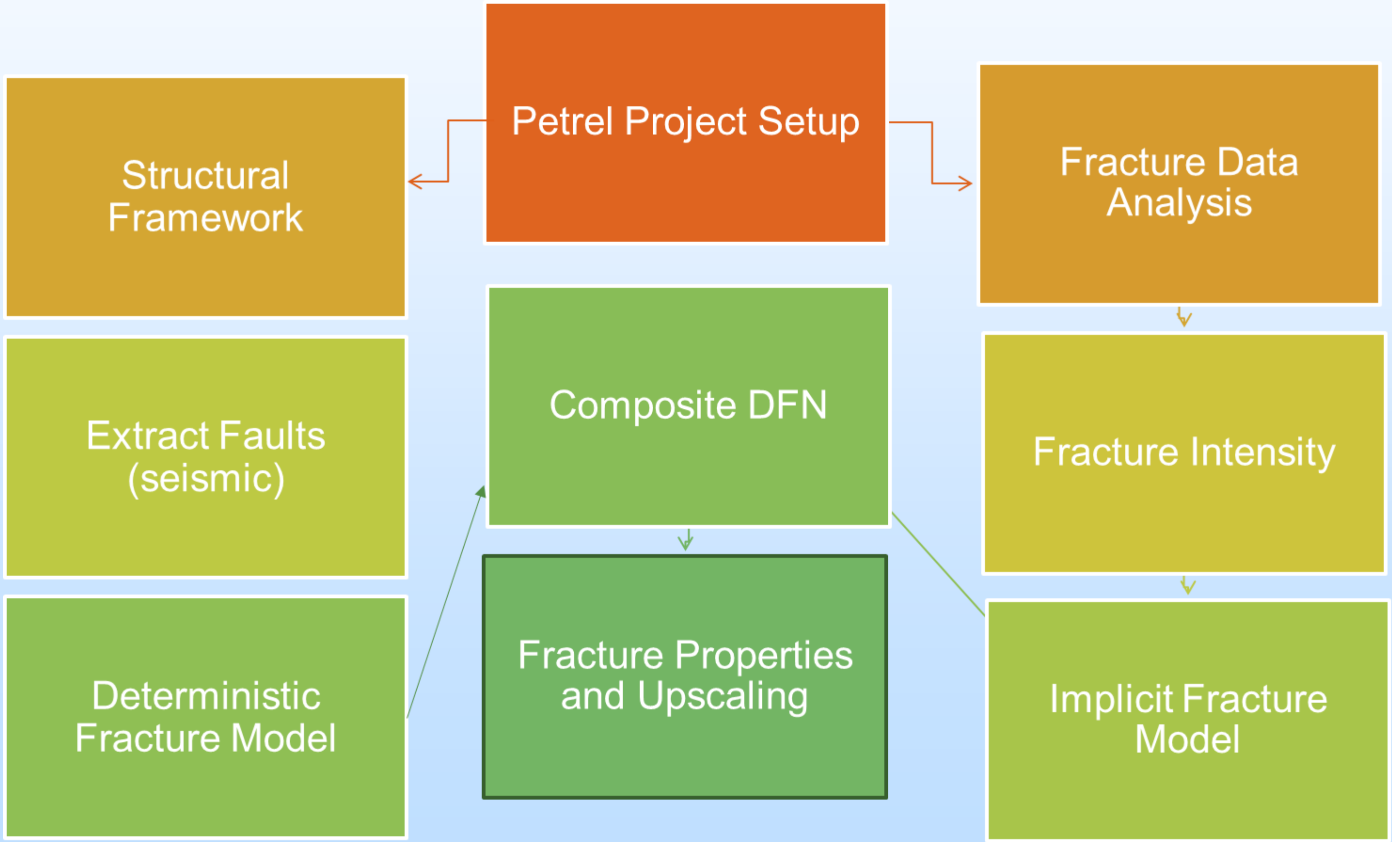
ME-2 (5wt%, 1750 psi)



ME-1 and ME-2 do not lower MMP

Integrating Results into Discrete Fracture Model

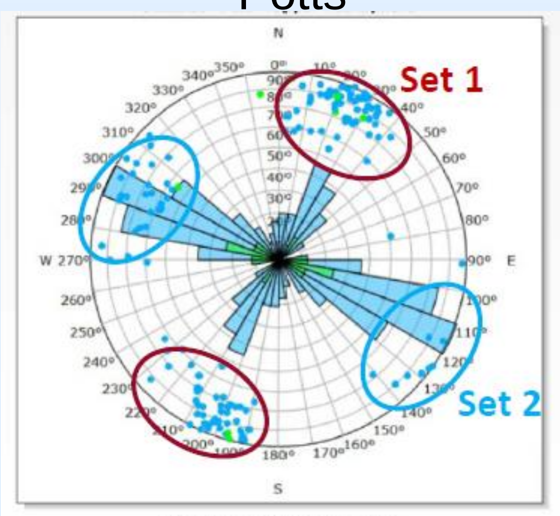
High-level Model Workflow



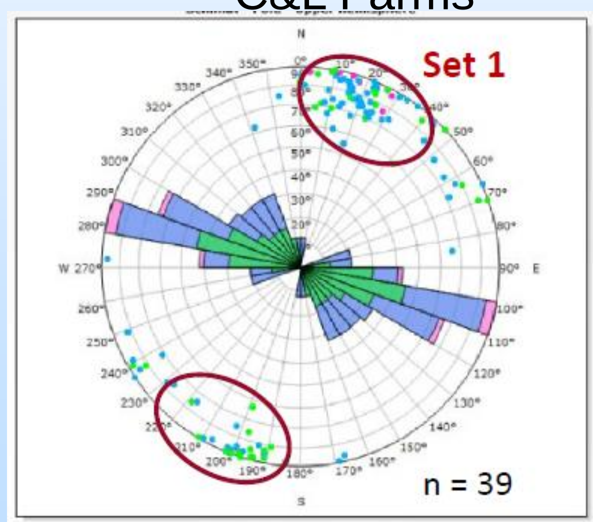
Fracture Orientation as Proxy for Porosity/Permeability Flow Direction

