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

DE-FE-0031792
DOE FOA-1988

Aubrey Collie
Battelle Memorial Institute

DOE Resource Sustainability Annual Meeting
04/02/2024

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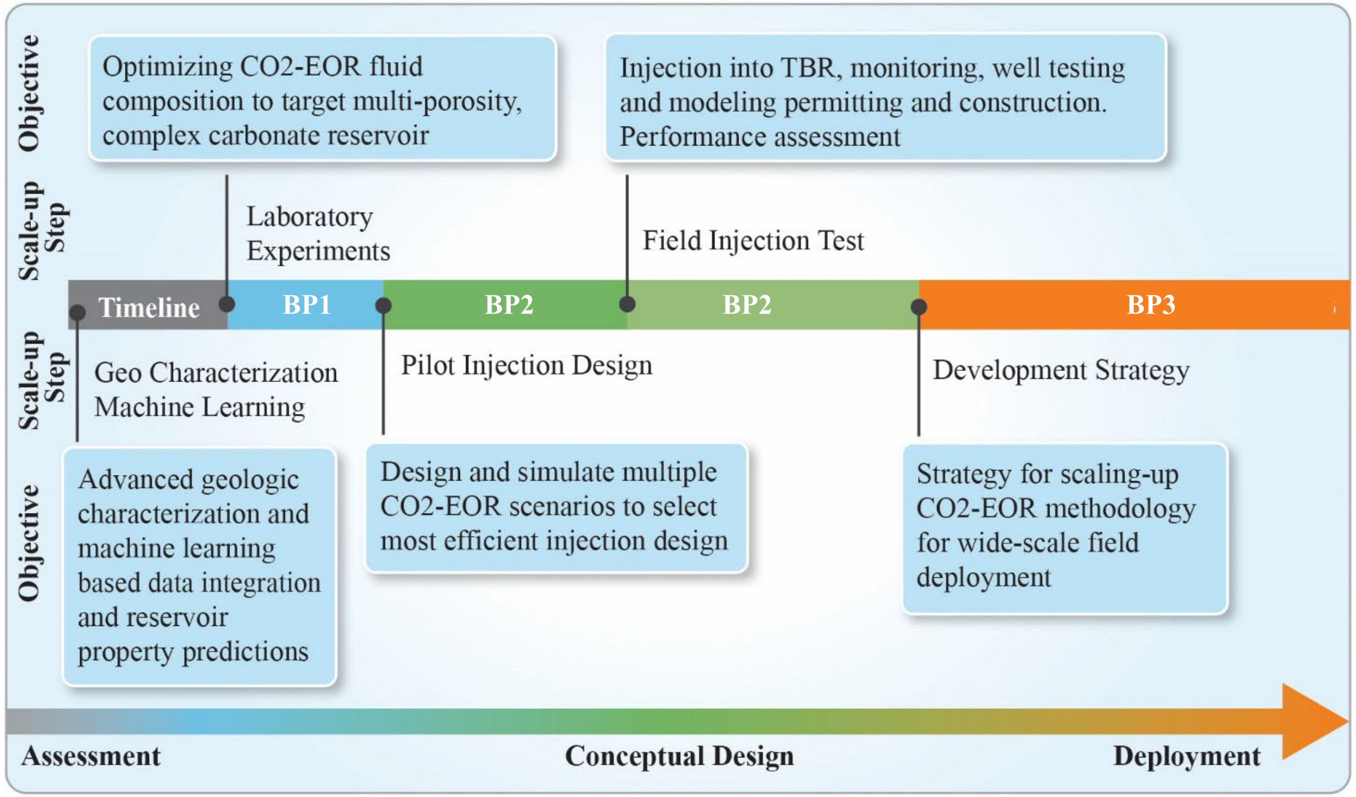
Project Overview and Team

- DOE Funds: $7,999,659
- Cost Share: $2,153,668
- Total Cost: $10,153,327
- October 2020-March 2026

Project Goals and Objectives



Project Objective: 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

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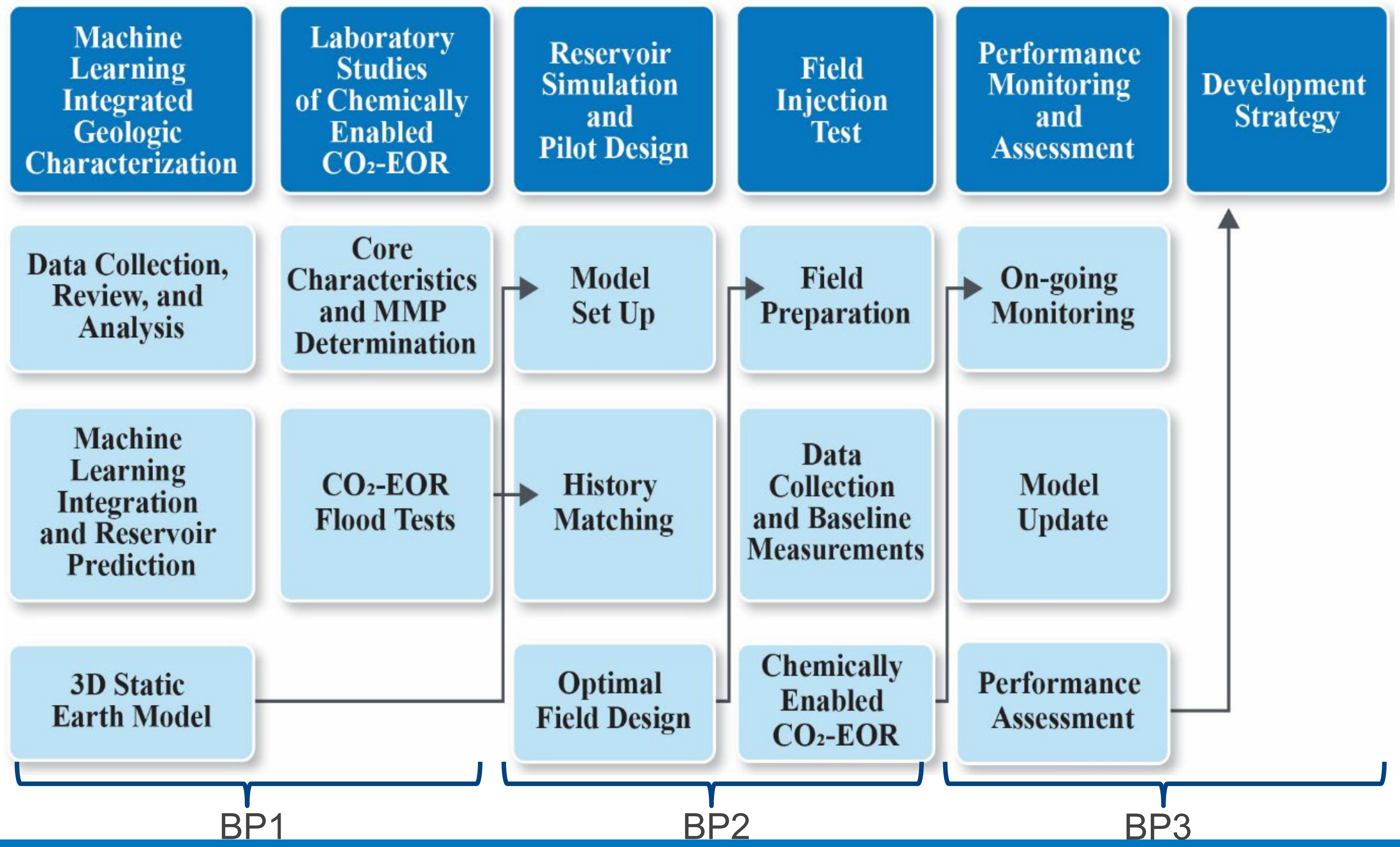
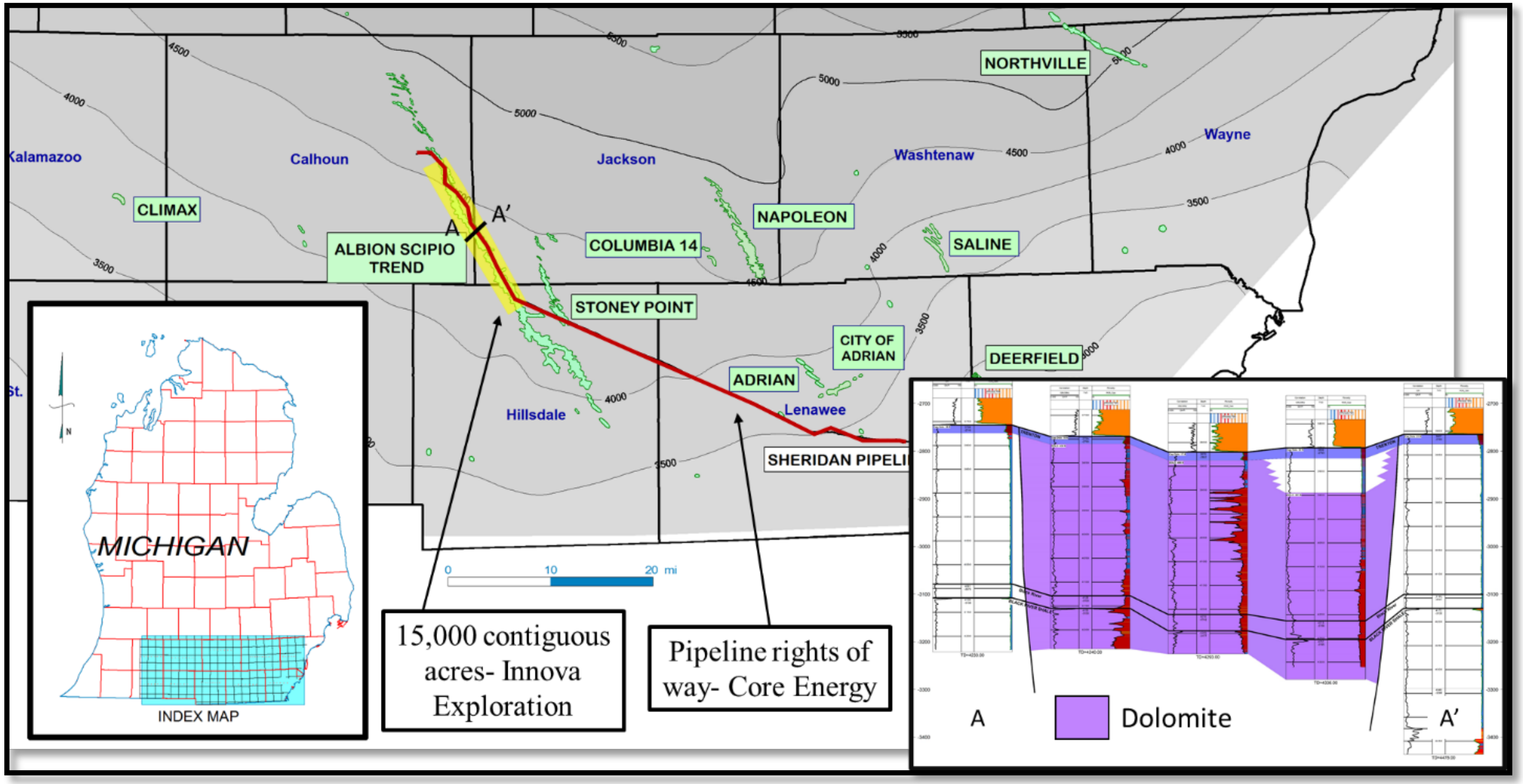
Summary of Tasks to be Performed



