Midwest Regional Carbon Sequestration Partnership

DOE/NETL cooperative agreement # DE-FC26-05NT42589

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U.S. Department of Energy

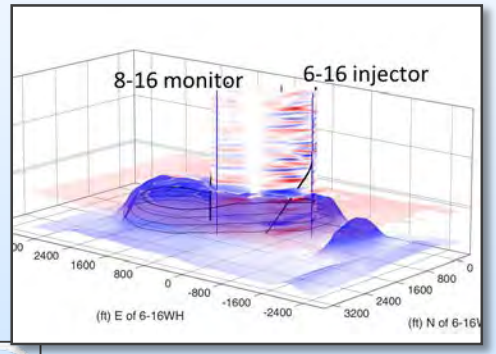
National Energy Technology Laboratory

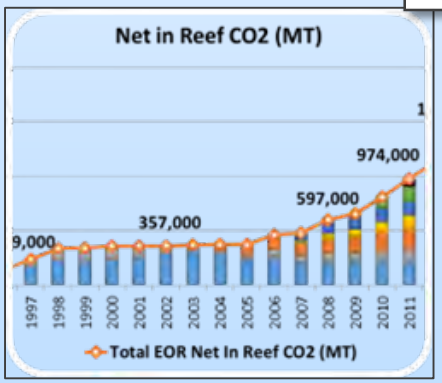
Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

Presentation Outline

- Introduction
- Technical Status
  - Characterization
  - Monitoring
  - MRV and Life-Cycle Analysis
  - Modeling
  - Outreach status
- Summary
  - Accomplishments
  - Lessons Learned
  - Synergy Opportunities



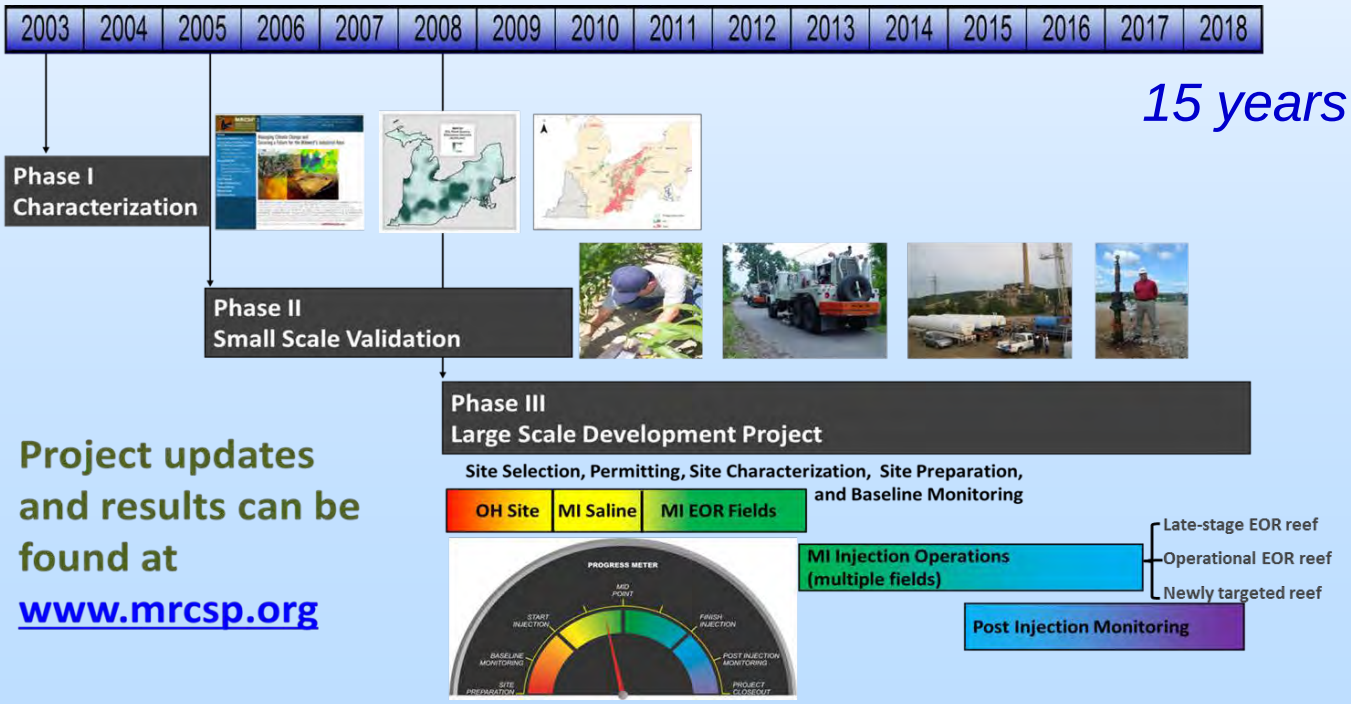


MRCSP Goals and Objectives

Primary goal: execute a large-scale CO_2 injection test to evaluate best practices and technologies required to implement carbon sequestration

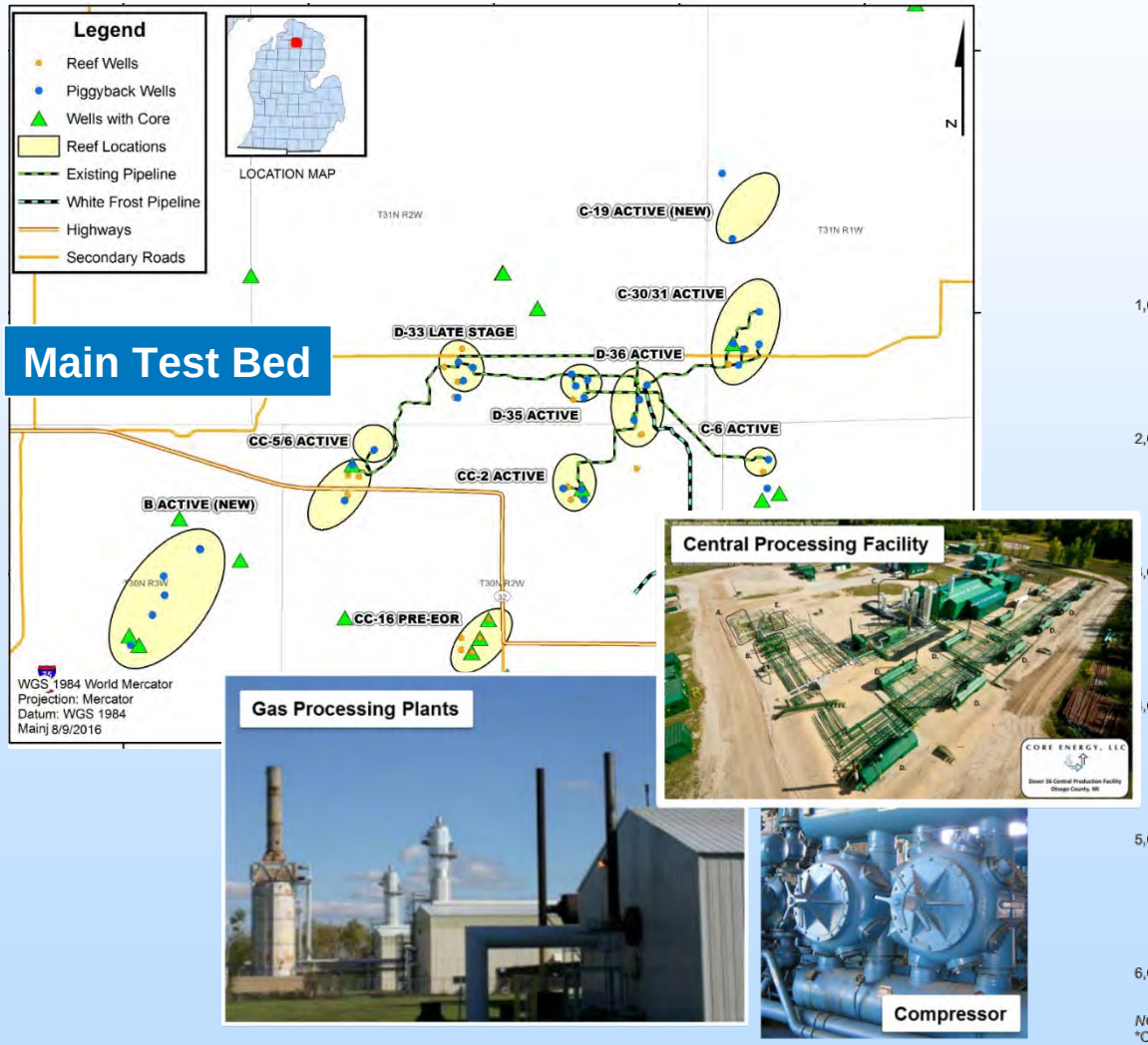
Objectives: Advance operational, monitoring, and modeling techniques needed to:

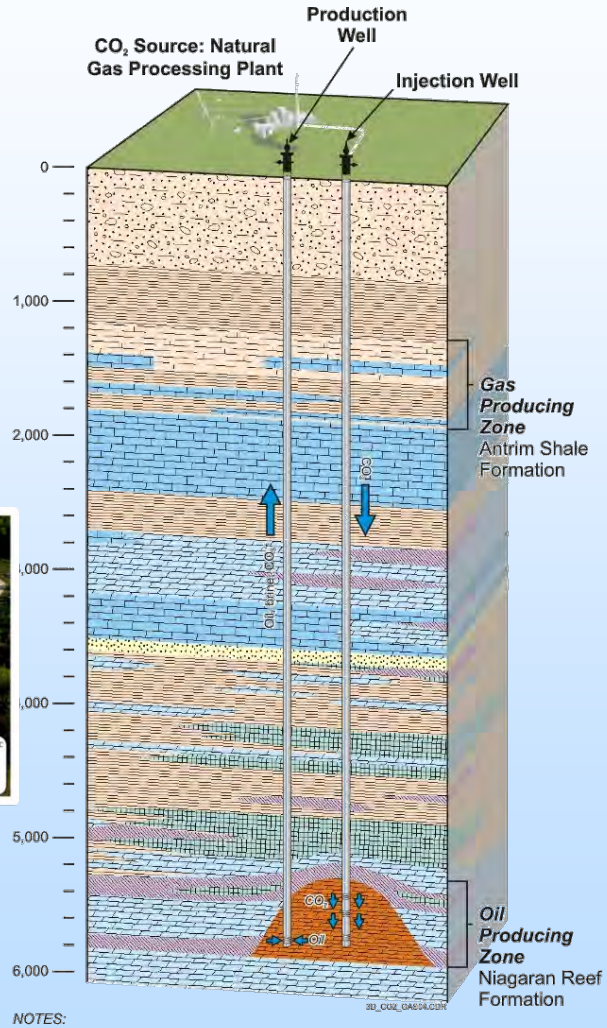
- Develop infrastructure for wide-scale CO_2 sequestration deployment
- Address public concerns such as leakage and long-term storage security
- Address other topics such as cost effectiveness and CCUS practicability



Large-Scale Injection Test

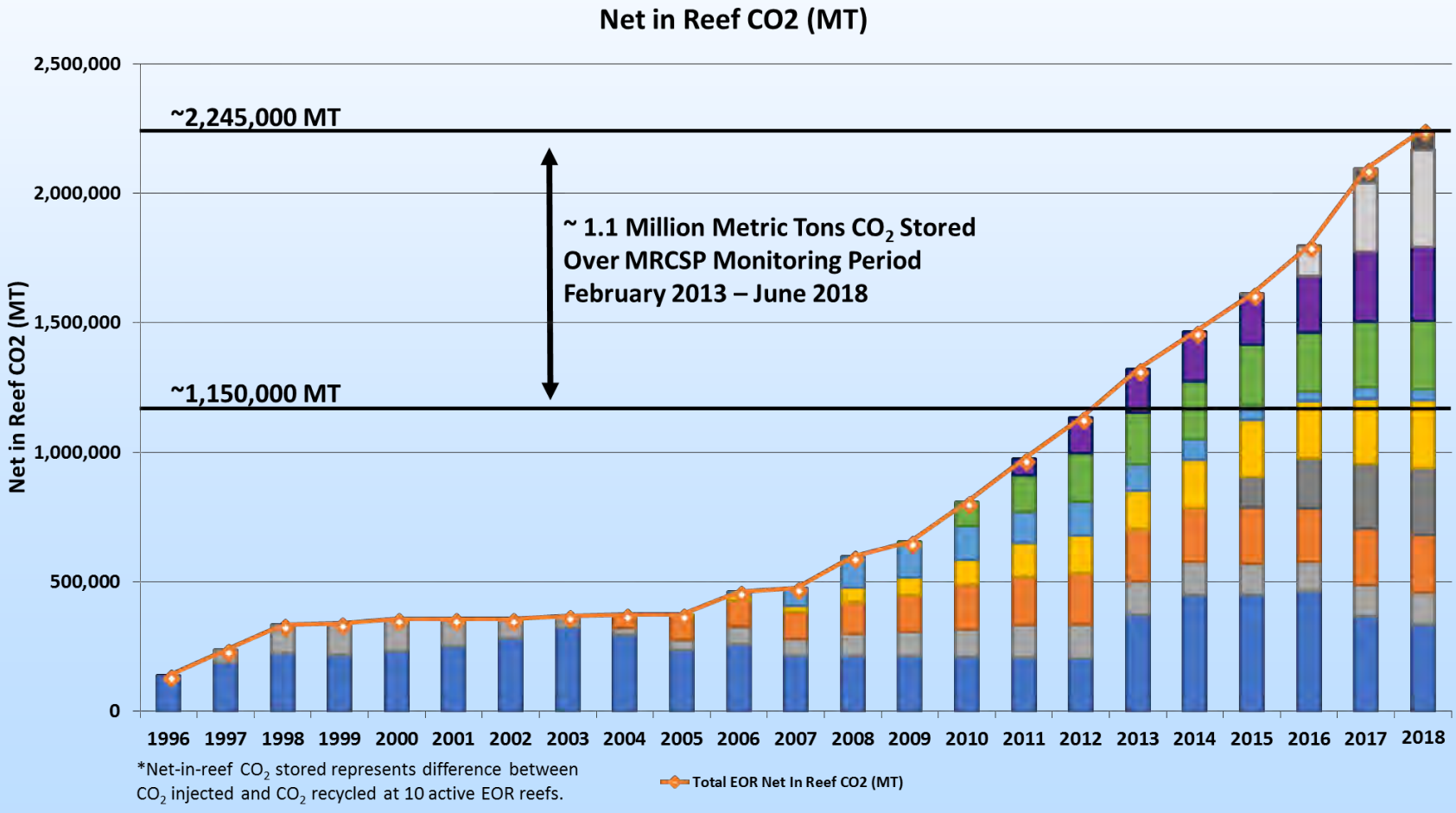
Geologic Setting in Michigan's Northern Niagaran Pinnacle Reef Trend