- Potts 1-20 and C&L Farms show a NW-SE orientation
- McCann shows WE orientation

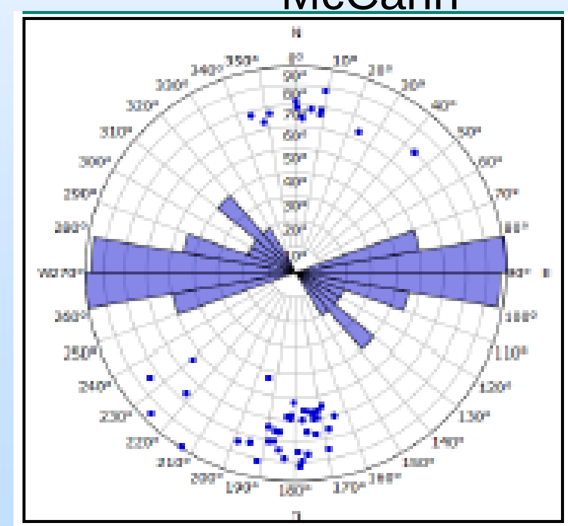
Potts



C&L Farms

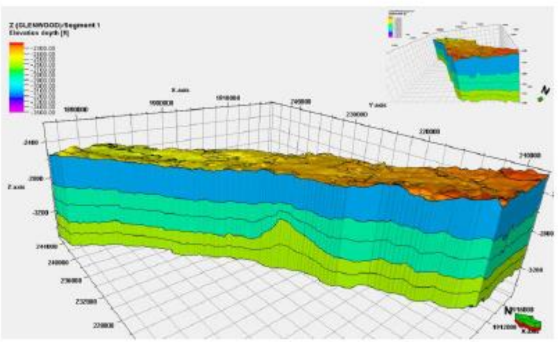


McCann

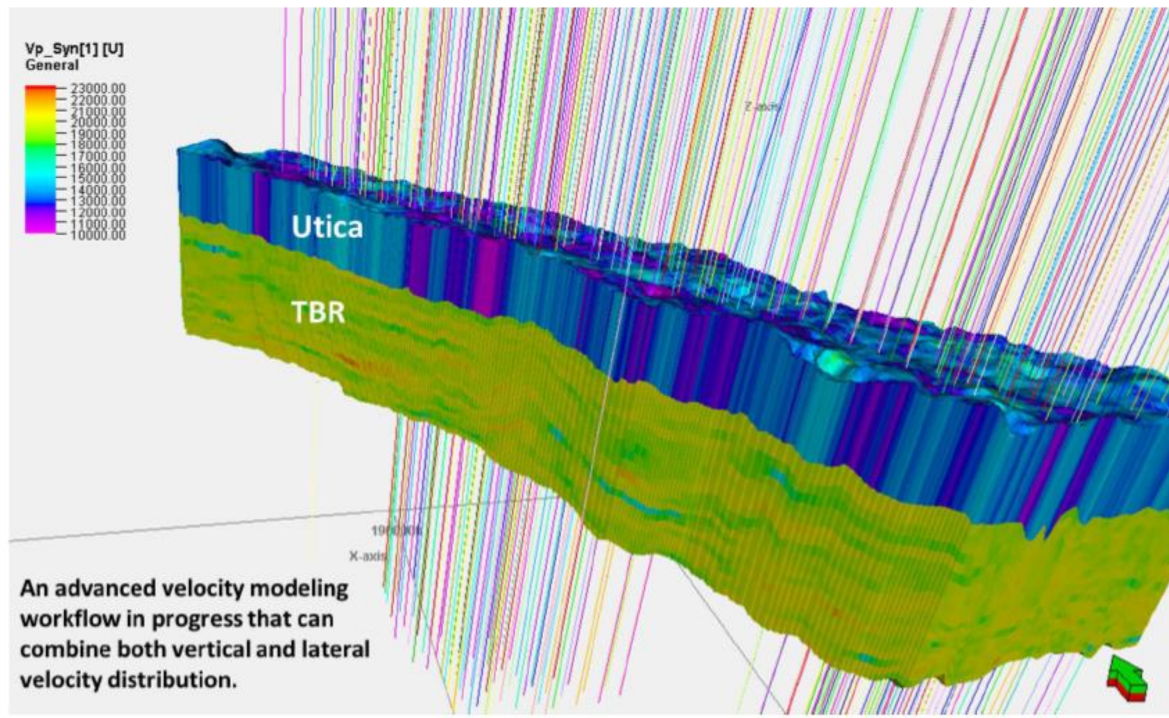


Velocity Modeling to Convert to Depth Domain

Advanced Velocity Modeling and Depth Conversion



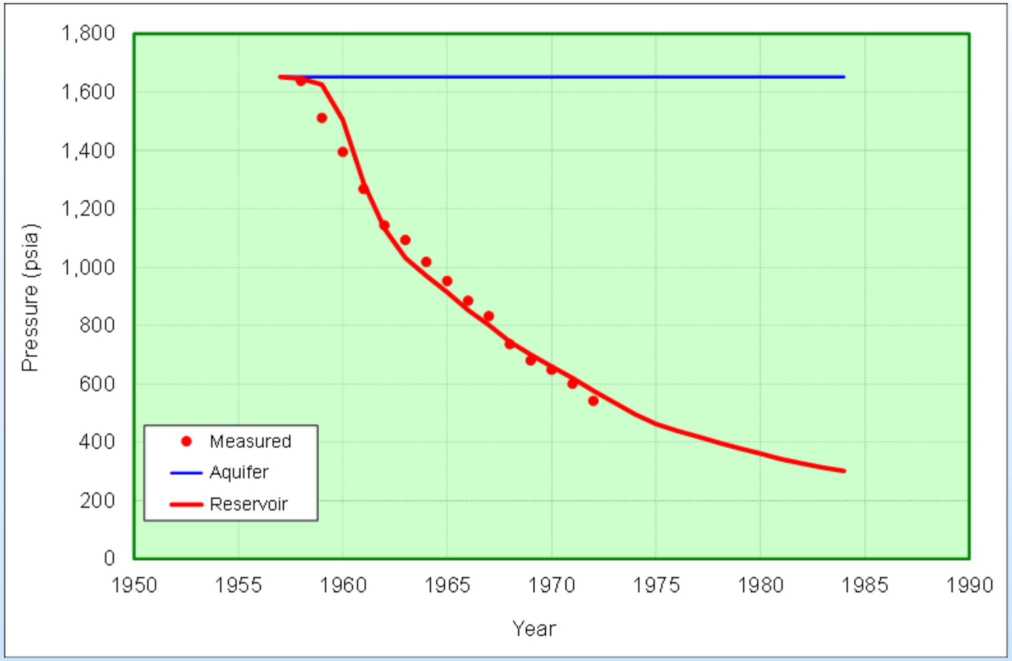
A 3D grid was populated with velocity information from actual sonic and sonic predicted from gamma-ray logs



Bureau of Economic Geology

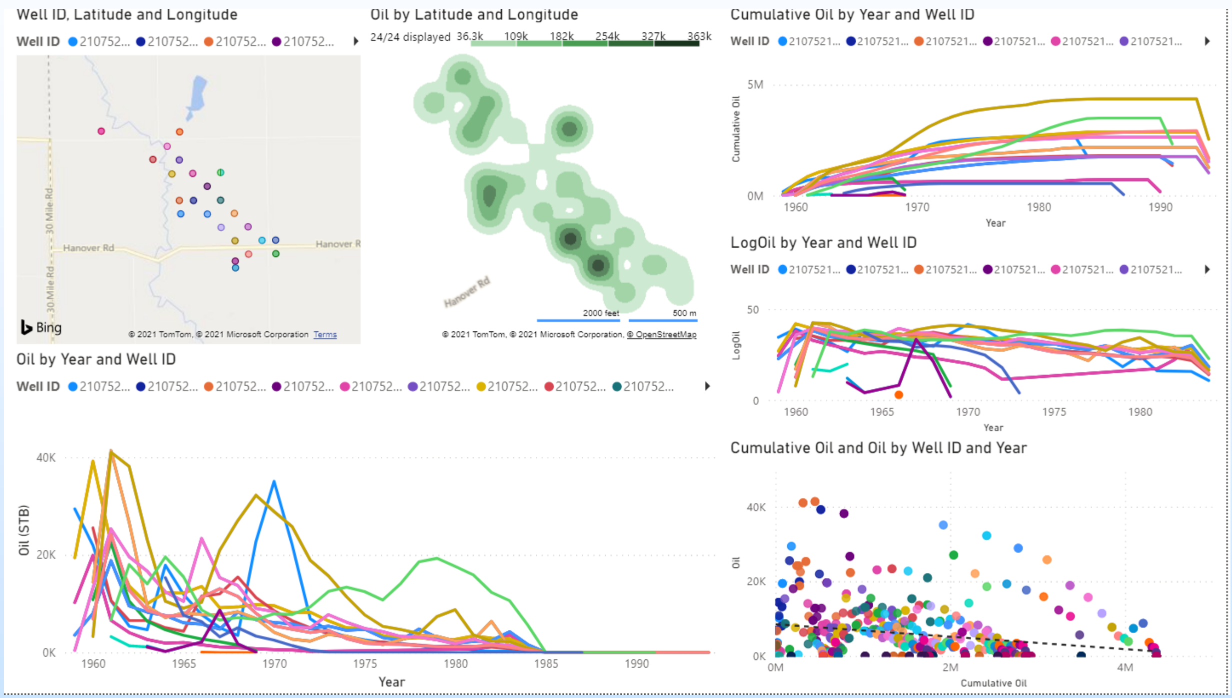
Material Balance of the North Scipio Pool