Regional Trenton-Black River Play

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



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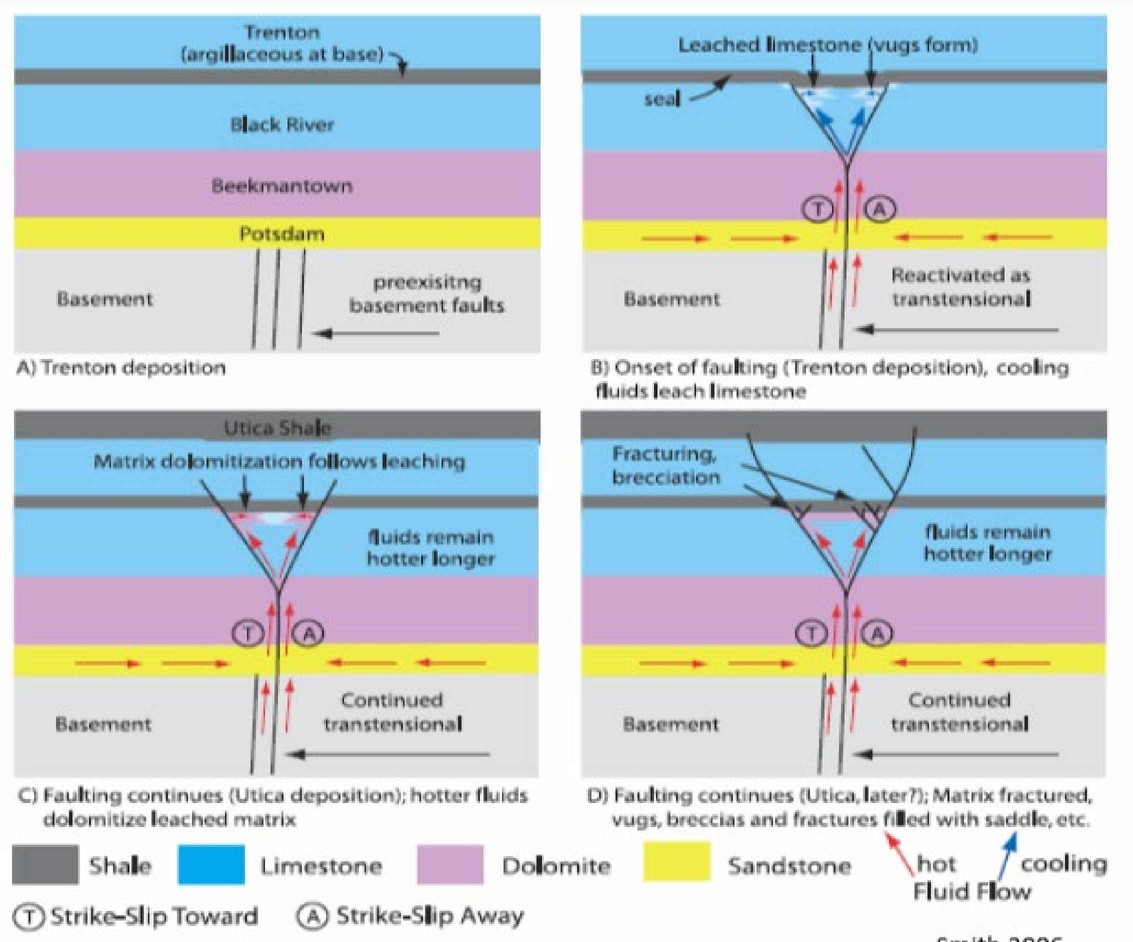
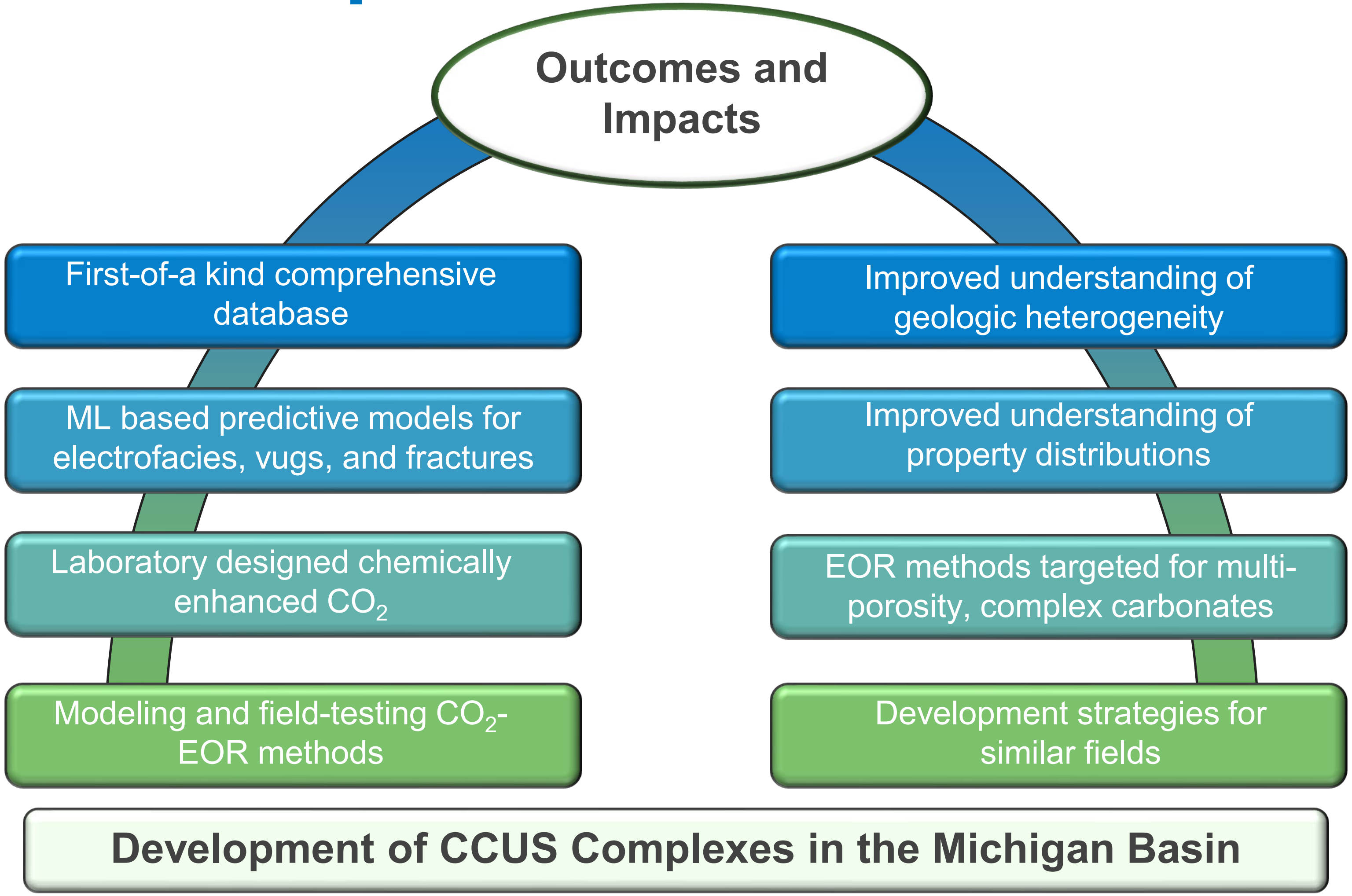
Complex Carbonate System

- 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

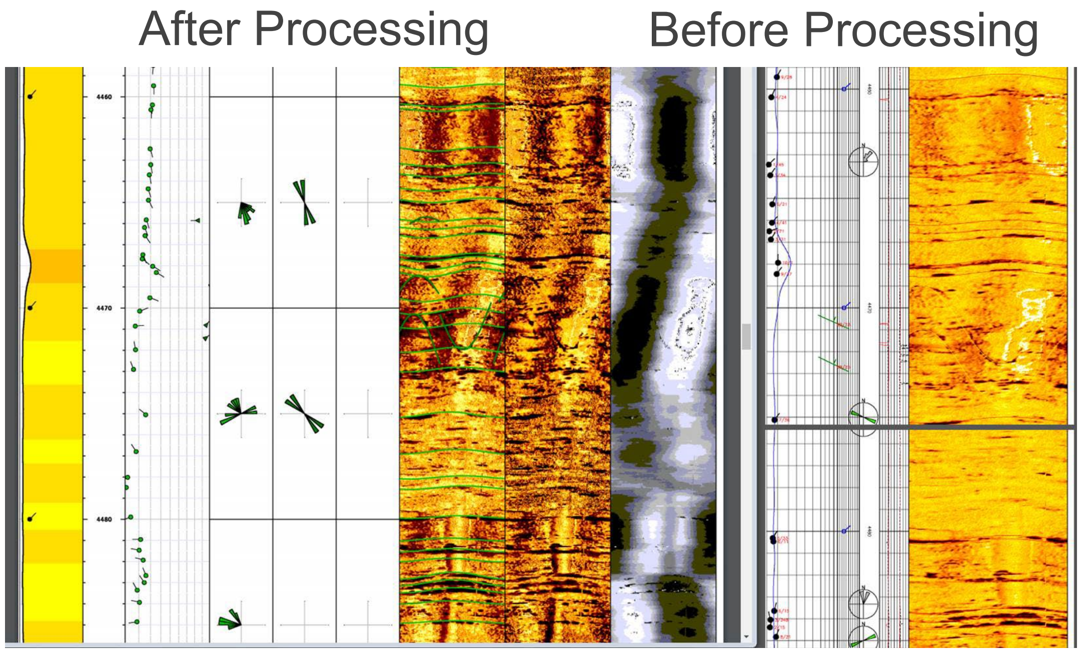


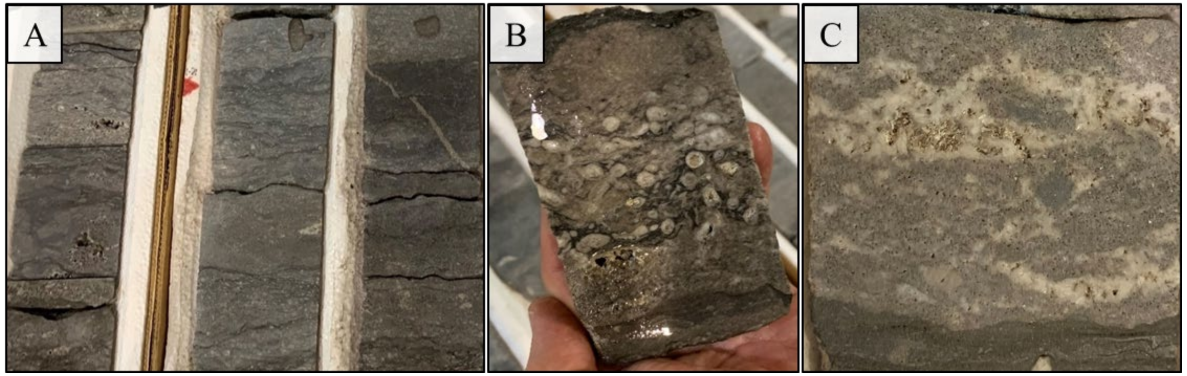
Smith,2006

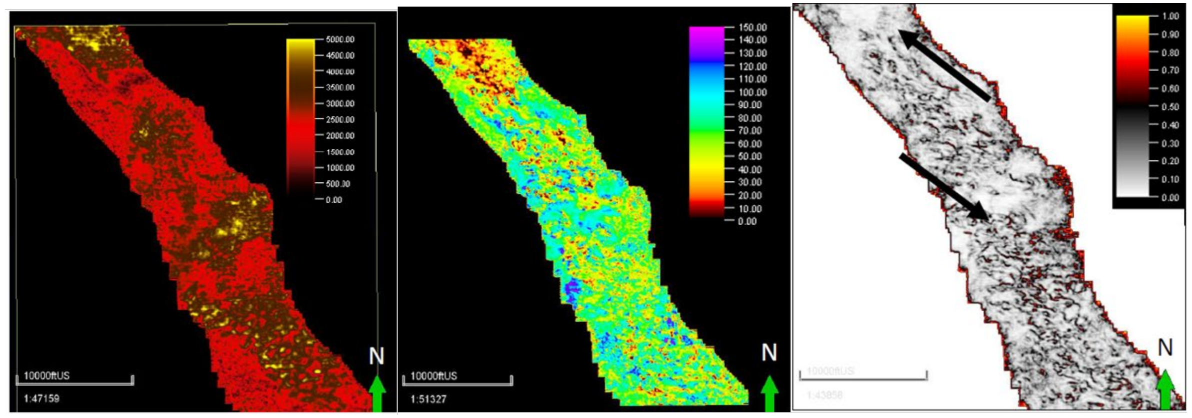
Outcomes and Impacts



BP1, Early 2020- Field Evaluation







Key Point: Full field characterization, including wireline, core, and seismic analysis were completed, indicating favorable conditions for CO_2-EOR in the Trenton-Black River trend.

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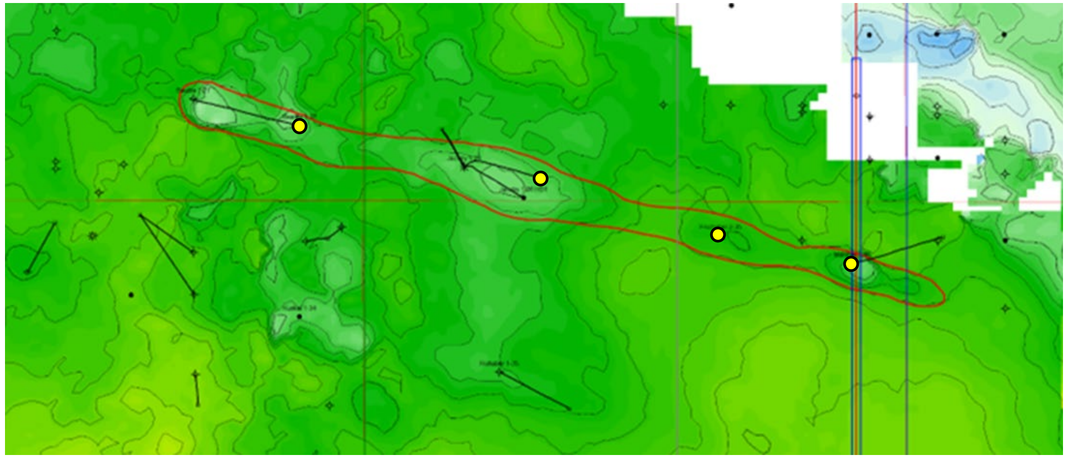
BP1, 2021 McCann #1-20 Production Analysis

- Drilling, logging, and completion successful.
- Oil production lower than expected; water production higher than expected.
- Conclusion: Proceed with initial CO_2 flood plan but move to location with suitable geology and existing wells.
  - Established production history, existing well pair, and known geology

- **West Bay Exploration's Lee 26 field**
  - Unitized field
  - Previously permitted and approved for injection
  - Onsite source of water for repressurization
  - OOIP ~1.4 MMBbls (324,000 bbls produced)



Pivot Point: Well drilling was a technical success, but oil production was not commercially viable. Project pivoted to an analogous field with proven production and available wells.