Injection Test Status Update

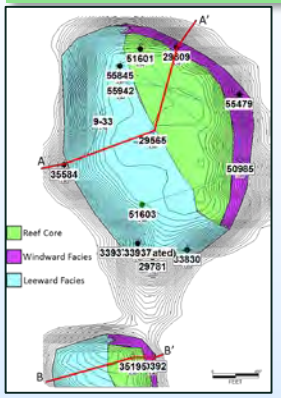
- ~1.1 MT tons CO_2 in net storage under MRCSP research
- >2 MT associated storage in 10 reefs over EOR lifetime since 1996



Large-scale Injection Test

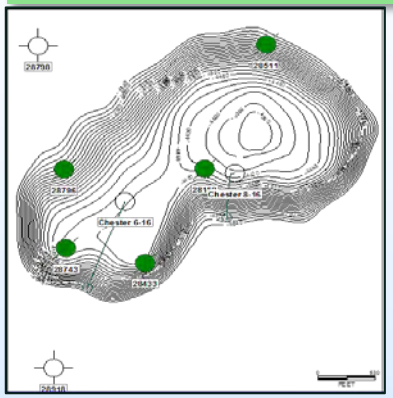
Key Reefs Vary in Setting and Operational History

Late-Stage Reef: Dover 33



1 Lobe
Operational since 1974
Primary Production + CO_2-EOR
MRCSP CO_2 Injection since 2013
- 1 CO_2 Injection Wells
- 2(+1) Monitoring/ Production Wells

Chester 16



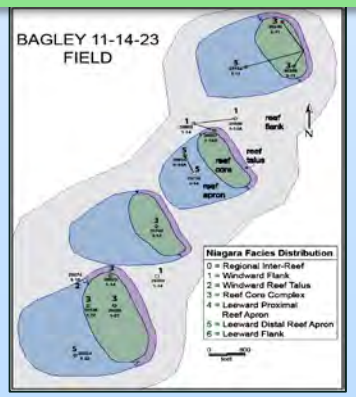
2 Lobes
Operational since 1971
Primary Production + Water EOR
MRCSP CO_2 Injection since 2017
- 1 CO_2 Injection Well
- 1 Monitoring Well

Charlton 19

2 Lobes
Operational since 1988
Primary Production
MRCSP CO_2 Injection 2015-2017
- 1 CO_2 Injection Wells
- 2 Monitoring Wells

Currently in CO_2-EOR

Bagley

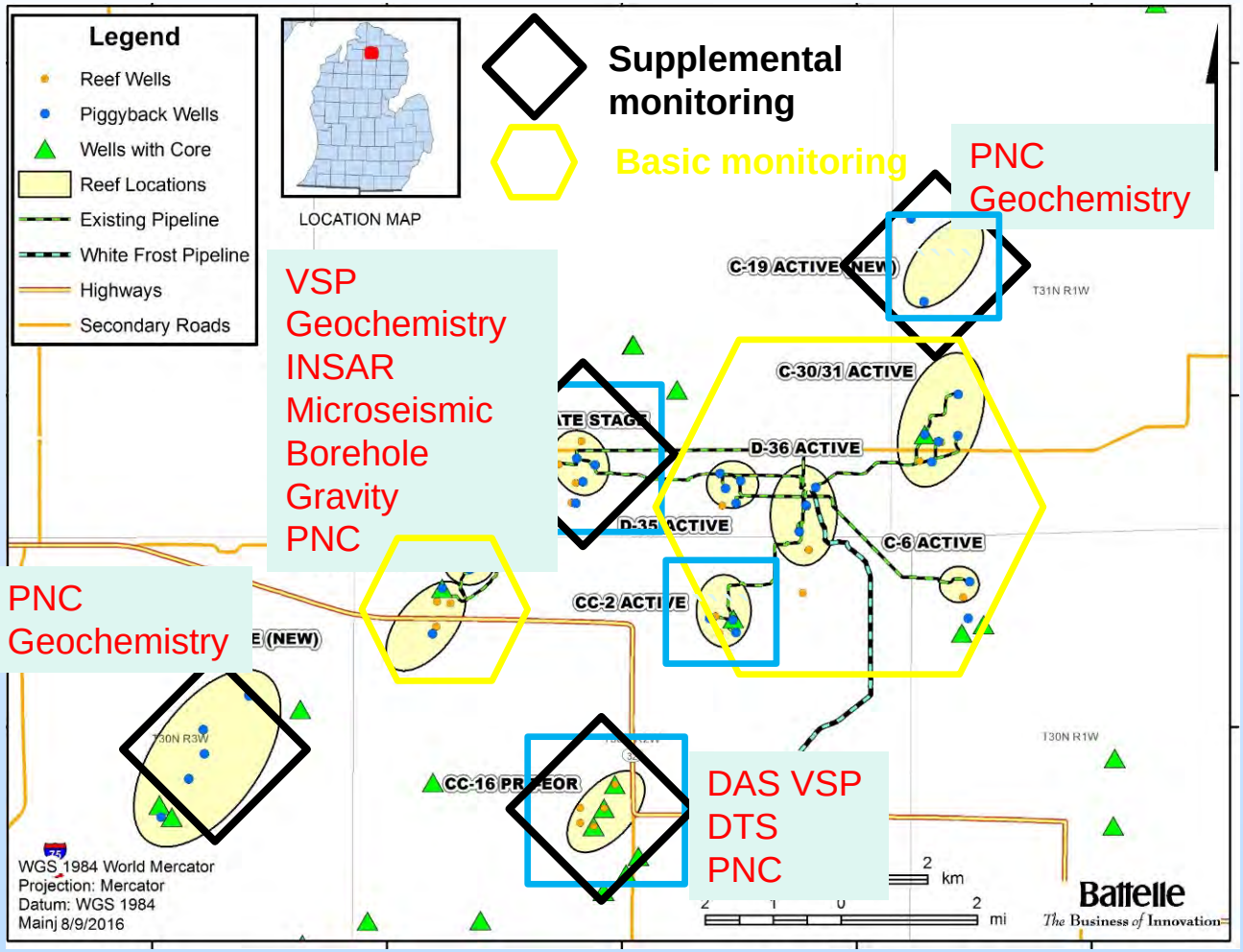


4 Lobes
Operational since 1973
Primary Production only
MRCSP CO_2 Injection since 2015
- 3 CO_2 Injection Wells
- 4 Monitoring Wells