- Reviewed production data for the North Scipio pool (1957-1984)
- Fluid property information extracted from a Marathon engineering study (1974)
- Good history match obtained estimating an OOIP=11 MM STB
  - Gas cap to oil zone ratio of .2 and initial water saturation= .2
- Results will be used to calibrate modeling efforts



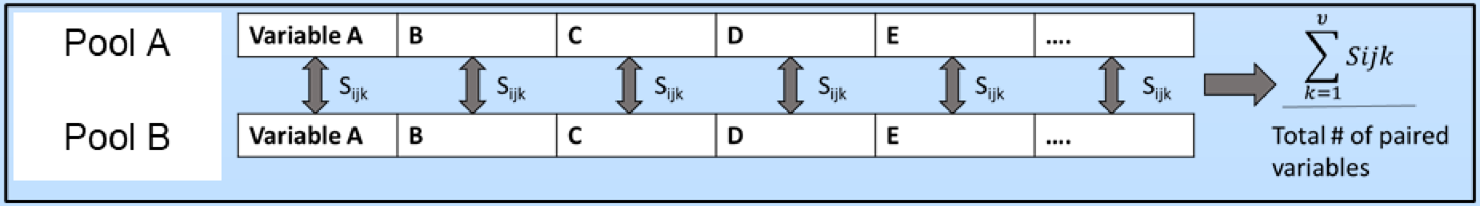
Interactive Production Database

- Database of production history by well for 47 wells in the North Scipio pool
  - Monthly production
  - Annual production
  - Cumulative
- Well and field scale
- Historical analyses
- Daily updates to the McCann 1-20