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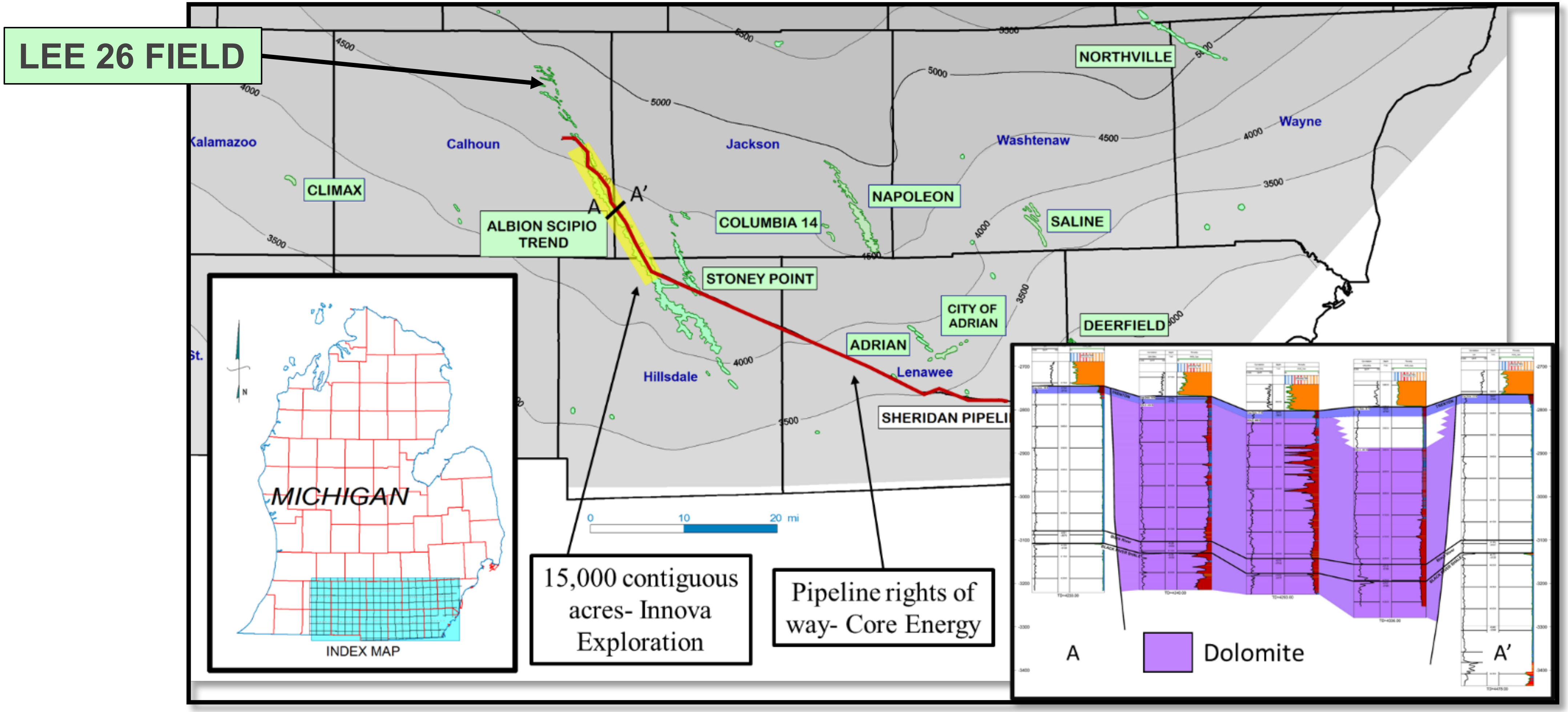
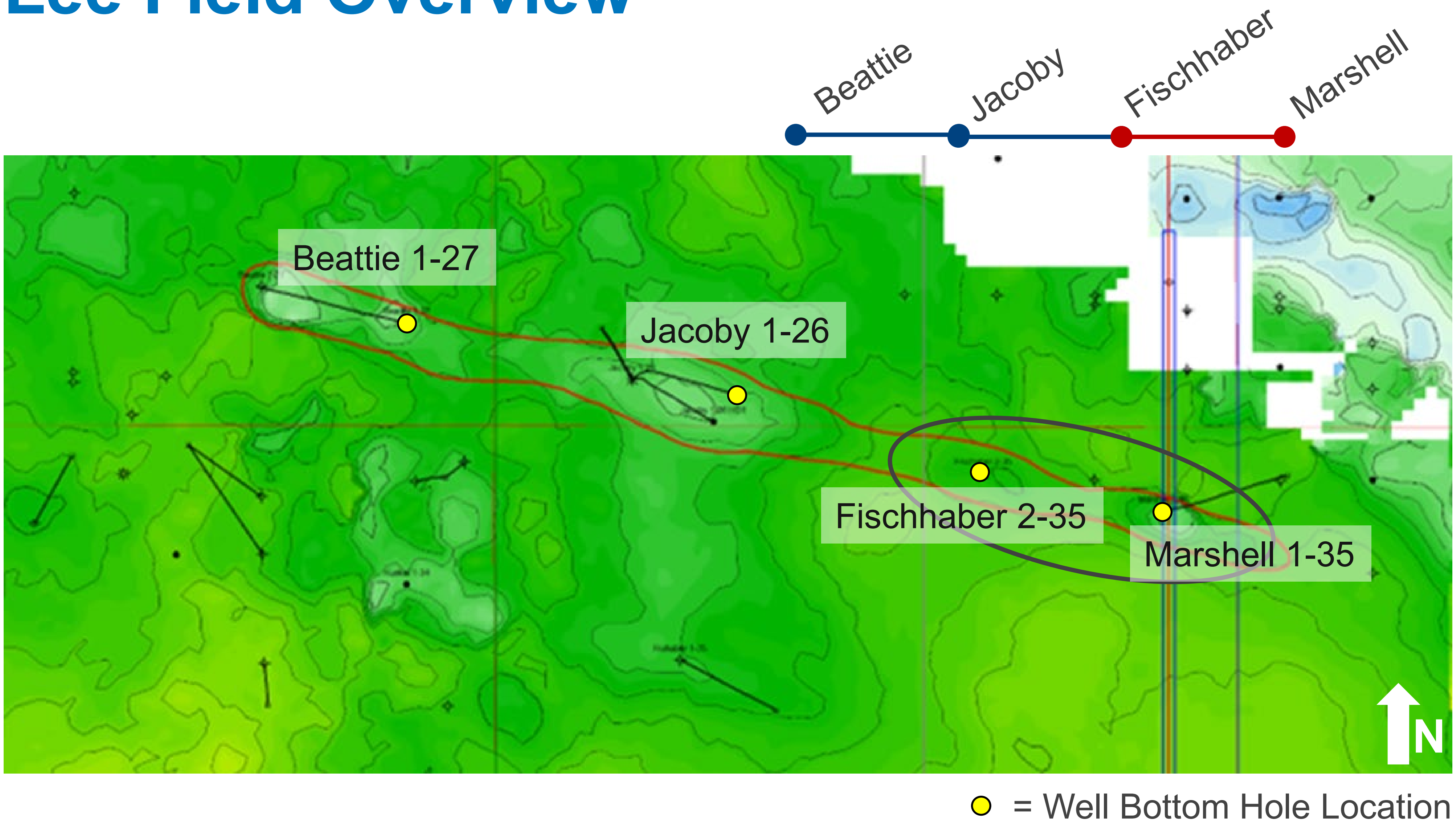
Lee 26 Field

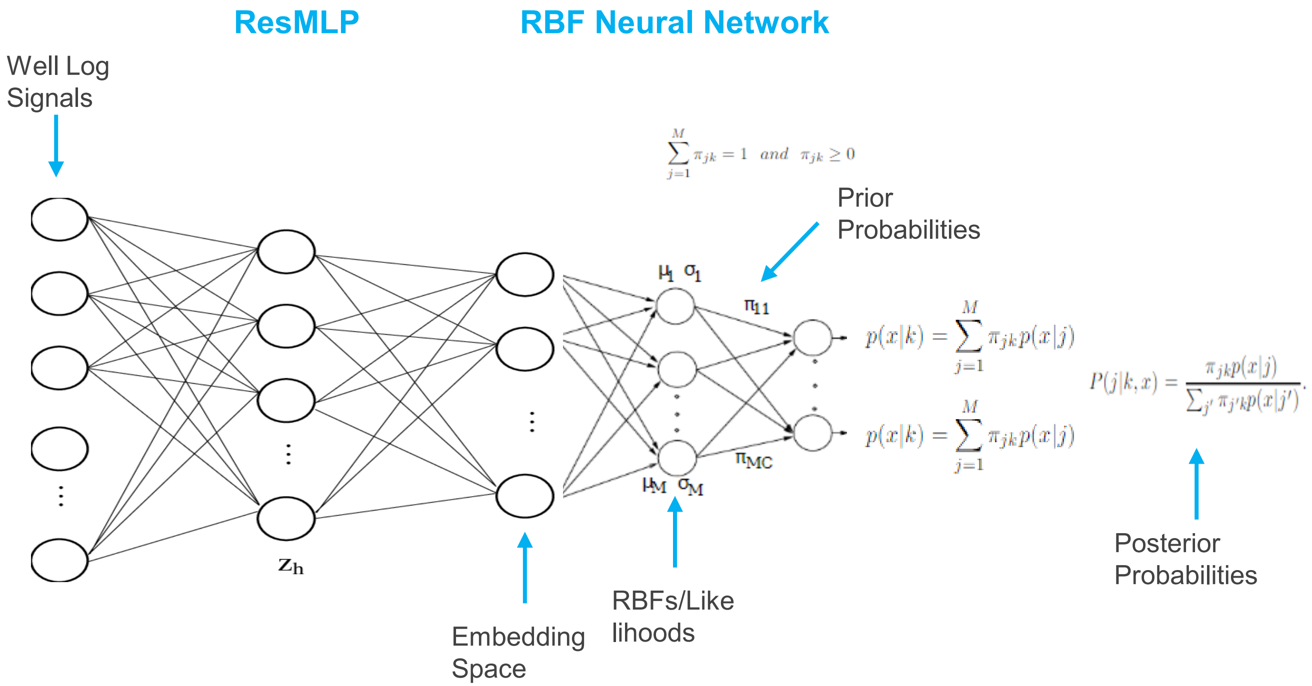


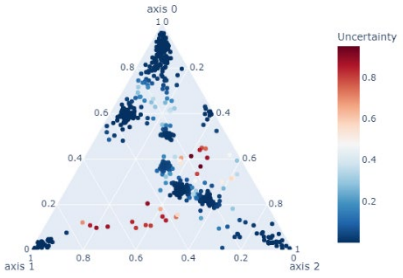
LEE 26 FIELD
Kalamazoo
Calhoun
Jackson
Washtenaw
Wayne
NORTHVILLE
CLIMAX
ALBION SCIPIO TREND
A
A'
COLUMBIA 14
NAPOLEON
SALINE
STONEY POINT
CITY OF ADRIAN
DEERFIELD
ADRIAN
Lenawee
Hillsdale
SHERIDAN PIPELI
MICHIGAN
INDEX MAP
0
10
20 mi
15,000 contiguous acres- Innova Exploration
Pipeline rights of way- Core Energy
A
Dolomite
A'

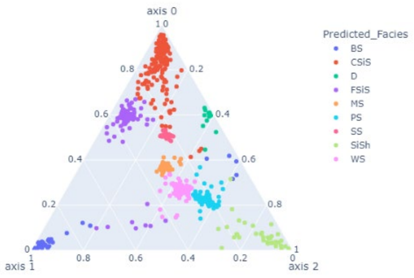
Lee Field Overview



Machine Learning Analysis of Image Logs







Pred	0	1	2	4	Total
True					
0	1181	11	30	1	1223
1	16	138			154
2	15	1	261		277
4	3			2	5
Precision	0.97	0.92	0.90	0.67	0.95
Recall	0.97	0.90	0.94	0.40	0.95
F1	0.97	0.91	0.92	0.50	0.95

Key Point: Trained model was able to predict the presence of vugs and fractures with moderate precision if a robust log suite is available in the target well.

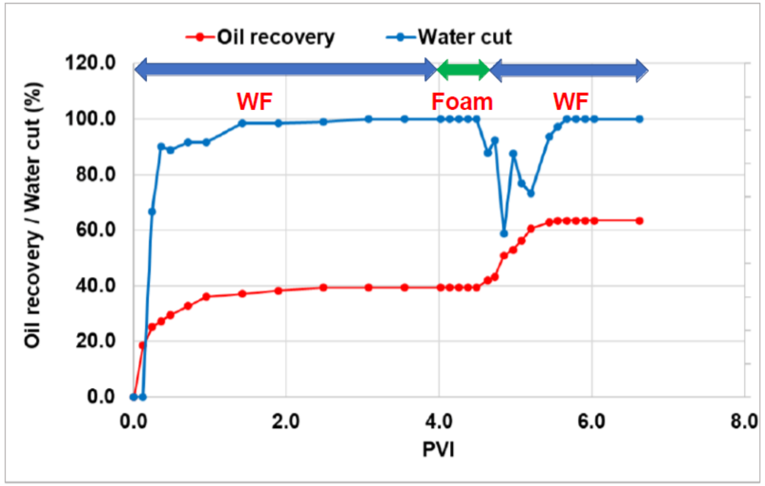
Lee Field Lab Testing

Foam and core flood preliminary results

	Produced water	CETAC-30
1 day	 Contact angle: ~ 180° Oil wet	 Contact angle: ~ 90° Intermediate wet
2 days	 Contact angle: ~ 180° Oil wet	 Contact angle: ~ 70° Water wet