Characterization and Monitoring Program

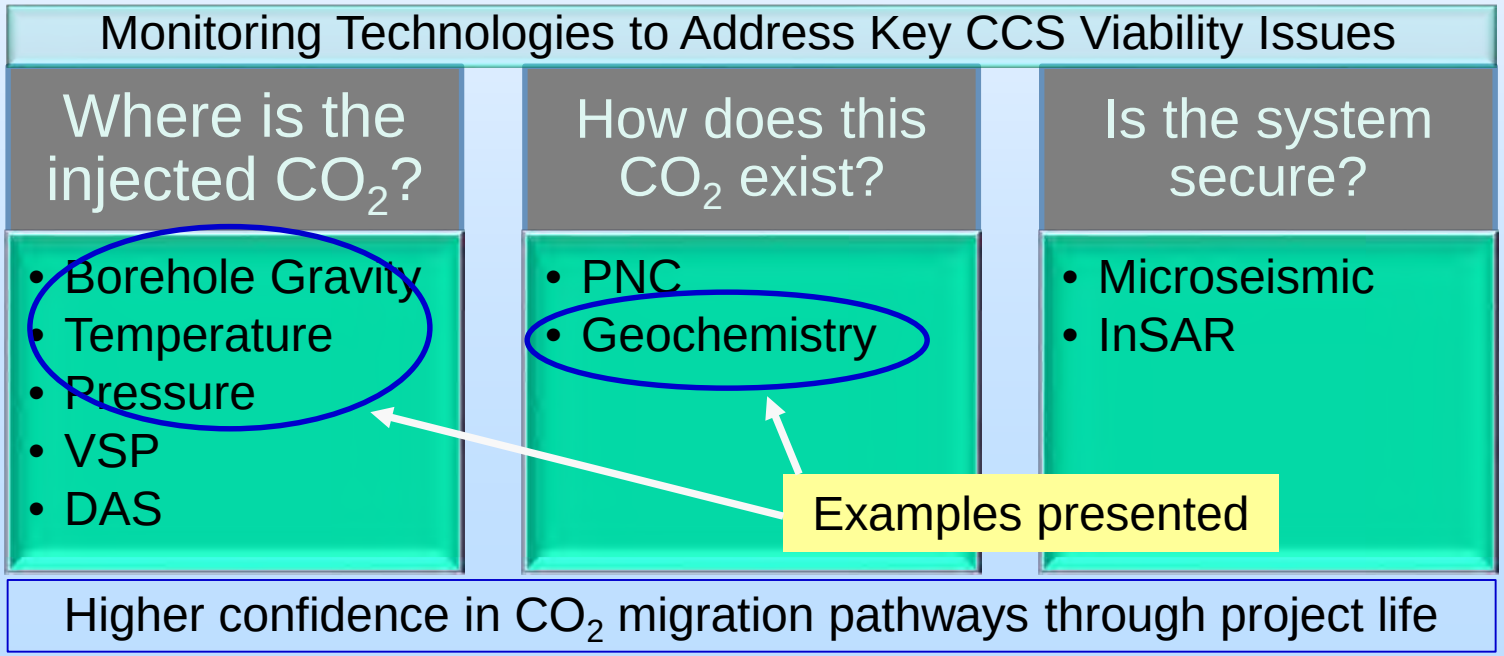
Well characterization data

- 10 reefs various stages of EOR
- All reefs monitored for CO_2 injection and reservoir pressure
- Additional monitoring on selected reefs
- Characterization (logs, cores, testing) in new wells



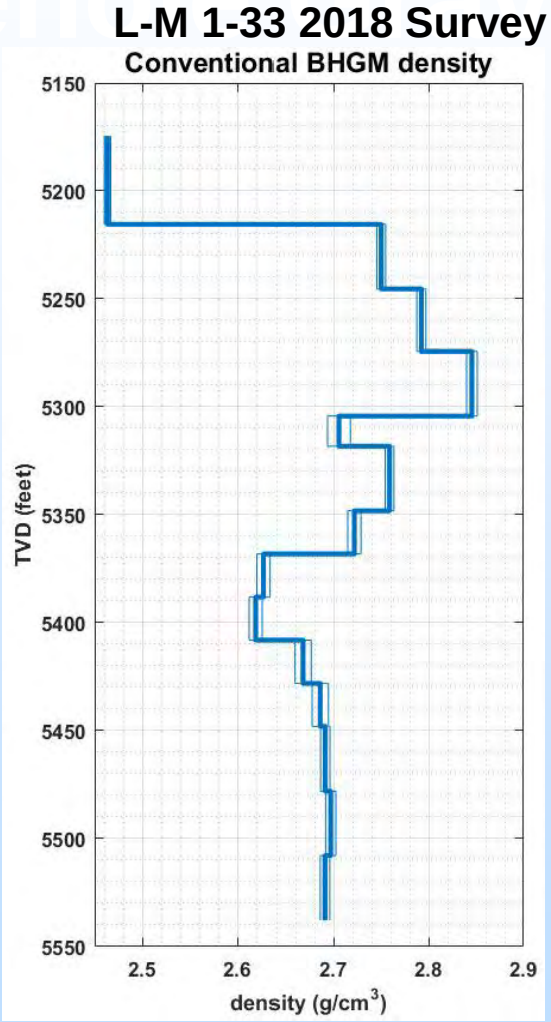
Monitoring Objectives

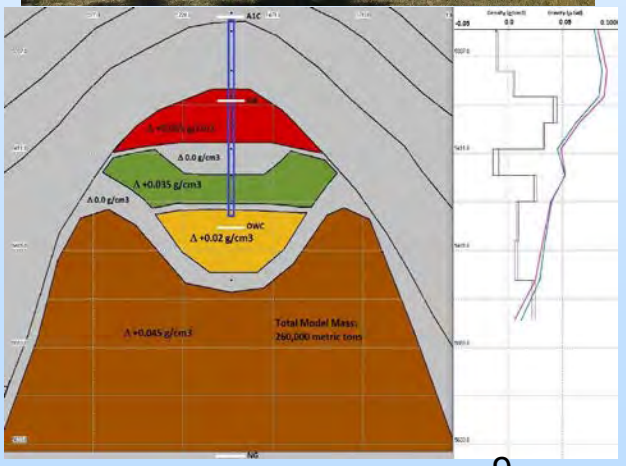
- Operational accounting for CO_2 during EOR
- Monitoring options to track and image plume
- Ensuring containment effectiveness by monitoring CO_2 storage integrity and retention



Borehole Gravity Monitoring

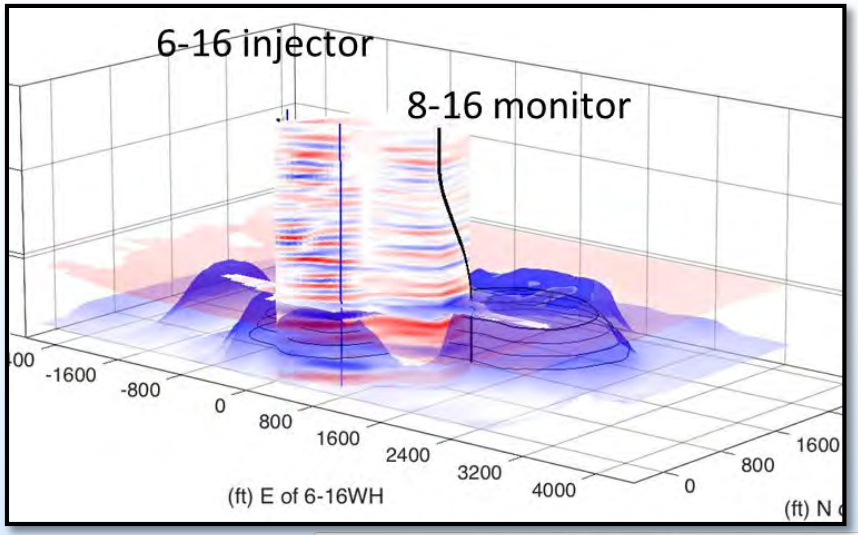
- Late Stage Reef
- Three surveys completed
  - Baseline – Pre-MRCSP CO_2 (Jan 2013)
  - First Repeat – 270K tonnes CO_2 (Sept 2016)
  - Second Repeat – 130K tonnes CO_2 (July 2018)
- 2016 data shows 90 µGal (0.05 g/cm^3) increase at top of reservoir – consistent with the mass of CO_2 injected
- Processing of 2018 survey underway