Pool Comparison Method to Inform Development Strategy

- Geologic variables
  - Thickness, dolomite thickness, porosity, permeability, net to gross, porosity height, etc
- Production variables
  - OOIP, initial pressure, oil API, GOR, and “rate”
- Applied Gower’s distance methodology
  - Measures the dissimilarity between a pair of variables and sums up for all pairs and averages



Pool Comparison Results

Reduced Geologic Variables

	Nal	CA	SA	NS	CS	NA	NB	NC	CD	NASF	NBSF	CSP	SCTP	STP
Nal	0	0.42	0.47	0.14	0.12	0.41	0.43	0.47	0.46	0.26	0.22	0.21	0.14	0.24
CA	0.42	0	0.15	0.54	0.42	0.41	0.37	0.32	0.51	0.29	0.64	0.63	0.54	0.65
SA	0.47	0.15	0	0.59	0.46	0.43	0.31	0.26	0.44	0.39	0.69	0.68	0.59	0.7
NS	0.14	0.54	0.59	0	0.12	0.46	0.41	0.44	0.5	0.38	0.1	0.15	0.2	0.16
CS	0.12	0.42	0.46	0.12	0	0.43	0.34	0.38	0.38	0.35	0.22	0.22	0.18	0.23
NA	0.41	0.41	0.43	0.46	0.43	0	0.34	0.32	0.36	0.21	0.49	0.48	0.39	0.5
NB	0.43	0.37	0.31	0.41	0.34	0.34	0	0.08	0.25	0.42	0.48	0.51	0.48	0.5
NC	0.47	0.32	0.26	0.44	0.38	0.32	0.08	0	0.28	0.4	0.51	0.55	0.52	0.53
CD	0.46	0.51	0.44	0.5	0.38	0.36	0.25	0.28	0	0.44	0.6	0.6	0.51	0.61
NASF	0.26	0.29	0.39	0.38	0.35	0.21	0.42	0.4	0.44	0	0.35	0.34	0.25	0.36
NBSF	0.22	0.64	0.69	0.1	0.22	0.49	0.48	0.51	0.6	0.35	0	0.08	0.13	0.07
CSP	0.21	0.63	0.68	0.15	0.22	0.48	0.51	0.55	0.6	0.34	0.08	0	0.1	0.06
SCTP	0.14	0.54	0.59	0.2	0.18	0.39	0.48	0.52	0.51	0.25	0.13	0.1	0	0.11
STP	0.24	0.65	0.7	0.16	0.23	0.5	0.5	0.53	0.61	0.36	0.07	0.06	0.11	0

Production Variables

	Nal	CA	SA	NS	CS	NA	NB	NC	CD	NASF	NBSF	CSP	SCTP	STP
Nal	0	0.26	0.36	0.18	0.26	0.21	0.26	0.2	0.19	0.62	0.6	0.37	0.31	0.3
CA	0.26	0	0.13	0.41	0.48	0.39	0.47	0.43	0.41	0.36	0.39	0.46	0.48	0.53
SA	0.36	0.13	0	0.5	0.54	0.48	0.56	0.52	0.5	0.42	0.34	0.55	0.57	0.62
NS	0.18	0.41	0.5	0	0.25	0.21	0.23	0.15	0.12	0.45	0.43	0.2	0.13	0.12
CS	0.26	0.48	0.54	0.25	0	0.37	0.43	0.34	0.33	0.66	0.65	0.41	0.35	0.37
NA	0.21	0.39	0.48	0.21	0.37	0	0.32	0.28	0.23	0.59	0.57	0.35	0.3	0.31
NB	0.26	0.47	0.56	0.23	0.43	0.32	0	0.11	0.13	0.42	0.49	0.23	0.28	0.26
NC	0.2	0.43	0.52	0.15	0.34	0.28	0.11	0	0.05	0.42	0.44	0.18	0.21	0.17
CD	0.19	0.41	0.5	0.12	0.33	0.23	0.13	0.05	0	0.44	0.43	0.19	0.18	0.14
NASF	0.62	0.36	0.42	0.45	0.66	0.59	0.42	0.42	0.44	0	0.18	0.29	0.4	0.42
NBSF	0.6	0.39	0.34	0.43	0.65	0.57	0.49	0.44	0.43	0.18	0	0.25	0.32	0.34
CSP	0.37	0.46	0.55	0.2	0.41	0.35	0.23	0.18	0.19	0.29	0.25	0	0.11	0.14
SCTP	0.31	0.48	0.57	0.13	0.35	0.3	0.28	0.21	0.18	0.4	0.32	0.11	0	0.07
STP	0.3	0.53	0.62	0.12	0.37	0.31	0.26	0.17	0.14	0.42	0.34	0.14	0.07	0