➢ **Foam flooding**

0.5wt% CETAC at low salinity



Oil recovery

WF (4PV) : 39.1%

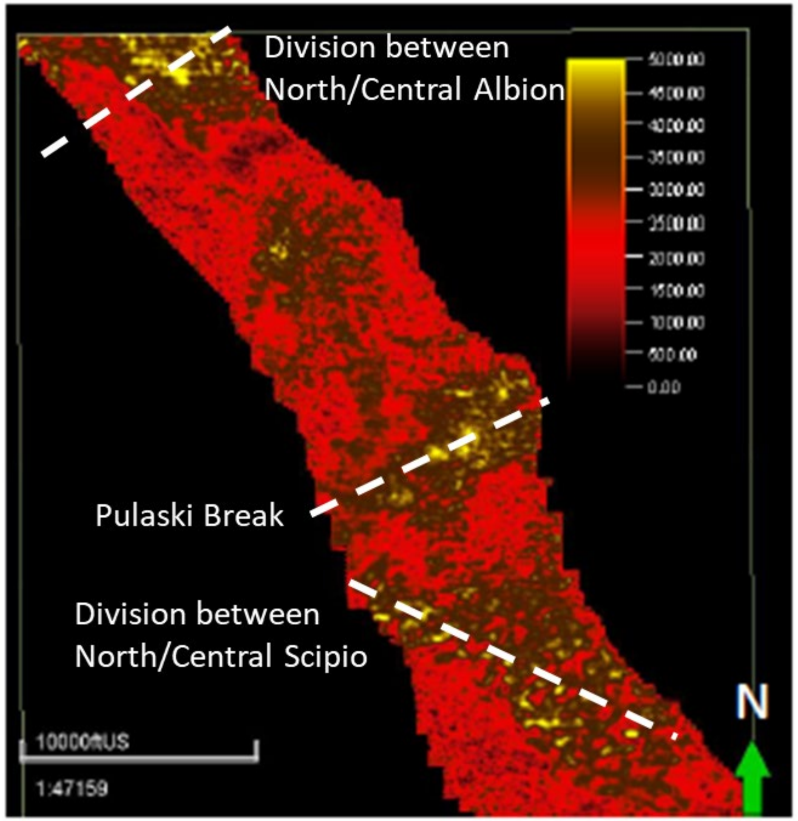
Foam (0.625PV) + CWF (3PV): 63.1%

Incremental: 24.0%

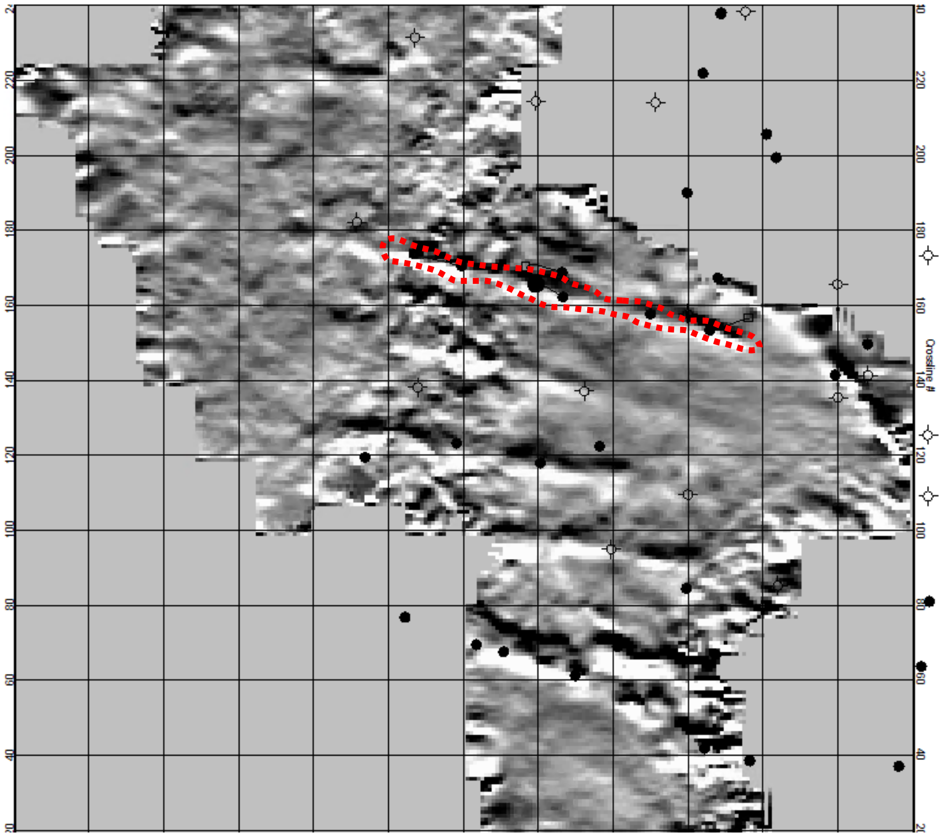
Key Point: Preliminary core flood with CO_2 and CETAC-30 boosts recovery by 24%.

Seismic Analysis of Albion-Scipio & Lee Fields

Albion-Scipio structural attributes



Lee Field structural attributes



Key Point: Reservoir-bounding and intra-reservoir faults identified and integrated into static earth model to spatially constrain fractures, vugs, and reservoir intervals.

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Facies Identification

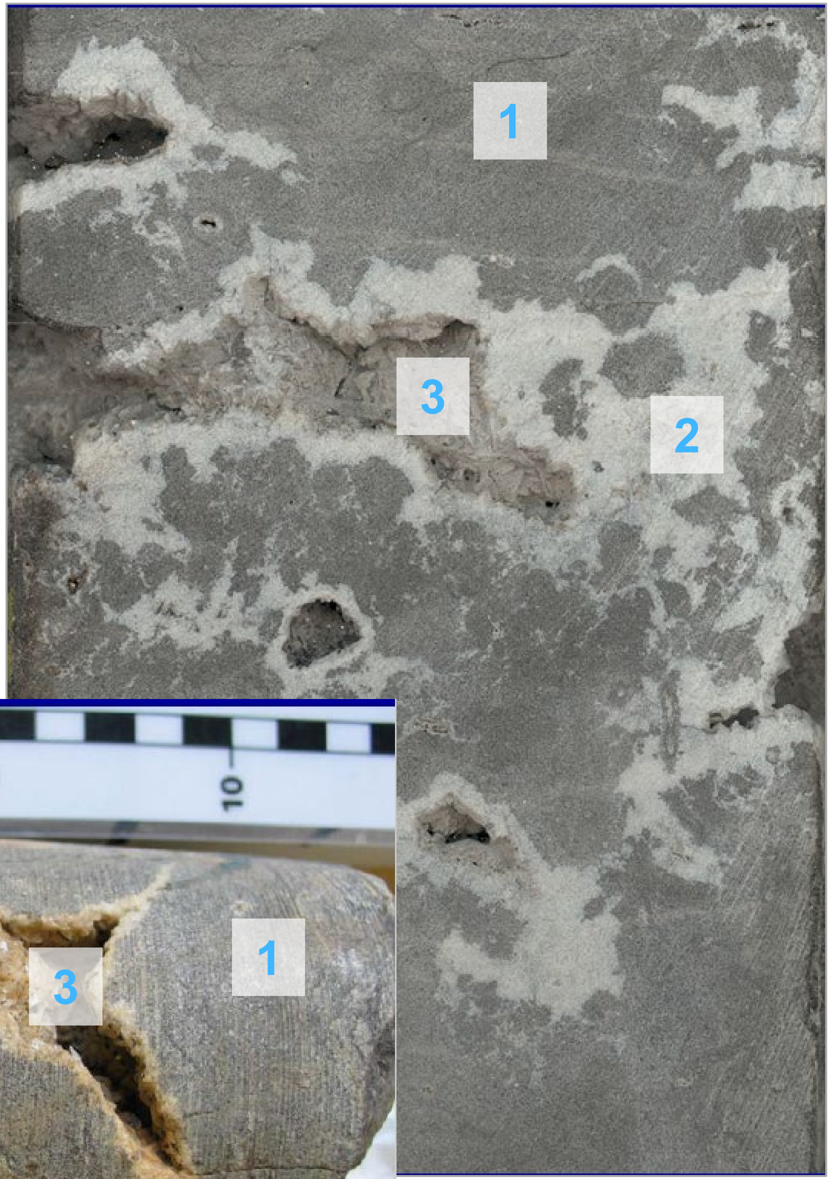
- Blocks in the static model were grouped according to three facies:

    1 – Tight limestone

    2 – Matrix dolomite

    3 – Cavernous dolomite

Assumption: Limestone facies (1) does not contribute to storage or pressure support – validated by core flood tests



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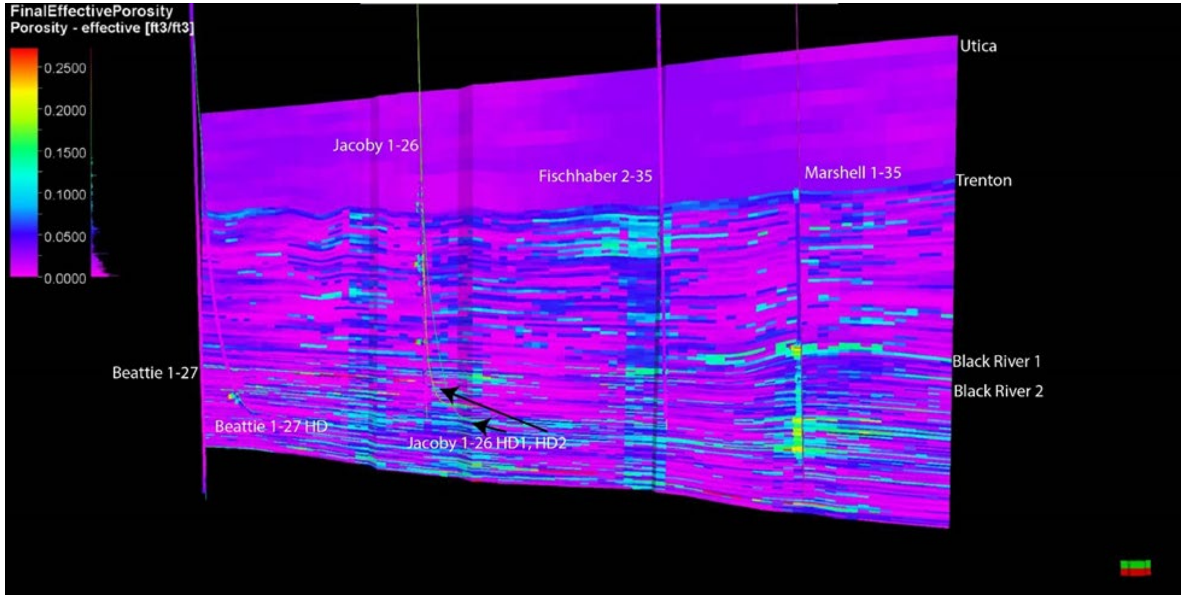
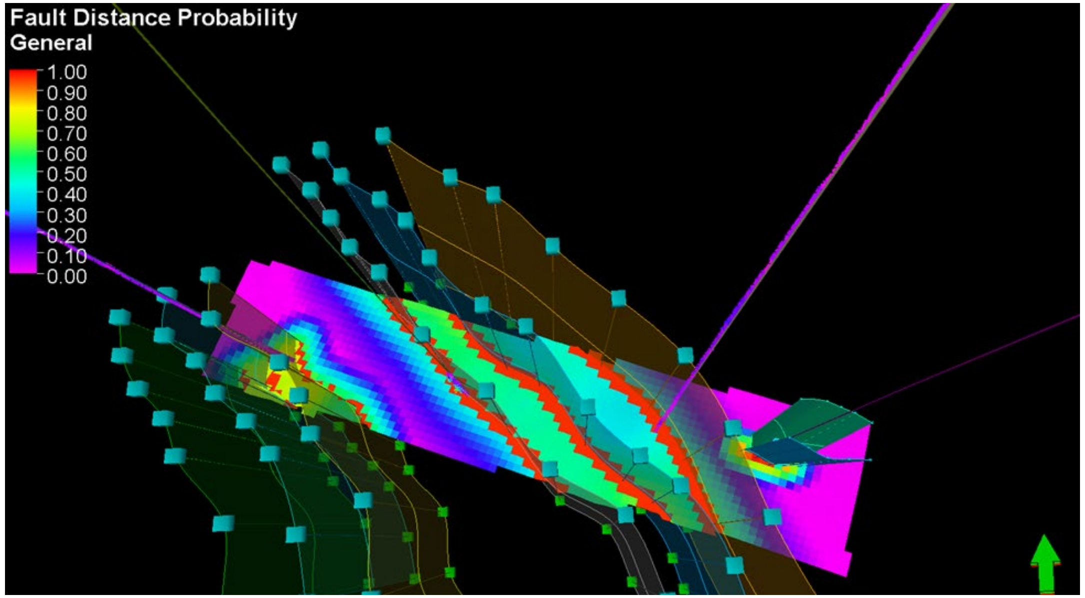
Static Earth Model

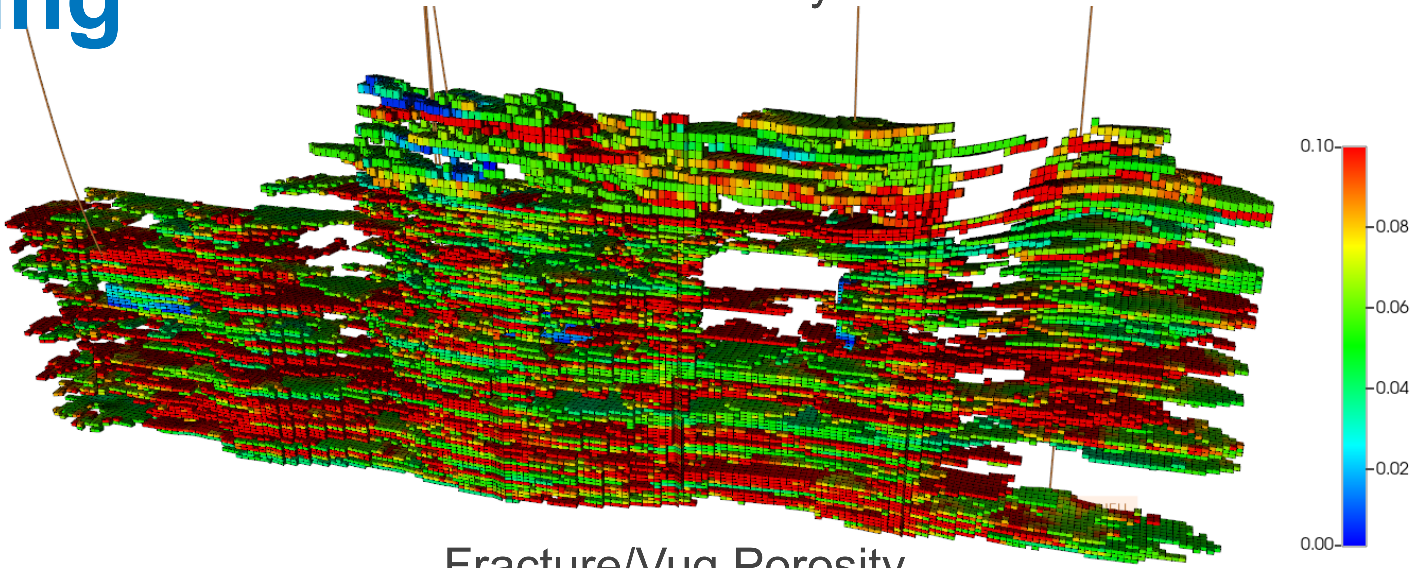


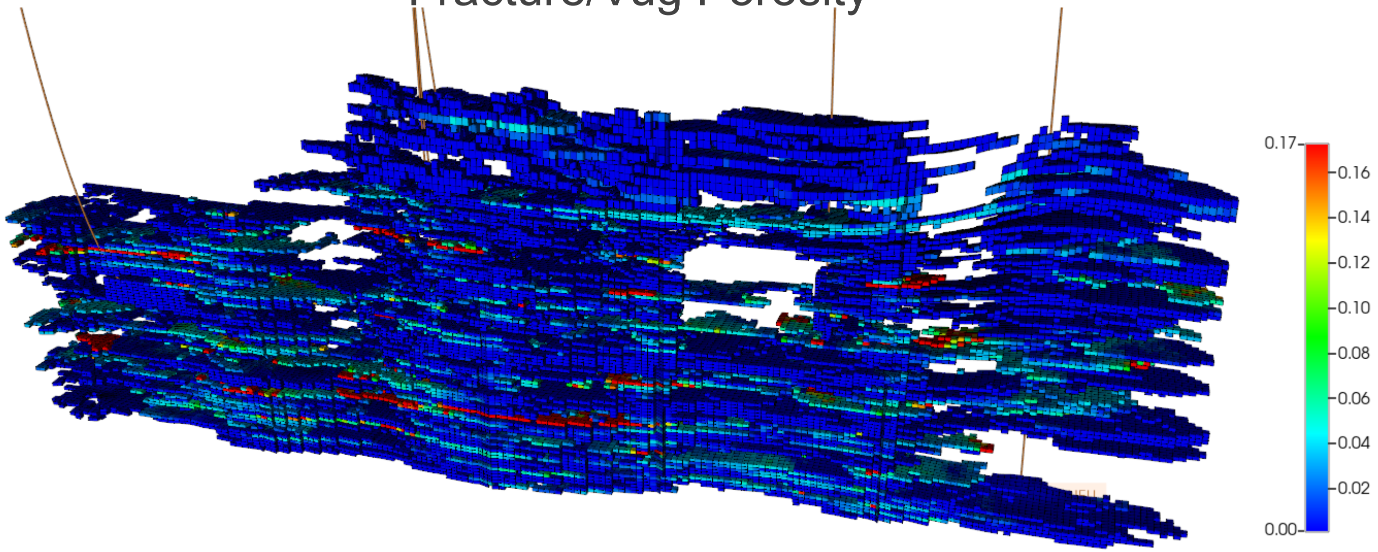


- Fault picks from seismic analysis integrated into model
- Hydrothermal facies distribution tied to fault proximity
- Addition of mud log information further constrained the facies distribution