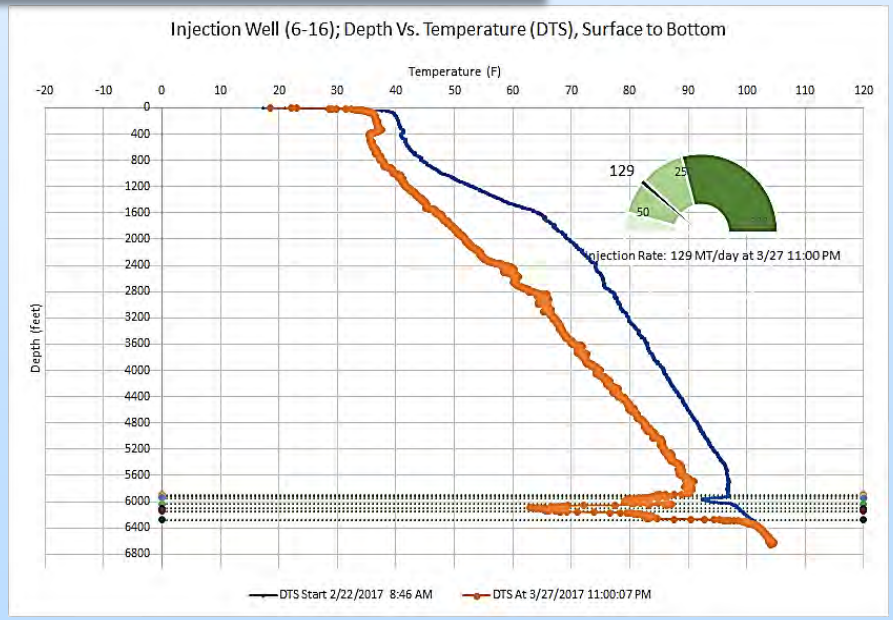


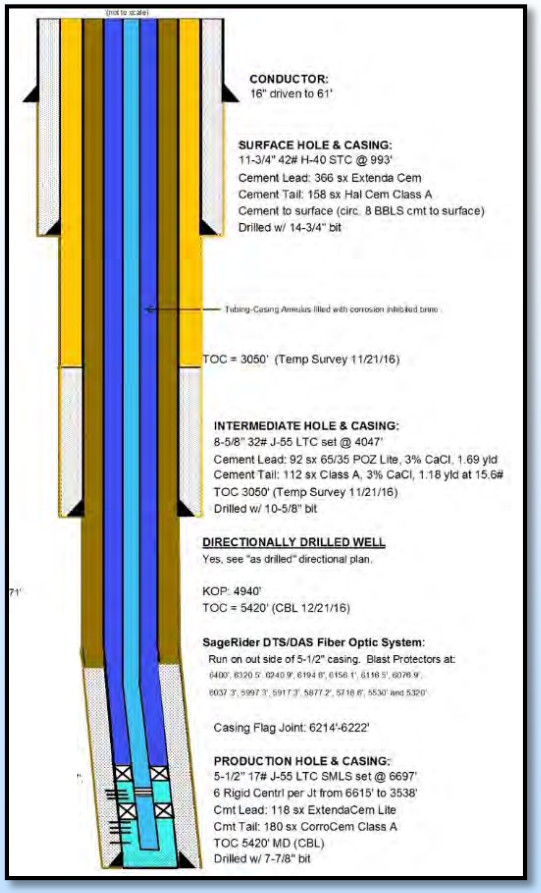


New EOR Reef 1: Chester-16

Advanced Monitoring - Distributed Fiber Optic Systems





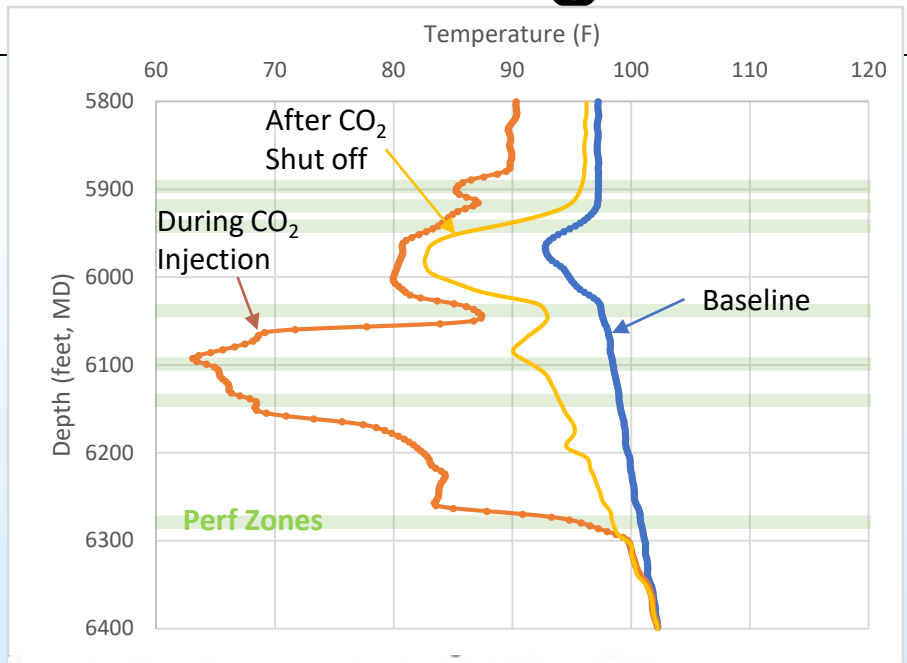


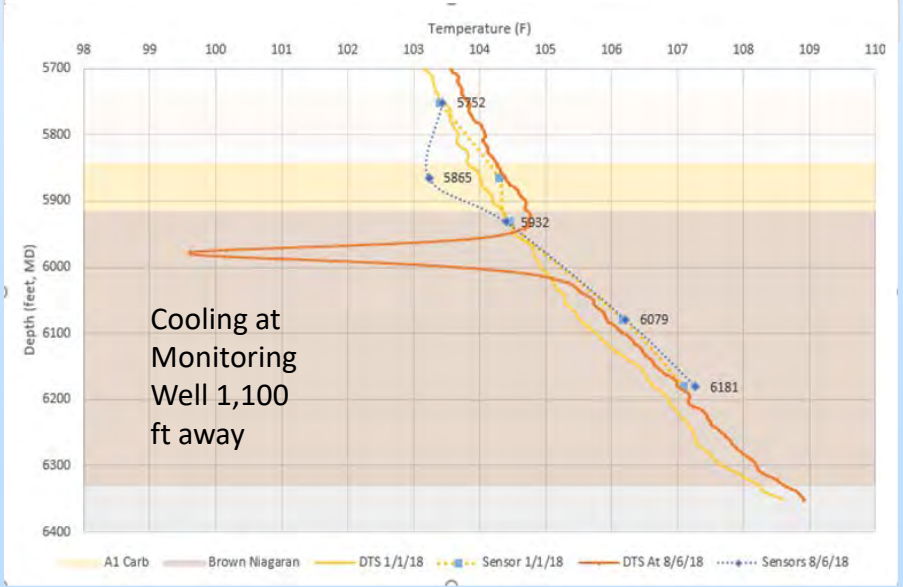
*Injection started in Jan 2017

DTS Temperature Monitoring

- New Reef
- Temperature data recorded continuously with DTS
- Injection well and monitoring well
- Cooling in injection well indicates injection intervals.
- Cooling in monitoring well shows CO_2 breakthrough