Geology and Production Variables

	Nal	CA	SA	NS	CS	NA	NB	NC	CD	NASF	NBSF	CSP	SCTP	STP
Nal	0	0.44	0.56	0.4	0.41	0.36	0.47	0.35	0.48	0.32	0.54	0.14	0.51	0.6
CA	0.44	0	0.3	0.41	0.38	0.36	0.36	0.18	0.18	0.48	0.4	0.5	0.25	0.29
SA	0.56	0.3	0	0.43	0.4	0.39	0.43	0.28	0.17	0.32	0.15	0.63	0.11	0.09
NS	0.4	0.41	0.43	0	0.33	0.3	0.31	0.33	0.36	0.37	0.52	0.45	0.35	0.42
CS	0.41	0.38	0.4	0.33	0	0.09	0.2	0.36	0.33	0.42	0.48	0.42	0.4	0.4
NA	0.36	0.36	0.39	0.3	0.09	0	0.19	0.36	0.32	0.41	0.48	0.37	0.39	0.38
NB	0.47	0.36	0.43	0.31	0.2	0.19	0	0.35	0.34	0.44	0.53	0.46	0.38	0.42
NC	0.35	0.18	0.28	0.33	0.36	0.36	0.35	0	0.16	0.41	0.38	0.42	0.21	0.27
CD	0.48	0.18	0.17	0.36	0.33	0.32	0.34	0.16	0	0.41	0.24	0.55	0.17	0.15
NASF	0.32	0.48	0.32	0.37	0.42	0.41	0.44	0.41	0.41	0	0.28	0.4	0.31	0.38
NBSF	0.54	0.4	0.15	0.52	0.48	0.48	0.53	0.38	0.24	0.28	0	0.54	0.21	0.18
CSP	0.14	0.5	0.63	0.45	0.42	0.37	0.46	0.42	0.55	0.4	0.54	0	0.58	0.67
SCTP	0.51	0.25	0.11	0.35	0.4	0.39	0.38	0.21	0.17	0.31	0.21	0.58	0	0.09
STP	0.6	0.29	0.09	0.42	0.4	0.38	0.42	0.27	0.15	0.38	0.18	0.67	0.09	0

- North Scipio pool greatest similarity:
  - Napoleon A, Napoleon B, Napoleon C for all variables

Accomplishments to Date

- Developed integrated database of well records, production records (modern and historical), core analyses, and wireline logs
- Developed and applied geologic characterization workflow to three key producing fields
- Drilled and characterized the McCann 1-20 well (producer/monitoring well)
- Analyzed and depth converted 3D seismic
- Developed and applied workflow to compare fields and pools across southern Michigan
- Evaluated the effects of surfactants and chemicals in reducing the MMP and enhancing oil recovery

Lessons Learned

- The carbonate reservoir is extremely complex which has led to difficulties in predicting permeability and presence of vugs and fractures
  - These challenges will be addressed during modeling to represent a range in outcomes
- DSWI showed strong correlation with seismic
- McCann 1-20 showed high potential in early production, but has declined, likely due to presence of fractures
  - Currently being evaluated to determine next steps to improve primary production
- Drilling delays caused slight project delays (seasonal restrictions, COVID, etc)
  - Developed alternative workflows to continue project progress

Project Summary and Next Steps

- Geologic characterization of three fields captured geologic variability and production variability which will be key in understanding the scale-up potential and development strategy
- Complete laboratory experiments to identify best chemical/surfactant/foam for EOR
- Complete discrete fracture model to begin dynamic simulations for the injection test
- Permit and drill injection well
- Evaluation injection test
- Development strategy plan