Dual Porosity Modeling

- Field and lab testing indicate limestone facies does not contribute to reservoir volume
- Top of model determined by HCPV constrained by Material Balance Analysis (MBA) – reservoir in Black River and lower Trenton
- Two porosity systems: matrix dolomite and cavernous dolomite/fractures
  - Porosity based on facies modeling
  - Log-based effective permeability split based on well test data, previous work (Brock & Baker, 2012)

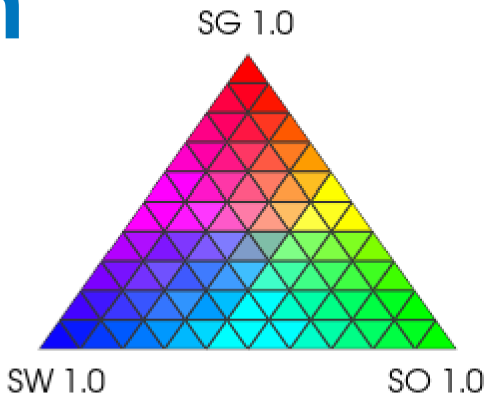


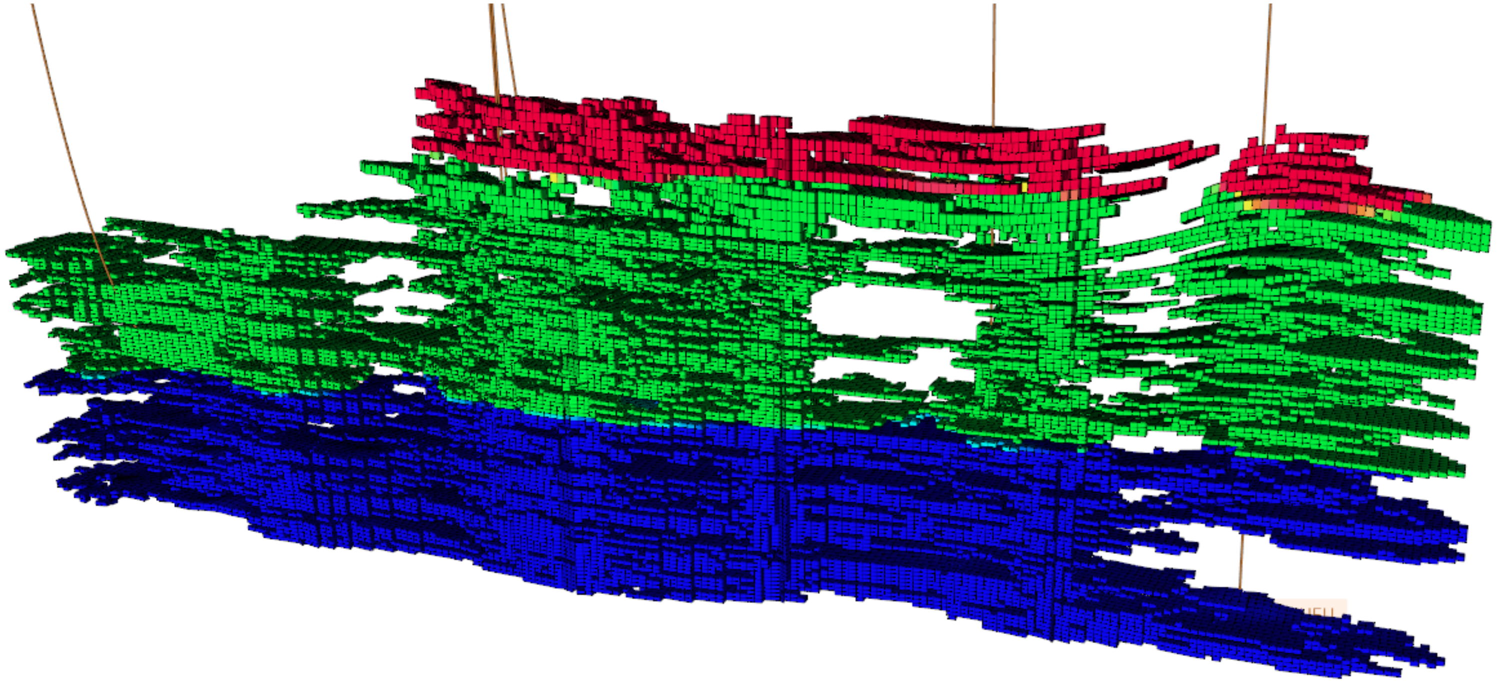


Brock, Timothy J. and Baker, Timothy L. (2012, September 22-26). *Analysis of Production Characteristics and Bottom Hole Pressure Buildup Data - Napoleon Field, Jackson County, Michigan.* AAPG Eastern Section Meeting, Cleveland, OH, United States. https://www.searchanddiscovery.com/abstracts/html/2012/90154eastern/abstracts/brock.htm

Model Initial Conditions & Fluid Saturation

- Fluid saturations and contacts based on MBA, well log and production data
- Initial pressure and temperature determined from field data
- Assume 15% Connate Water from analogous field
- Relative permeability curves from standard correlations for carbonates (Honarpour et al., 1986)





Honarpour, M., Koederitz, L., and Harvey, A.H.: Relative Permeability of Petroleum Reservoirs, CRC Press Inc., Boca Raton, 1986.

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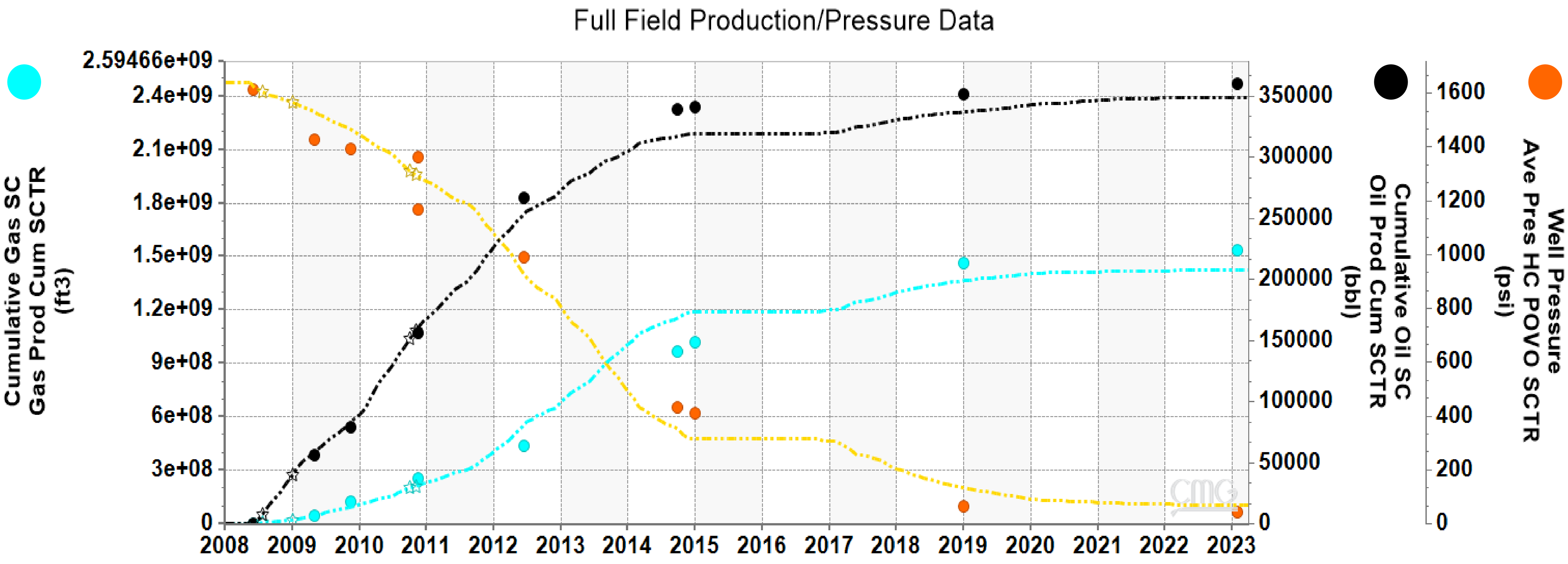
Full Field History Match

- Calibrated model matched to field and well production/pressure data



Well Drainage Area

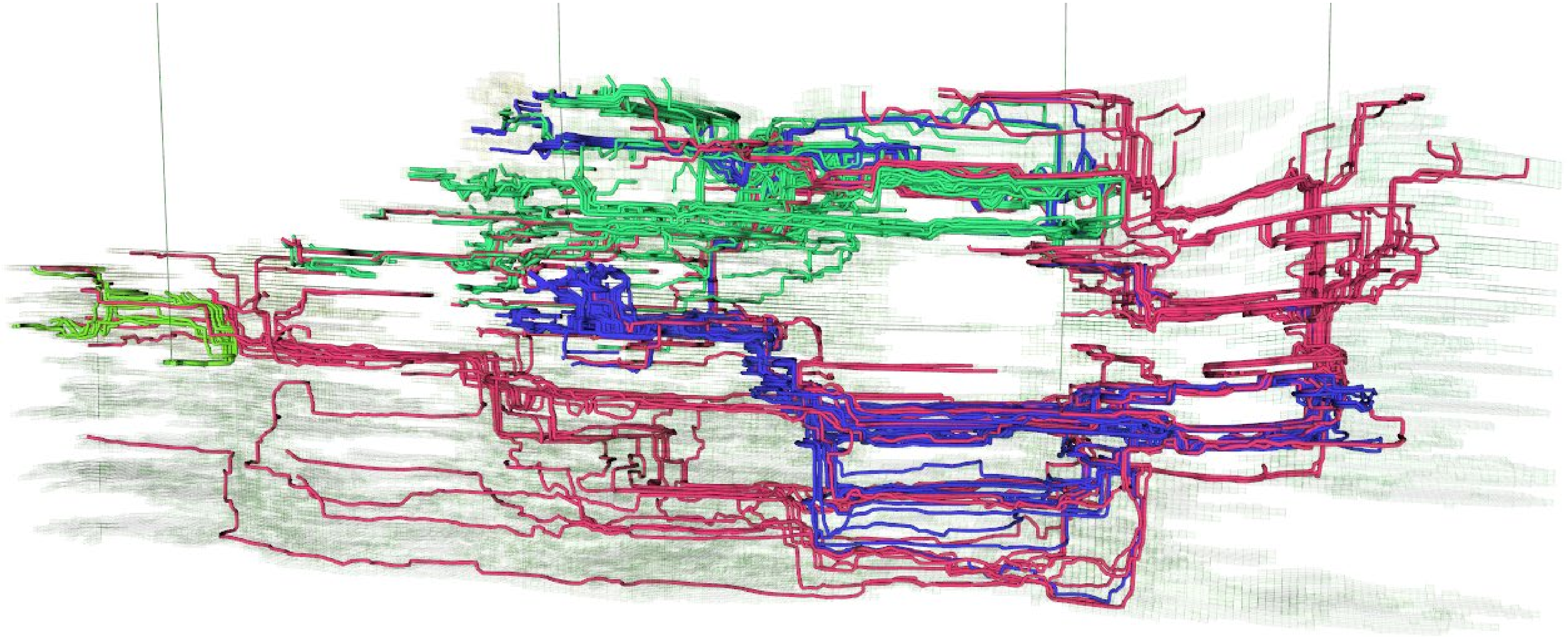
- Drainage flow-lines show approximate area of reservoir impacted by each well; representative of production history of the field

Marshell

Fischhaber

Jacoby

Beattie



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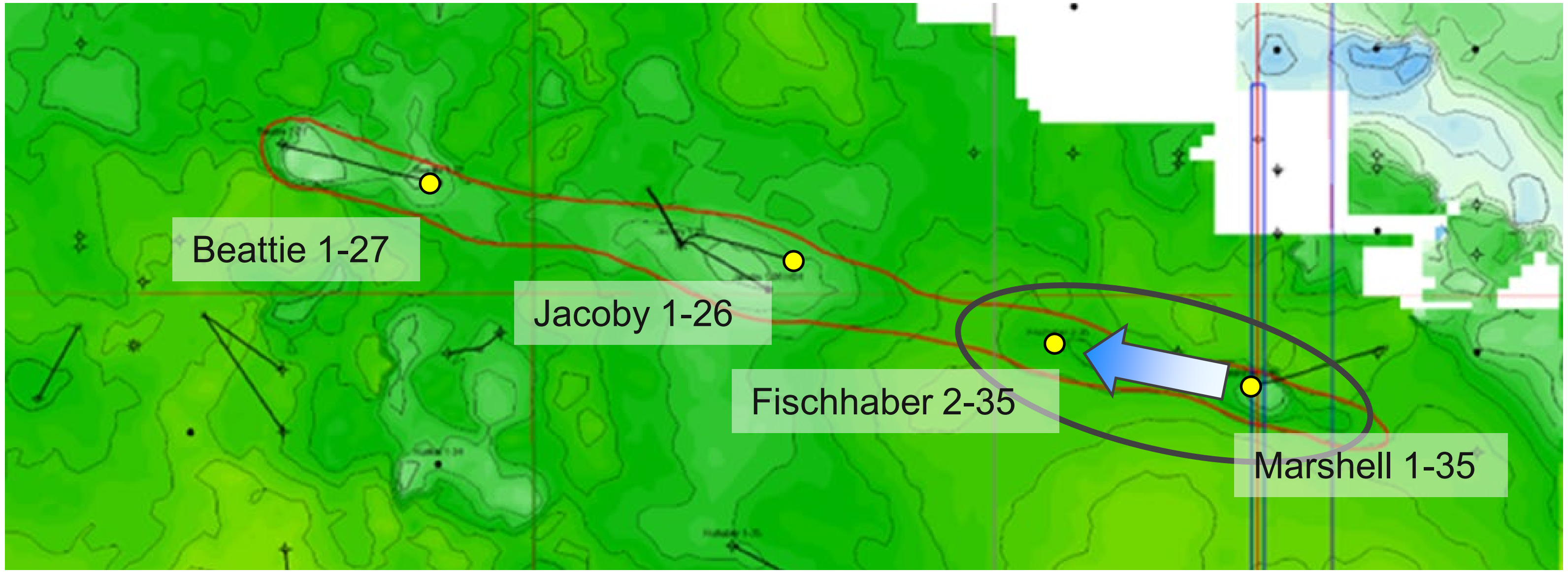
2022 Field Repressurization Plan

- Install downhole pressure gauges in Fischhaber and Marshell wells.
- Begin field repressurization through the Marshell 1-35 well.
- On achieving minimum miscibility pressure, initiate CO_2 flood, sweeping from the Marshell 1-35 to the Fischhaber 2-35.