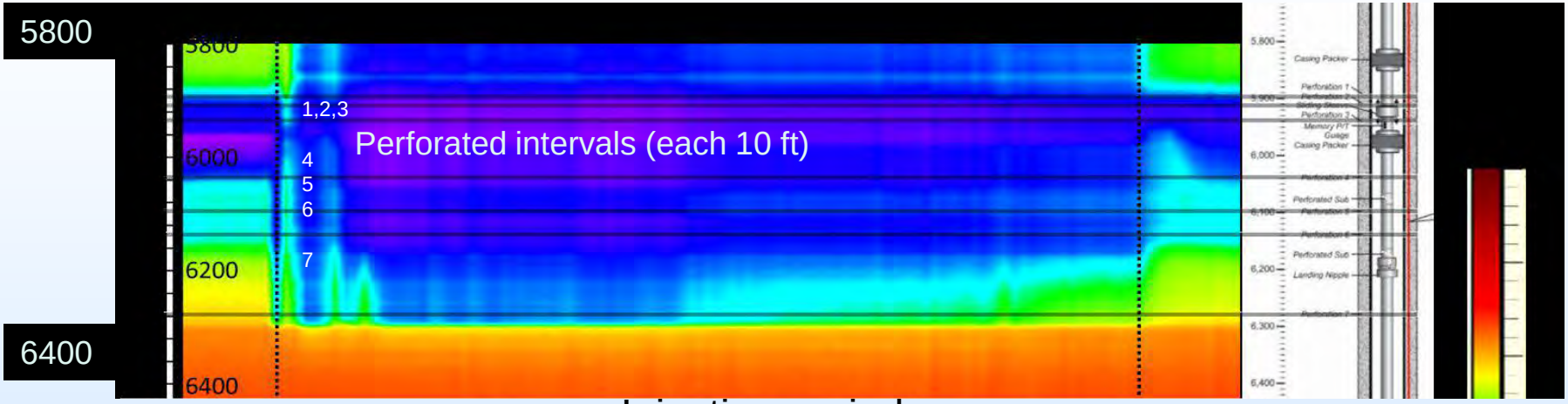
One of the first examples of CO_2 breakthrough using temperature data





DTS Monitoring (cont'd)

Warmback & Differential Temperature Analysis

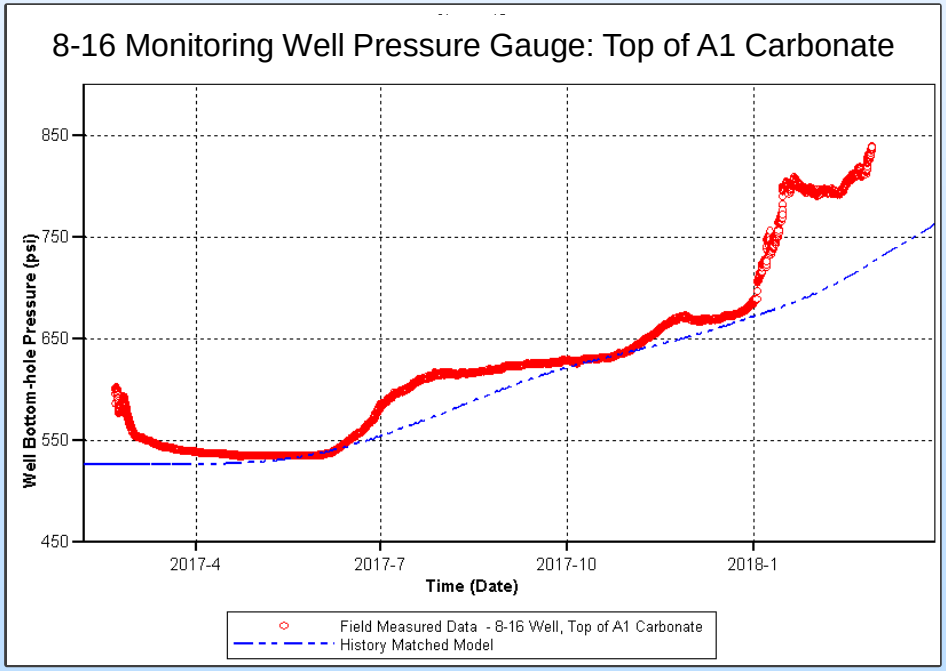


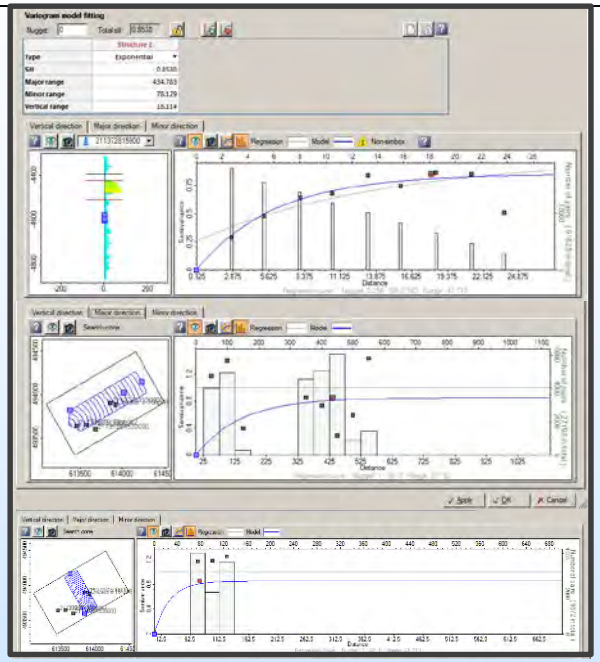
- "Warmback" analysis – how quickly formations warm back to reservoir temp after injection stops
- Differential temperature analysis – with some reference depth-temperature
- Identify perforated zones which received CO_2

Blue color (cooling) during shut-in periods provides more reliable indicator of which perf zones took CO_2

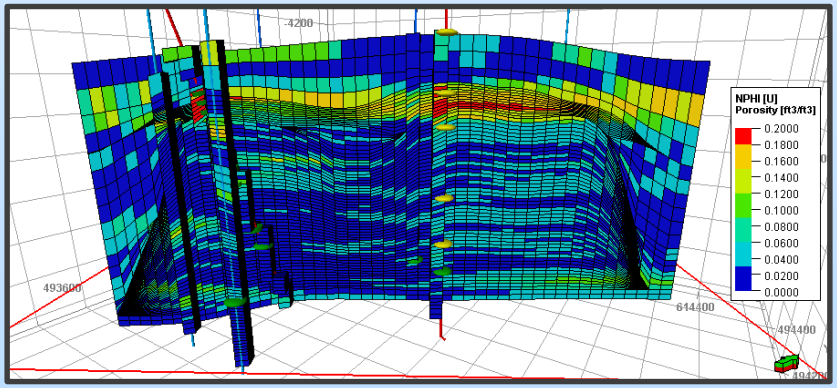
Dynamic Modeling of CO_2 Injection
(Chester-16)

- Model successfully reproduced *reservoir* behavior during primary and waterflood production.
- Pressure response at monitoring well during CO_2 injection adequately replicated.