Appendix

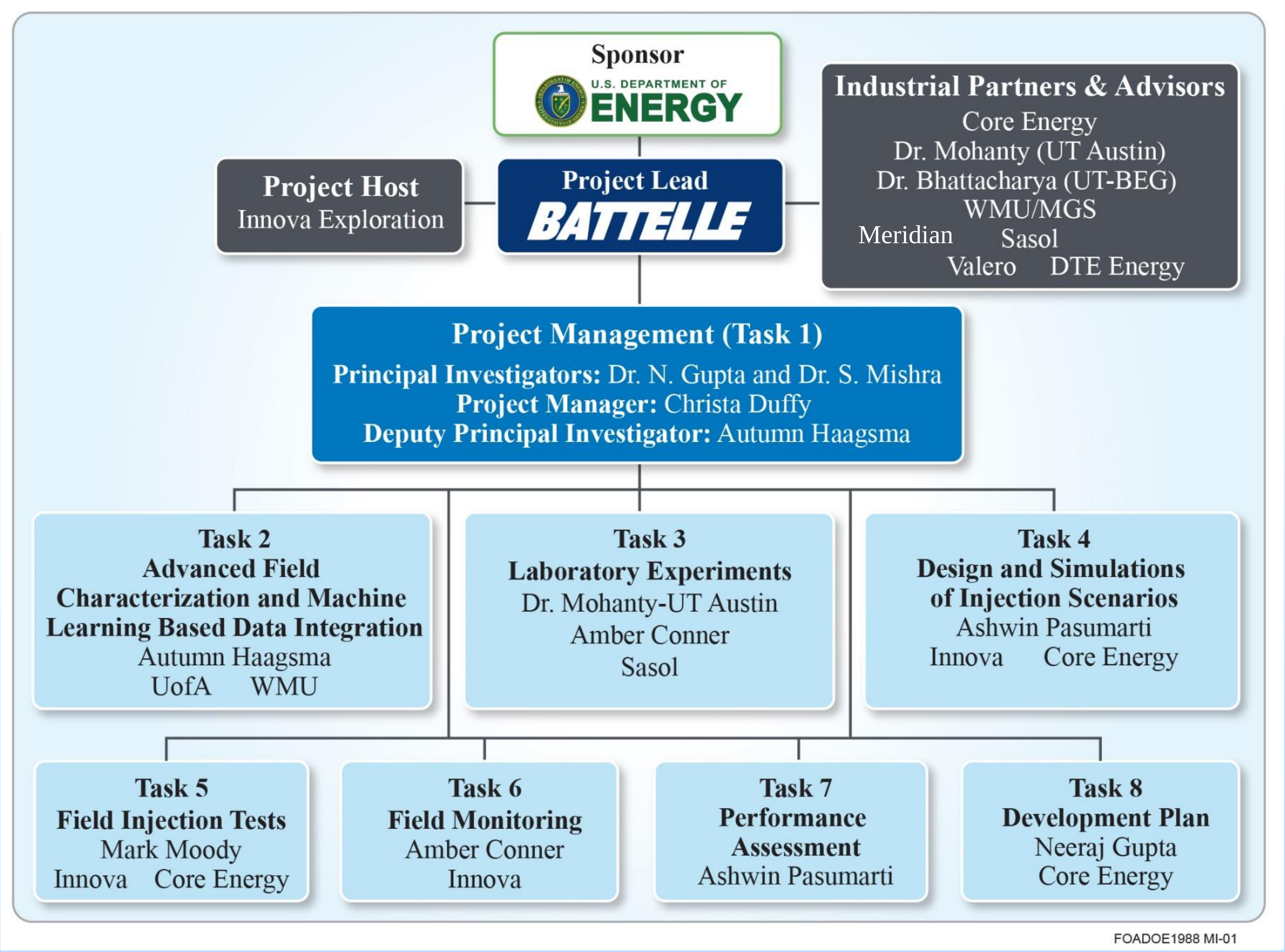
Benefit to the Program

The TBR is a significant HTD play in Michigan but is also a prominent play throughout the eastern United States and Canada, with documented production in Indiana, Ohio, New York, West Virginia, and southwestern Ontario. Additionally, there are more than 35 documented HTD plays worldwide, which makes up approximately 20% of carbonate reservoirs and includes the world's largest oil field (i.e., Ghawar, Saudi Arabia). EOR advancements in the TBR in southern Michigan would be applicable to numerous fields and improved methodologies for enhancing oil recovery in complex carbonate systems. Project results will initiate CO_2-EOR infrastructure in the Midwest, which will also lay the groundwork for future work and demonstrate the path forward in re-evaluating historical plays. This work will greatly benefit local oil and gas operators, CO_2 emitters and providers, and other industrial businesses.

Project Success and Impacts

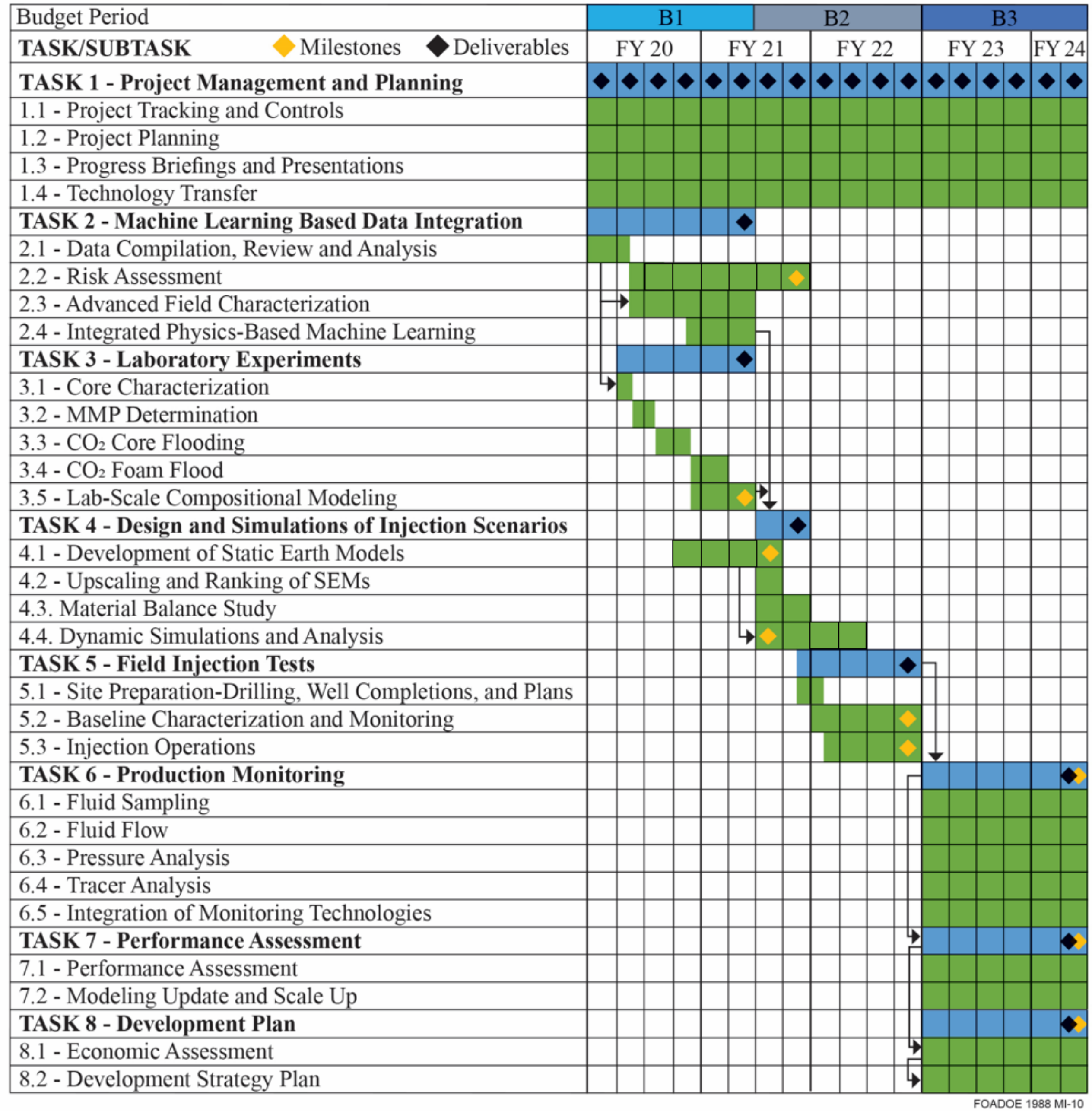
- We anticipate the following key outcomes and impacts:
  - First-of-a-kind comprehensive database and TBR characterization in southern Michigan
  - Understanding of the distribution and extent of vugs and fractures in the TBR reservoir using traditional ML and deep learning techniques
  - Laboratory experiment driven improved design of chemically-enabled CO_2 EOR which targets multi-porosity, complex carbonate reservoirs and improves flood efficiency
  - Modeling and field testing-based evaluation of the viability of chemically CO_2-EOR for stranded oil recovery in the TBR & similar HTD plays, along with field development plan.
- EOR advancements in the TBR in southern Michigan would be applicable to numerous fields and improved methodologies for enhancing oil recovery in complex carbonate systems.
- Project funding will initiate CO_2-EOR infrastructure in the Midwest, which will also lay the groundwork for future work and demonstrate the path forward in re-evaluating historical plays.
- This work will greatly benefit local oil and gas operators, CO_2 emitters and providers, and other industrial businesses.