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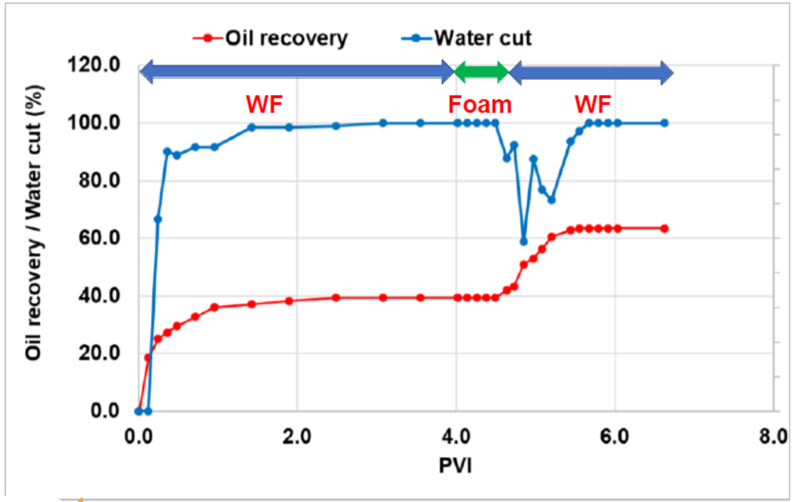
Calculated CO_2 volumes

- Initial flood design called for 30,000 tonnes to implement minimum useful flood.
- Project approval in 2019 when CO_2 prices were ~$170/tonne. Current price: ~$500+/tonne.
- Project budget for CO_2 injection is $1.75 million. At current price, **flood would cost $15 million**.

➢ **Foam flooding**

0.5wt% CETAC at low salinity



Oil recovery

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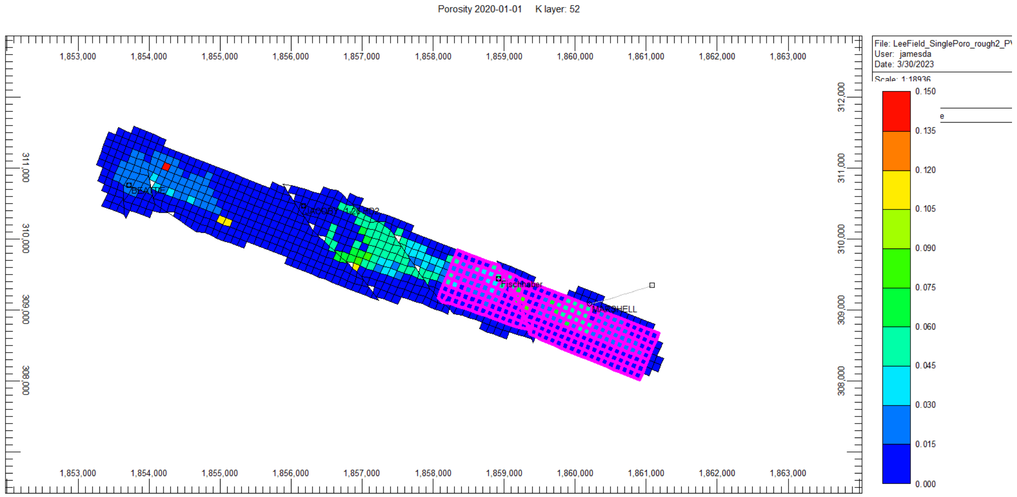
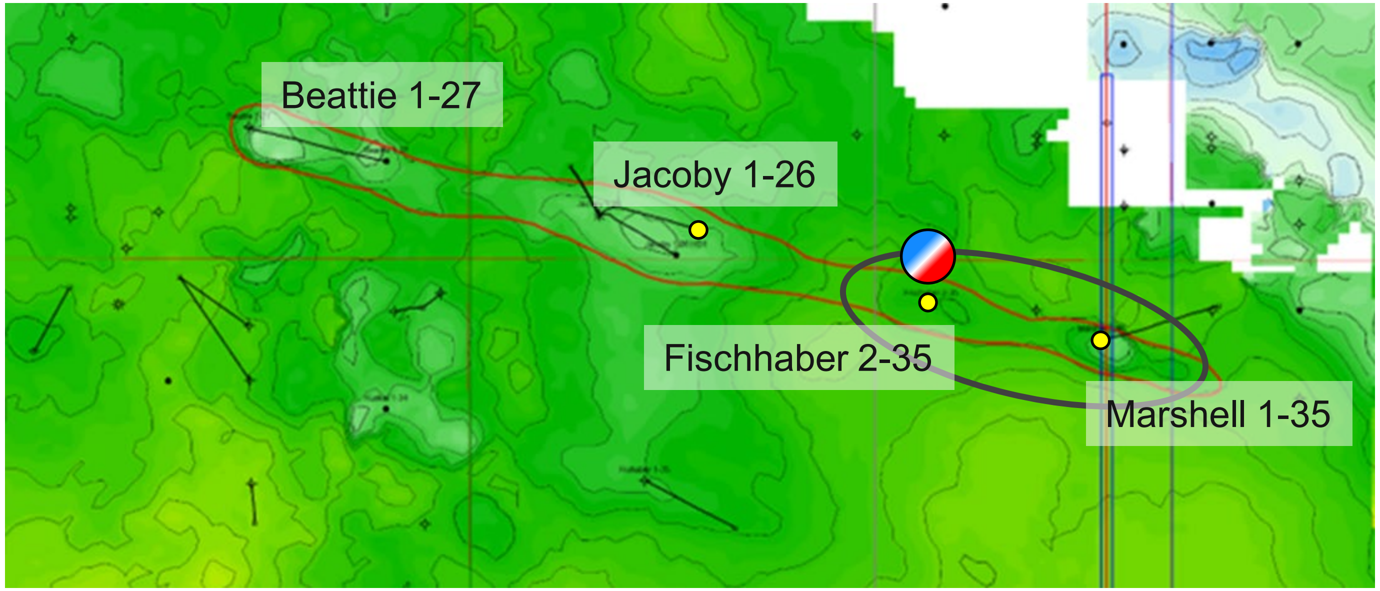


Pivot Point: Market conditions preclude a chemically enhanced CO_2 flood. Modeling indicates that a chemically enhanced CO_2 huff and puff will allow us to deliver project objectives.

Pivot Point: Huff & Puff



CO_2 Huff & Puff with Tracer Test

- Deviation from original project plan, but has been discussed as a back-up plan over the life of the project.

- Test huff & puff the Fischhaber 2-35:
  - 1,000-2,000 tons with partitioning tracer to understand efficacy of CO_2 at mobilizing residual oil.

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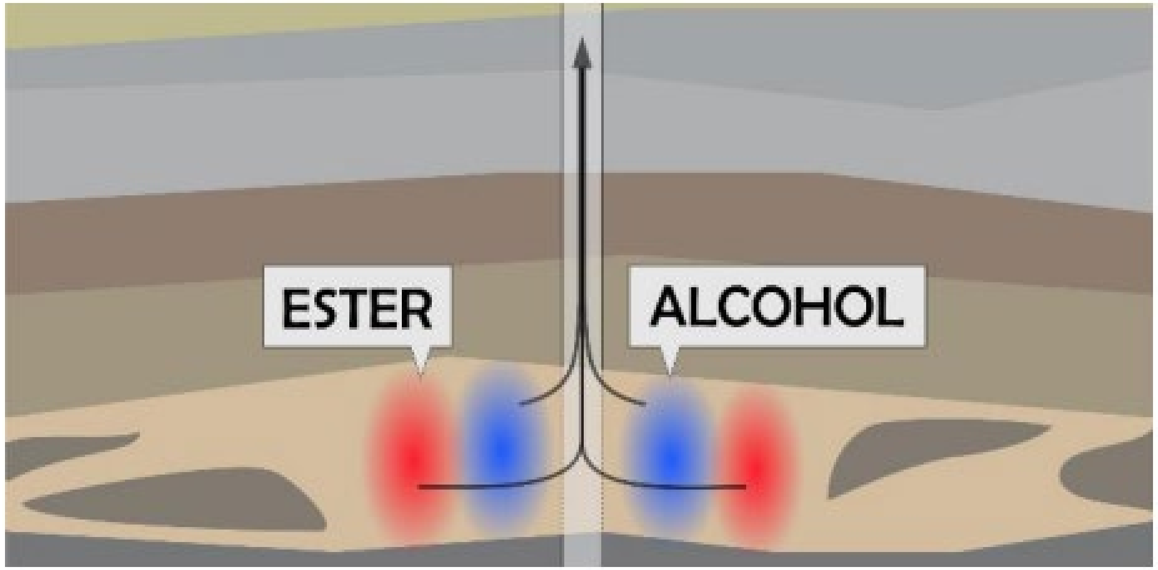
Huff & Puff Single Well Chemical Tracer Test

- The SWCTT is a non-intrusive test based on injection of a partitioning tracer (ester) into the reservoir.
- Some of the ester hydrolyses to alcohol during shut-in, and back-production of the well yield tracer production curves with different retention times.
- Analysis of tracer production curves yields residual oil saturation and percentage of oil mobilized by CO_2.



Partitioning ester lags behind the alcohol and the time-difference is directly related to oil saturation in the formation.

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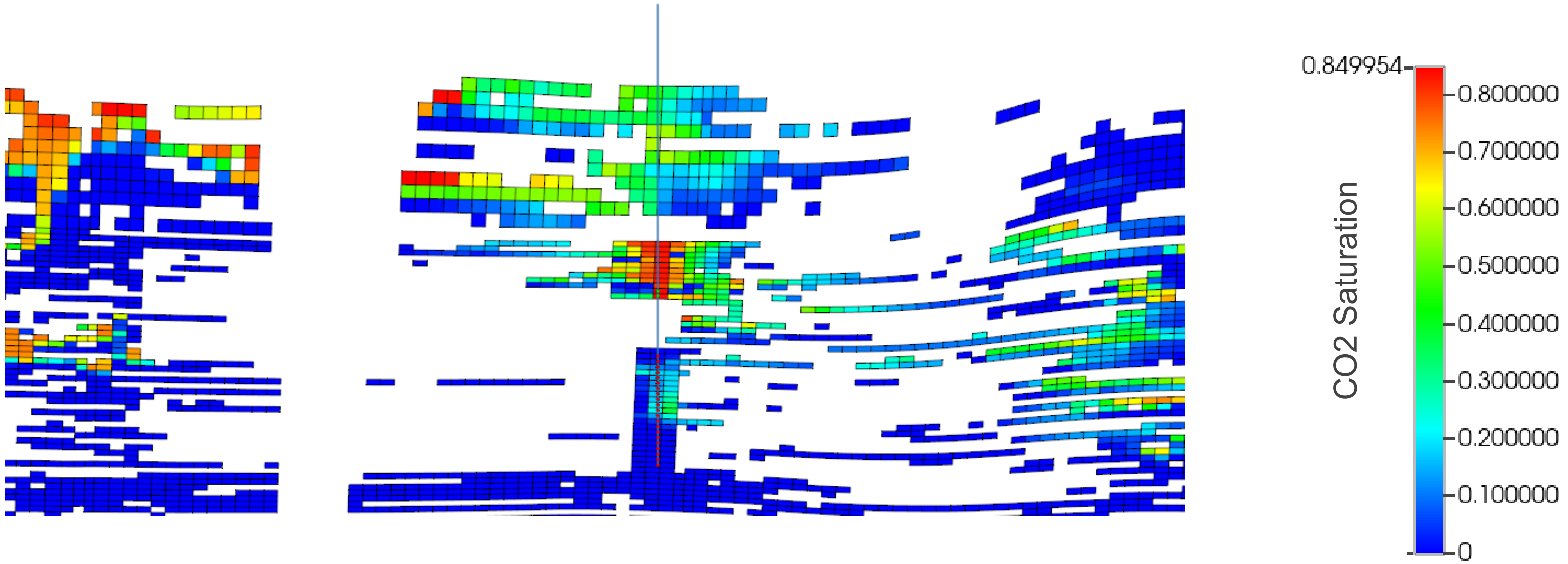
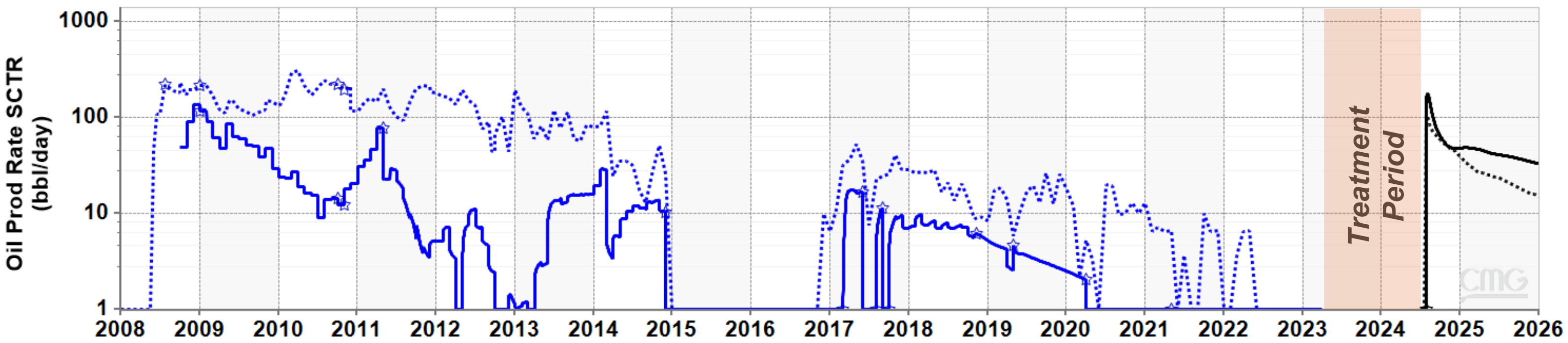
Forecasting Simulations – CO_2 Huff and Puff