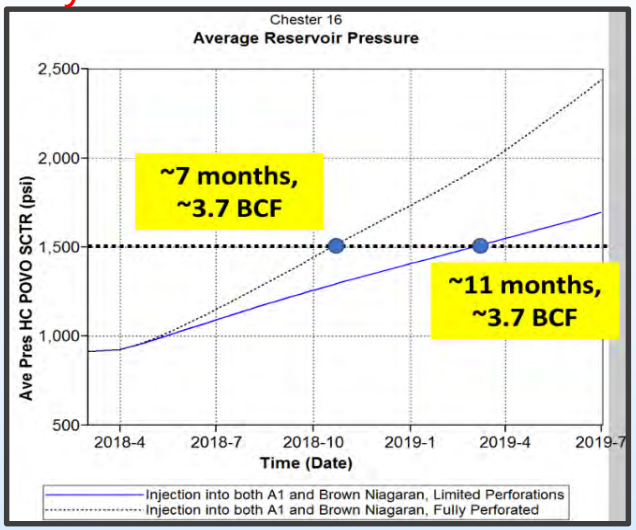
Geostatistics-Based Static Earth model



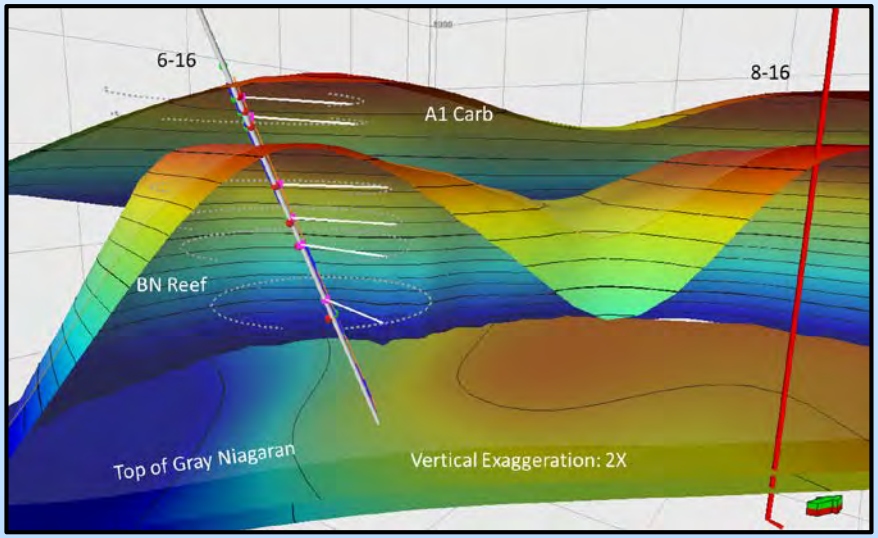
Using Model to Evaluate Alternate Engineering Solutions to Improve CO_2 Injectivity

- Increasing the number of perforations provides only marginal improvement
- Drilling radial "tunnels" is more effective; performs similar to a horizontal well