Organization Chart

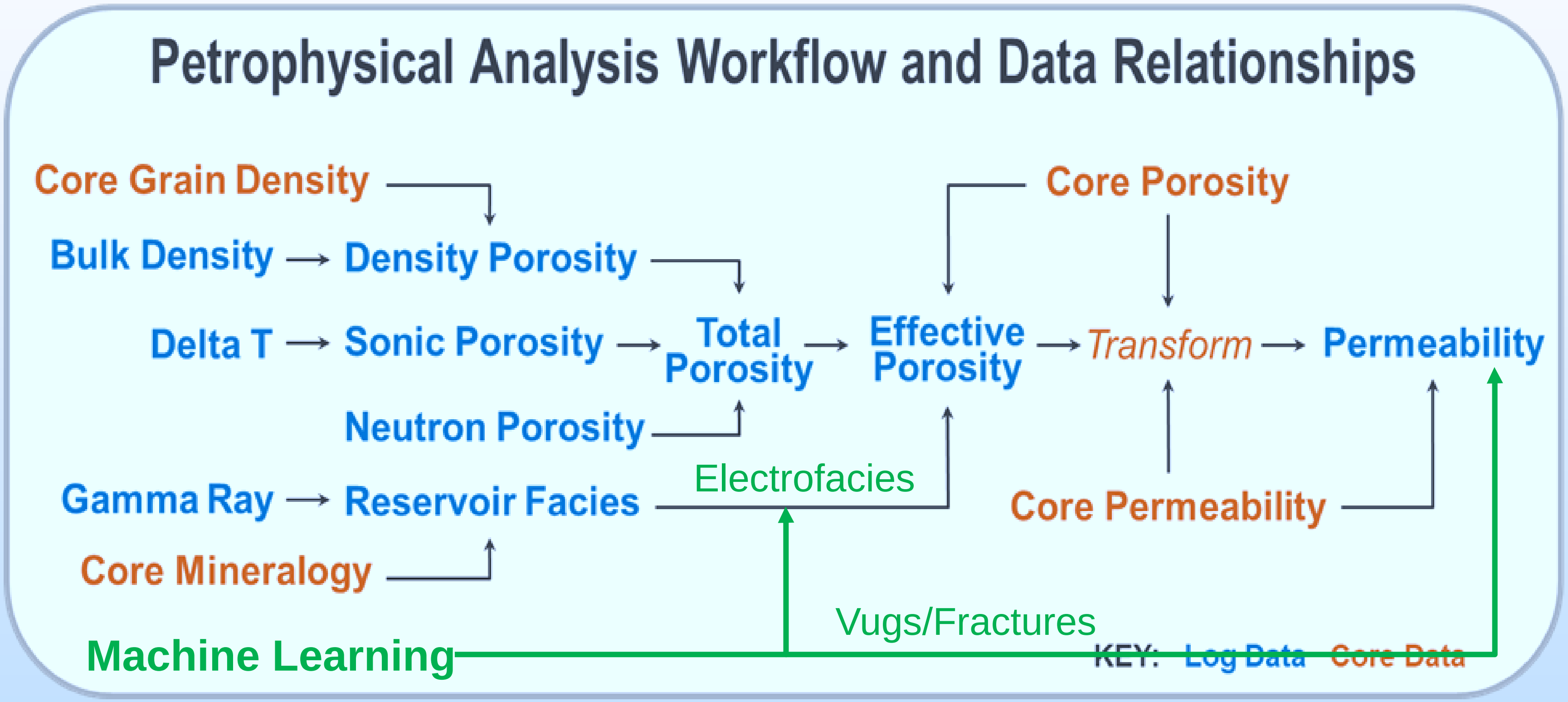


Gantt Chart

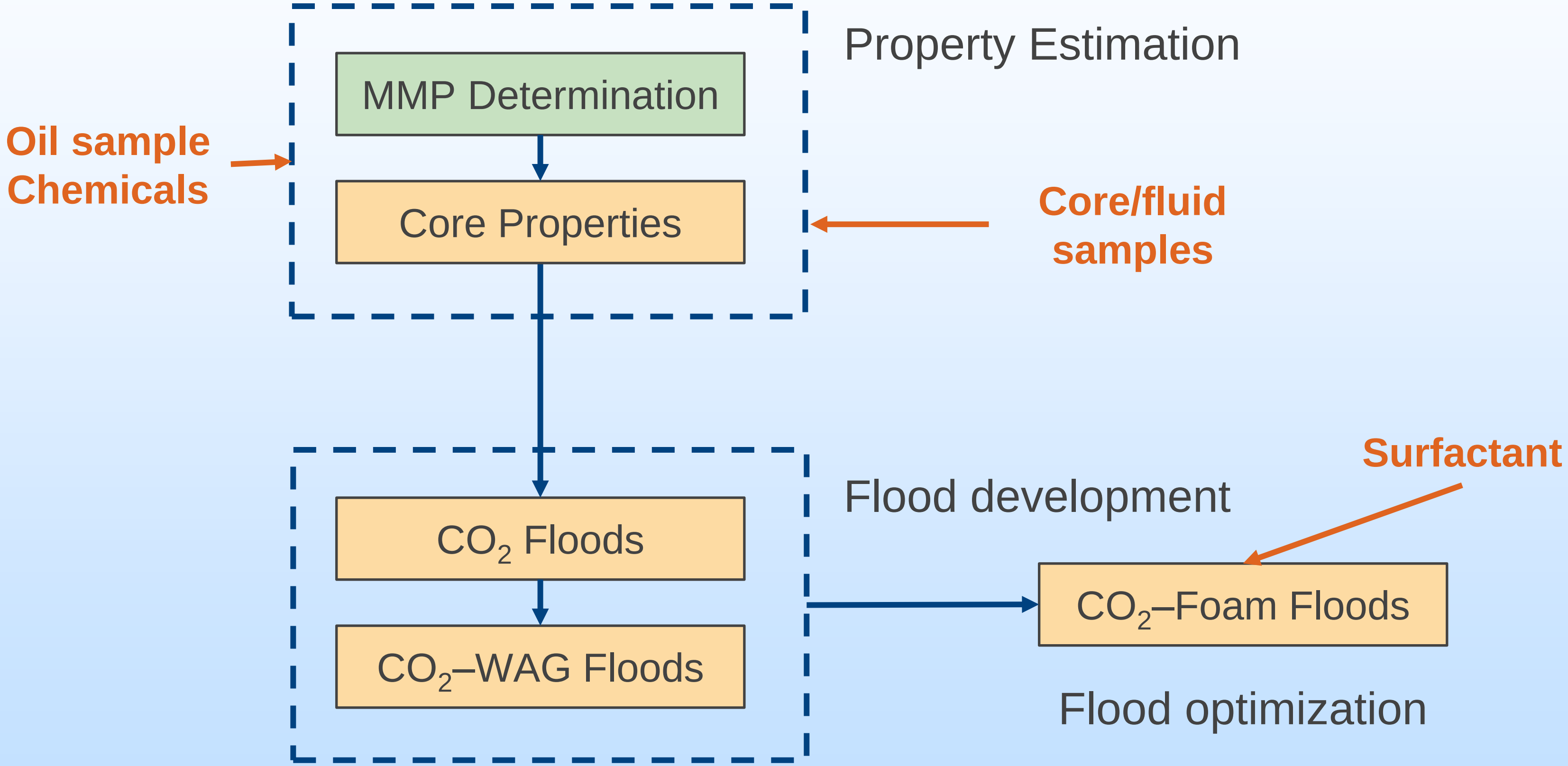
- 3, 18-month budget periods spanning 4.5 years
- 8 tasks



Machine Learning Integrated Geologic Characterization

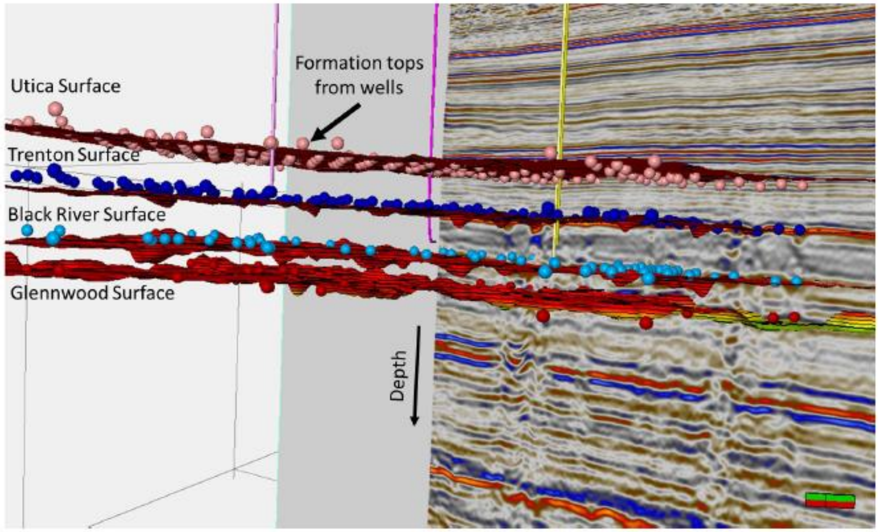


Laboratory Testing Workflow



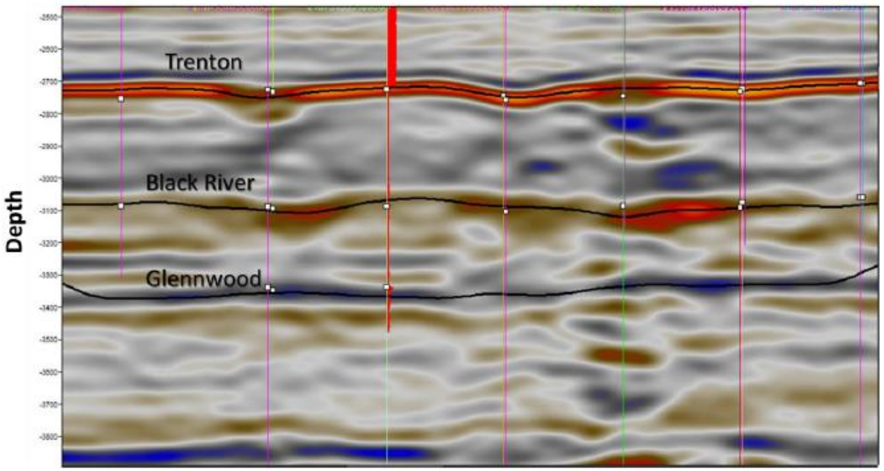
Velocity Modeling to Convert to Depth Domain

Depth-converted Seismic and Surfaces



The displays shows the depth-converted seismic along with depth-converted seismic horizons. **The depth-converted seismic horizons match reasonably well with formation tops.**

An example of seismic in depth domain in the TBR



On the right image (seismic section), the black lines indicate depth-converted seismic surfaces and white squares indicate formation tops in individual wells.

Bureau of Economic Geology