- Simulating CO_2 Huff and Puff following re-pressurization through Fischhaber well
  - Pseudomiscible black-oil simulation
  - 1000 tonnes CO_2 injected, chase injection with water, 3-week soak
- CO_2 spreads out through the reservoir due to conductive fracture system
- Production rates are improved (~100 bpd peak) after treatment
  - Oil in matrix mobilized by pressurization and CO_2
  - ~50% recovery of injected CO_2



Oil Rate at Fischhaber (BPD)



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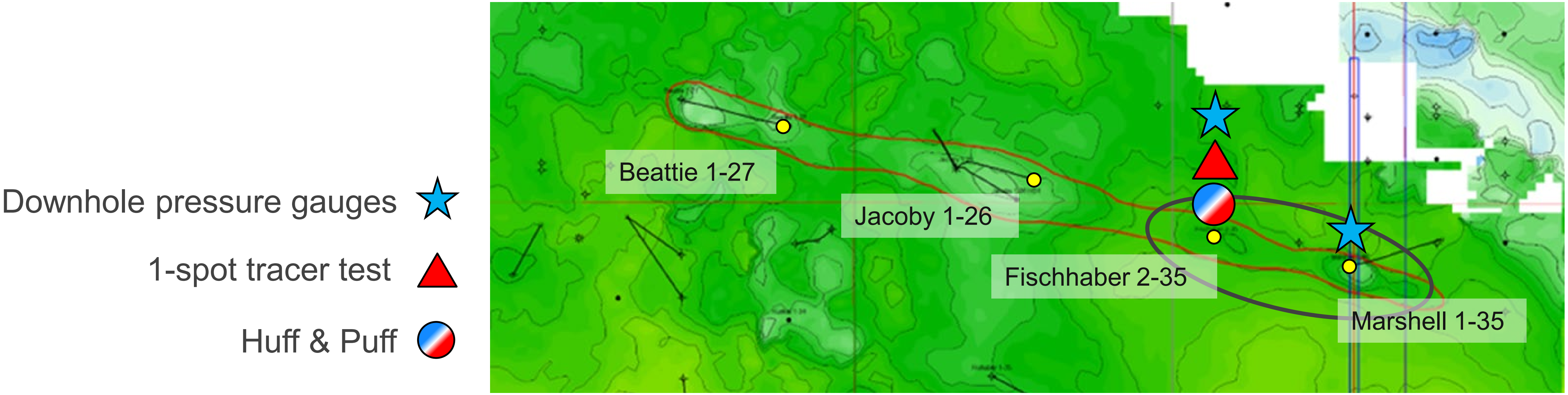
Field Repressurization and Monitoring

- Install downhole pressure gauges in Fischhaber and Marshell wells.
- Begin field repressurization through Fischhaber well.
- On achieving minimum miscibility pressure, complete single-well partitioning tracer test in Fischhaber.
- Inject CO_2, flow back, and monitor pressure and production.



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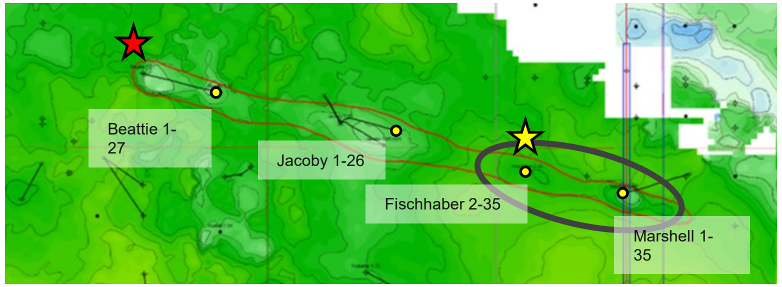
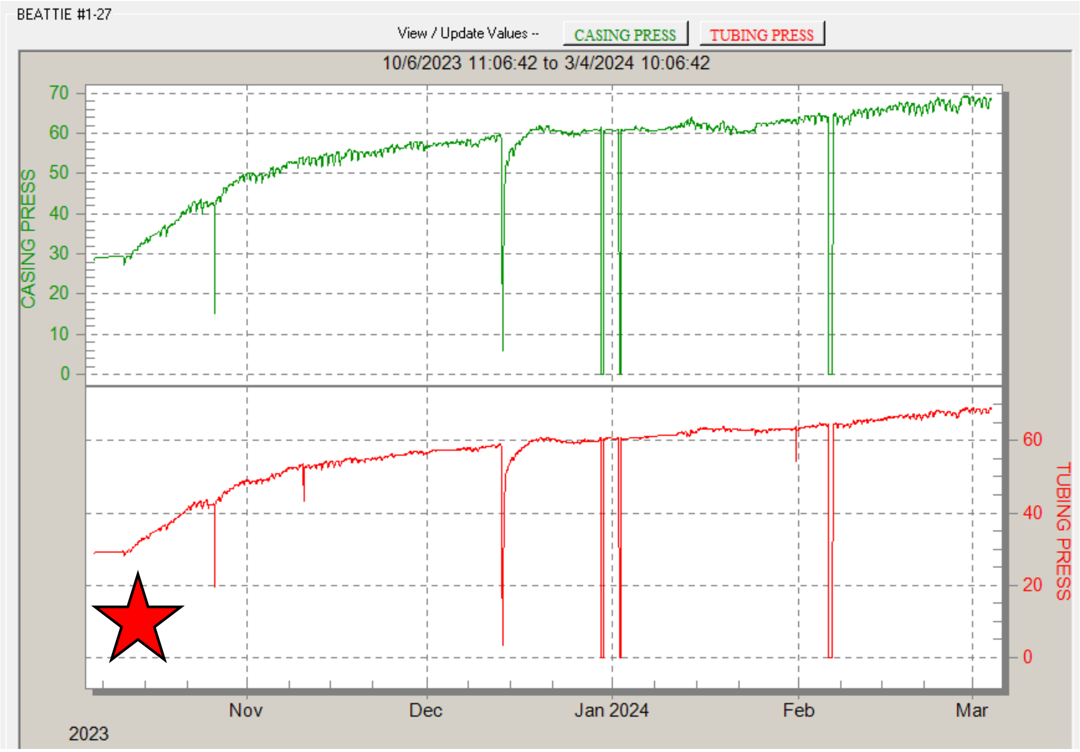
Pressure Monitoring

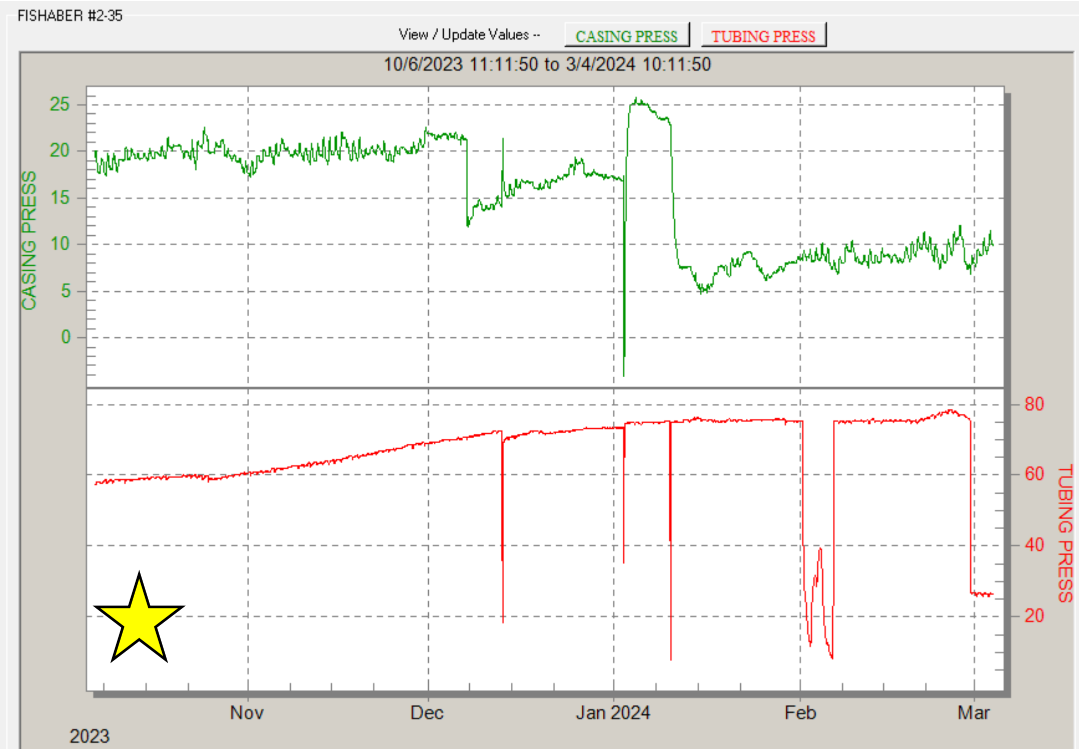
~400,000 barrels injected to date



Beattie (westernmost well in Lee 26 field)



Fischhaber (Nearest offset to injector)

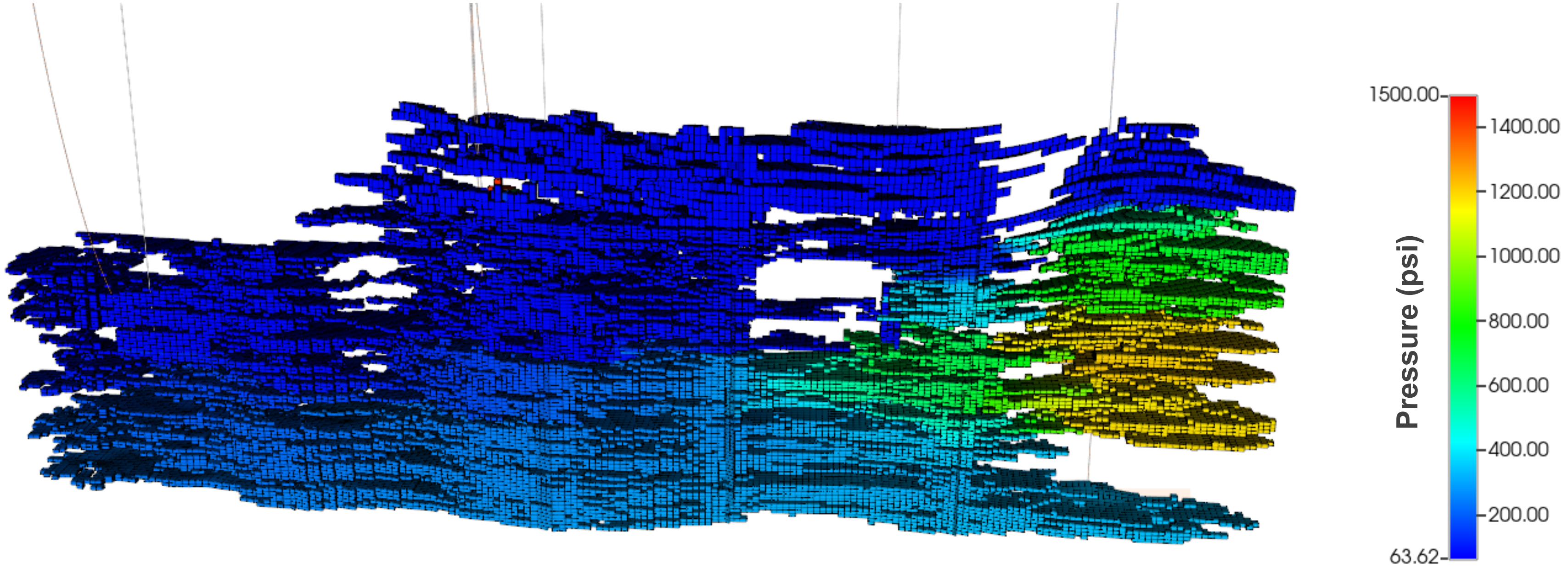


Key Point: Pressure buildup observed across the field, indicating reservoir well connected by fractures and/or vugs. Anticipated total injection 800,000-1 million barrels water.

Assessing Pressurization Operations

- Tracking field pressure monitoring against anticipated pressure gain from history matched black-oil simulation model
- *Observed pressurization is not a perfect match to predictions from black oil model, but sufficiently close to merit continued injection and continued confidence in our model build.*

Modeled pressure distribution after 4 mos. injection at 3000 bbl/d through Marshell. We are currently injecting at ~2400 bbl/d



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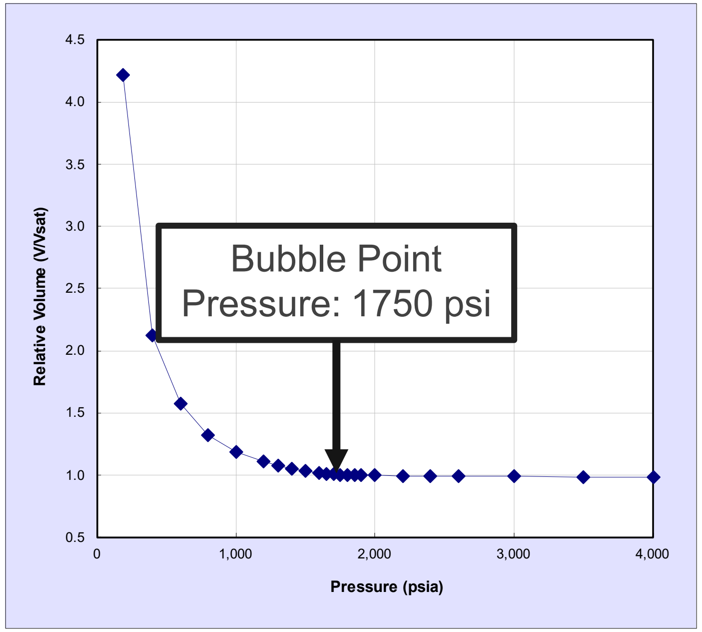
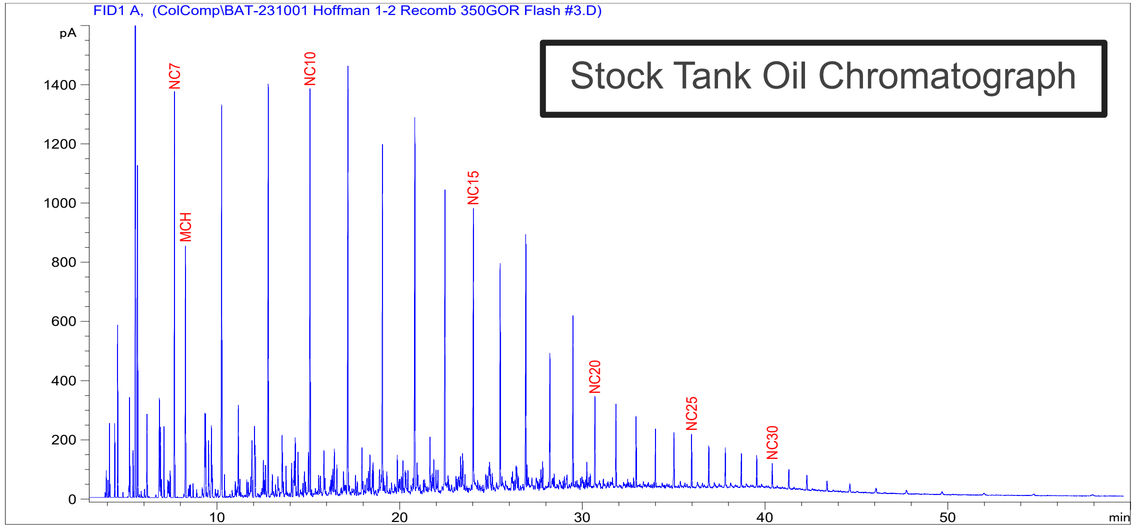
PVT Results

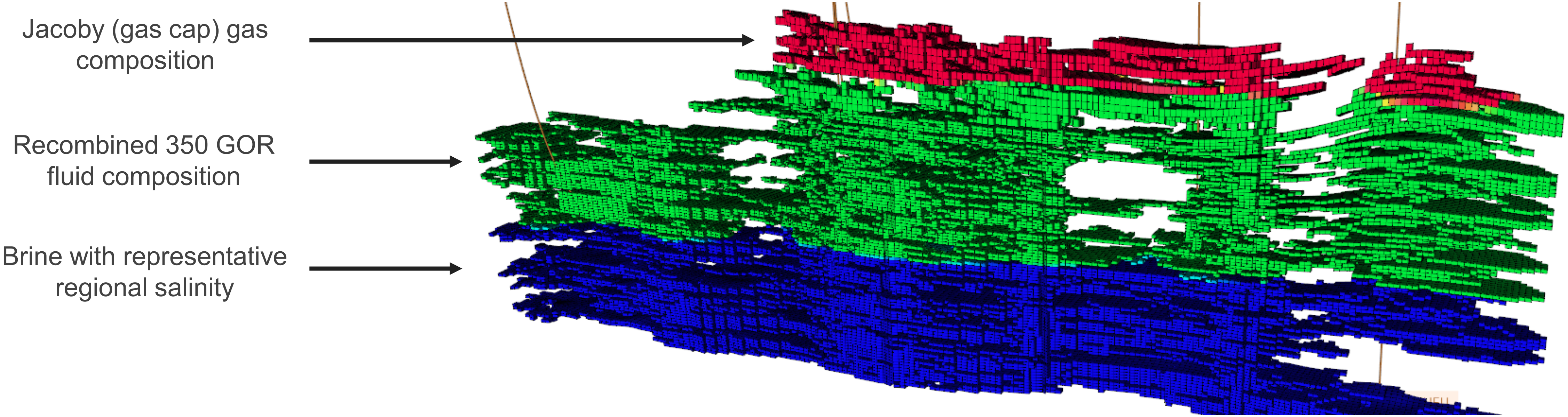
- PVT analysis of analogous oil completed by GeoMark 12/1
  - Gas gravity = 0.85 (consistent with Lee 26)
  - Oil density = 0.83 g/cc
  - Recombinations performed at 512 & 350 GOR
- Fluid deemed most representative of saturated reservoir oil was 350 GOR recombined fluid
  - Bubble point = 1750 psi, very close to initial reservoir pressure
  - GOR matches initial producing GOR of field





Incorporating PVT Results – Compositional Models

- **Next step:** Populate HM reservoir model with compositional fluid models and re-tune history match with new fluid interactions.
- Modeling full compositional behavior will greatly improve accuracy of CO_2 Huff & Puff forecasting simulations.



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Two Oral Presentations at GSA Connects 2023

- Submitted as two-part discussion featuring two project geologists and one reservoir engineer
- Presentation was well received, with audience questions focusing on characteristics of hydrothermal alteration, integration of faults into the 3D geomodel, and CO_2 sourcing.

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Project Impacts and Scale-up Opportunities

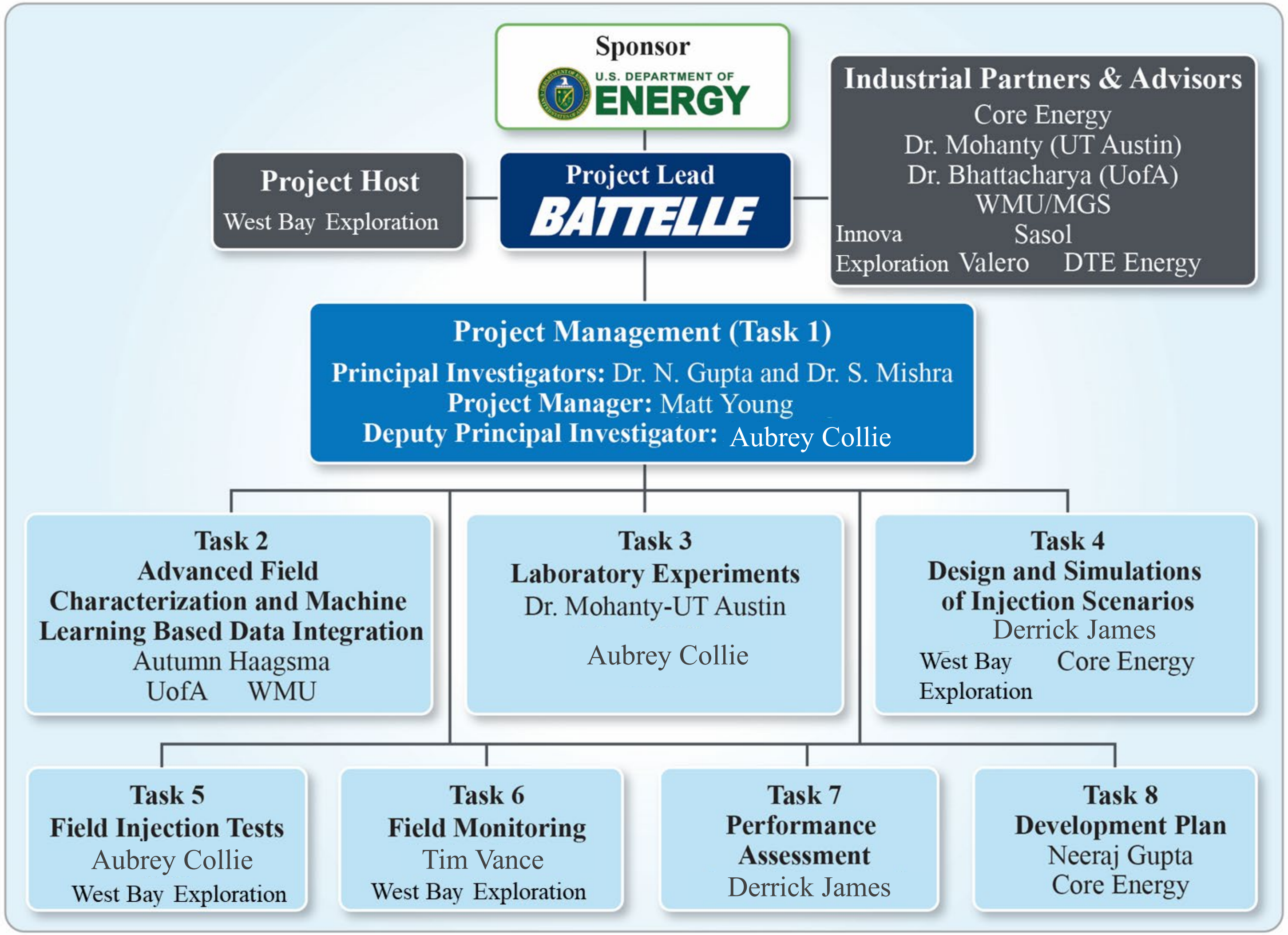
- Key outcomes and impacts:
  - Gained an understanding of the distribution and extentof vugs and fractures in the TBR reservoir using traditional ML and modeling techniques.
  - Laboratory experiment driven improved design of chemically-enabled CO_2 EOR which targets multi-porosity, complex carbonate 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 and 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 will illuminate CO_2-EOR infrastructure needs 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 local and regional industrial businesses.

Summary

- Key Technical Findings
  - Core floods indicate that CO_2 EOR should provide a 14% uplift to production within the accessed pore volume.
  - Lab testing indicates that CETAC-30 optimizes pore surface wettability, improving oil recovery by an additional 9.6%.
  - Modeling and repressurization data indicate that the Lee 26 reservoir is fully connected by fractures and/or vuggy intervals.
- Future Plans
  - Continue repressurization until semi-miscible pressure achieved in region surrounding Fischhaber 2-35
  - Conduct 1-spot chemical tracer test to assess residual oil in the Fischhaber 2-35 near wellbore region
  - Complete large-scale huff & puff stimulation and production monitoring at the Fischhaber 2-35.

Take-away Message: Maintaining agility in the face of scientific and market challenges is critical to delivering results for complex projects in complex field environments.

Project Organization



FOADOE1988 MI-01

Key Individual Contributors

Current Project Team

- Dr. Neeraj Gupta- Principal Investigator
- Tim Vance- Geologist
- Derrick James- Reservoir Engineer
- Stuart Skopec-Geologist
- Dan Brugeman- West Bay Energy
- Shane Jones- West Bay Energy
- Dr. Shuvajit Bhattacharya- UT Austin, BEG
- Dr. Kishore Mohanty- UT Austin
- **Gary Covatch- DOE**
- **Kyle Clark- DOE**

Past Contributors

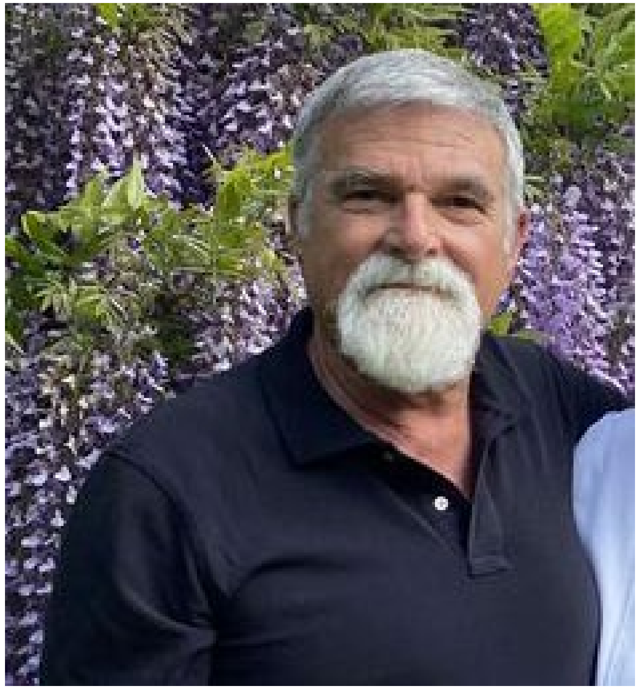
- Dr. Srikanta Mishra- Principal Investigator
- Tim Baker- West Bay Energy
- Dr. Autumn Haagsma- Geologist, DPI
- Amber Connor- Geologist
- Ashwin Pasumarti- Reservoir Engineer

In Memoriam

Mark Moody- Battelle

1952 - 2022

Ron Budros- Innova Exploration



1950 - 2023

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Thank You!

For questions or comments, reach out to:

Aubrey Collie– collie@battelle.org

Acknowledgements: The primary funding is from the US Department of Energy's National Energy Technology Laboratory (NETL) under DOE project number DE-FE-0031792.

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It can be done

800.201.2011 | solutions@battelle.org | www.battelle.org

Project Gantt

Chem Enhanced CO2 EOR - Battelle/West Bay 2024

FY2024: Mar Apr May Jun Jul Aug Sep | FY2025: Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep | FY2026: Oct Nov Dec Jan Feb Mar

→ = critical path

Task	duration
BP2 - current DOE budget period	
Permitting	
CO2 and Water Inj permitting complete for Fishaber and Marshell	
Lab	
Baseline Fluid Sampling and PVT	
Modeling	
Create compositional fluid model from PVT	
Convert Black Oil model to compositional	
Compositional model history match	
Forecasting simulations for CO2 ops	
Update of Dynamic Modelling results	
Procurement	
CO2 procurement	
Surfactant Procurement	
Huff & Puff injection equipment procurement	
Field Work	
Quarterly Downhole Pressure Measurements	
Chemical Tracer sampling	TBD until presence in all 4 wells
Repressurization	1300 psi or end of BP2
Injection Site Prep & Staging	2 months
BP3	
One Spot Tracer	
Injection Ops	
Huff & Puff - injection	2000t @ 500t/day
CO2 Soak	1 month
Huff & Puff - production/flowb	TBD
Post-injection	
Monitor	
Development Strategy	
Reporting	
DOE End of Program	

X (BP2 end, Mar FY2025)

BP3

X - injection expected to take place 3/25 but could happen as early as 11/24

Program End Date - X

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