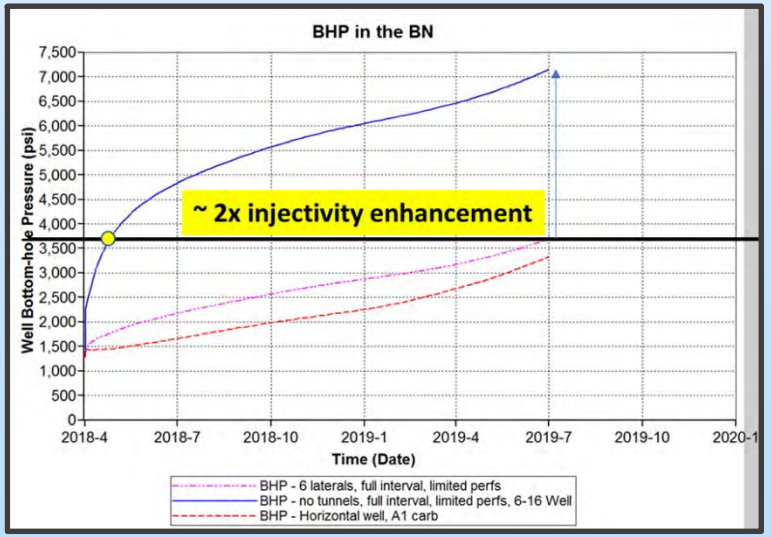
Injectivity with Increased Perforations



Radial Tunnels are small open boreholes drilled laterally from existing well



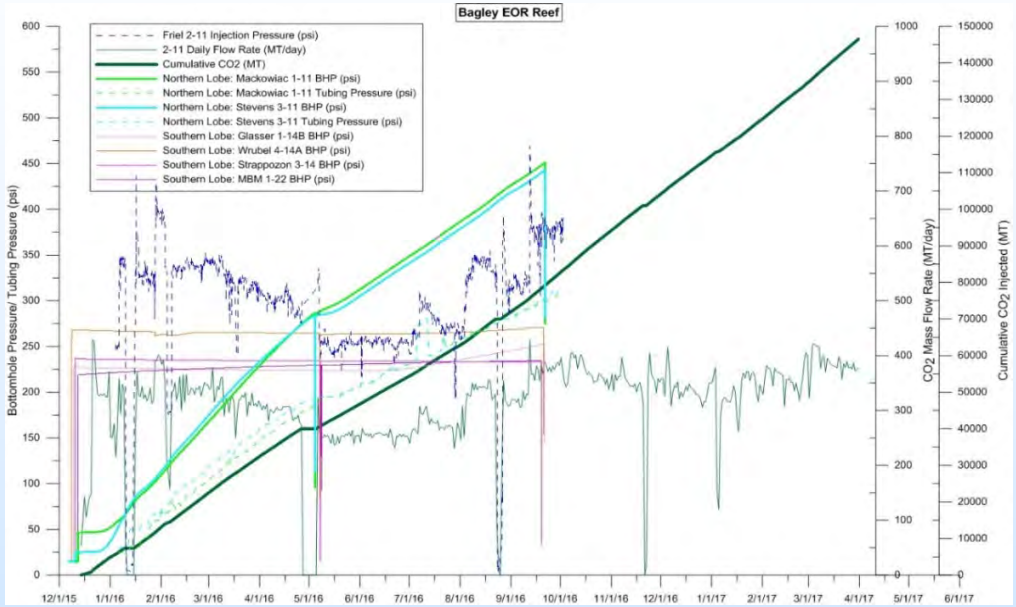
Injectivity with Radial Tunnels

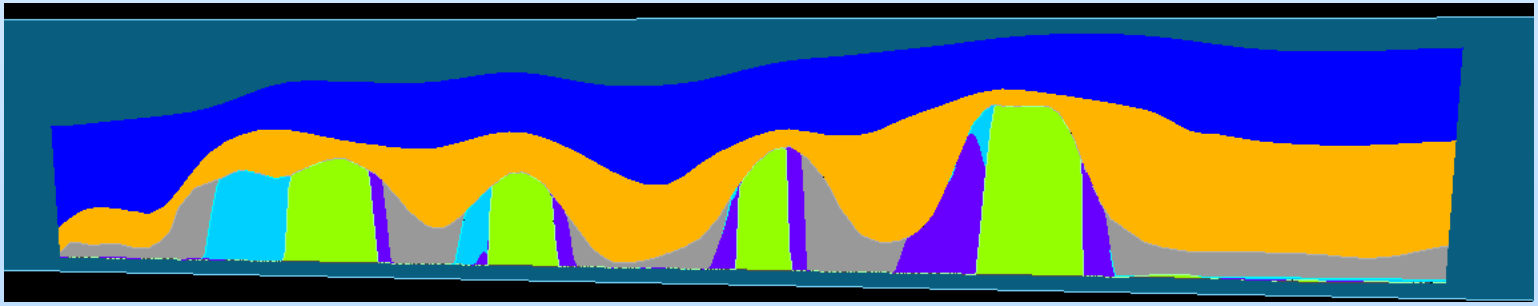


New EOR Reef 2: Bagley

Pressure Data Analysis to Infer Complex Reef Hydraulic Properties

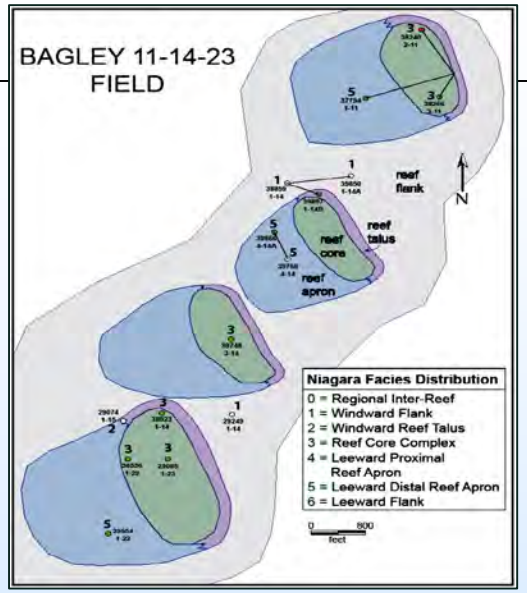
- Reef with 3 to 4 partly connected lobes having multiple CO_2 injection and monitoring wells
- Suite of basic and advanced monitoring deployed
- Continuously monitored pressure data subjected to hydraulic interference analysis to estimate inter-lobe connectivity



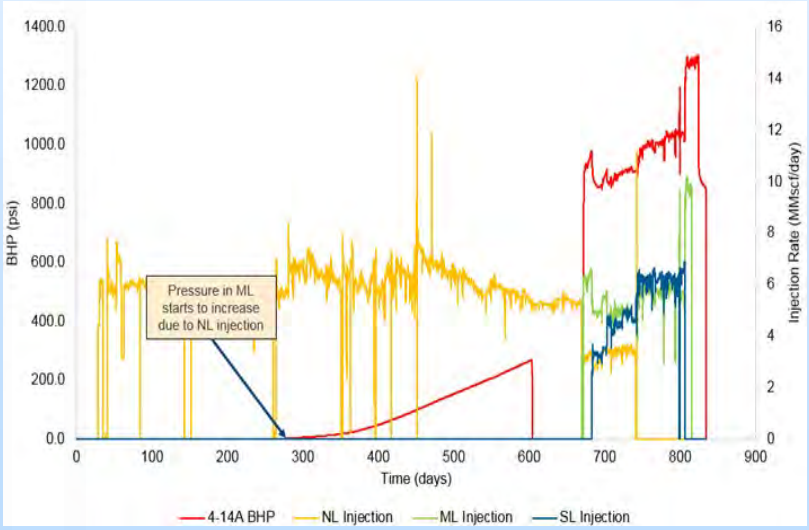


Pressure Interference Analysis

- Evident hydraulic communication between multiple lobes in the reef
- Analysis of delay time and well spacing allows calculation of reservoir diffusivity and permeability

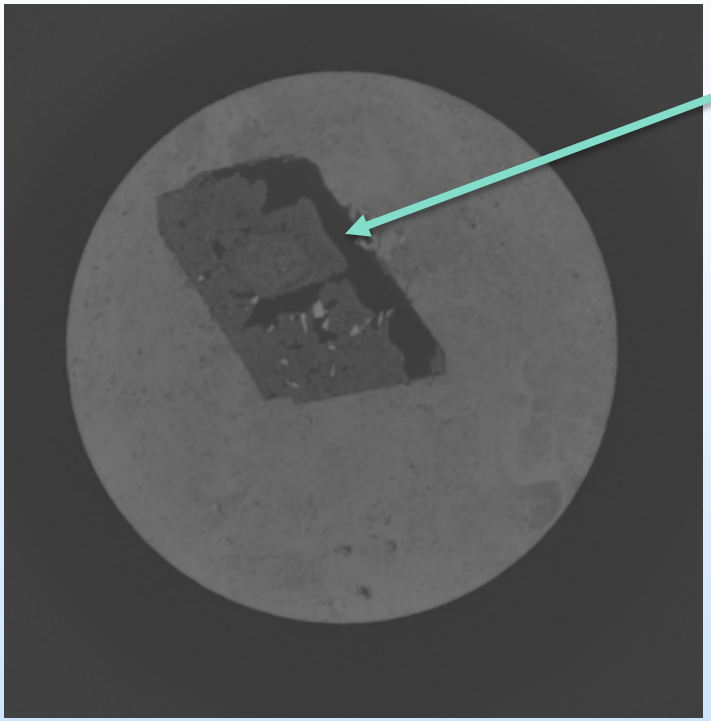


Injection Lobe	Injection well Name	Response well Name	Arrival time (days)	Distance (ft)	Diffusivity (ft^2/s)	Permeability (md)
North	Friel 2-11	Mackowiac 1-11	13	1482	1.95	162
		Stevens 3-11	15	1200	1.11	92
		Glasser 1-14B	182	3252	0.67	56
		Wrubel 4-14A	228	4131	0.87	72
		Strappozon 3-14	555	6090	0.77	64
Middle	Wrubel 4-14A	Glasser 1-14B	--	1312	-	-
South	MBM 1-22	Strappozon 3-14	38	1624	0.80	67



Pressure in middle lobe injection well showing effect of injection in northern lobe

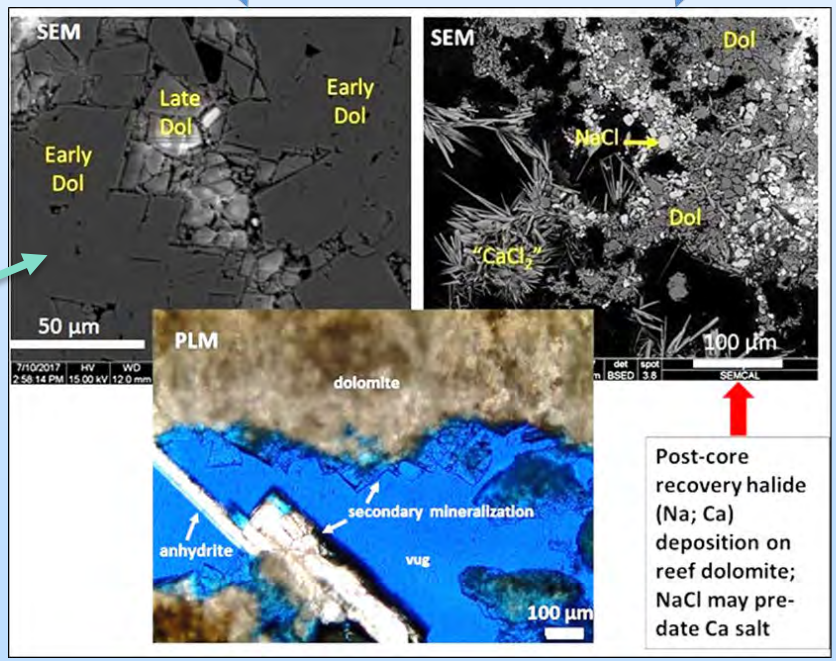
Geochemical Monitoring: Visualization of pore-scale CO_2 behavior



One XCT shows the formation of complex secondary mineralization within a rhombohedral-shaped vug (black) in dolomite (light gray groundmass).

"Early Dol" is primary rock matrix; "Late Dol" is secondary pore-filling mineral.

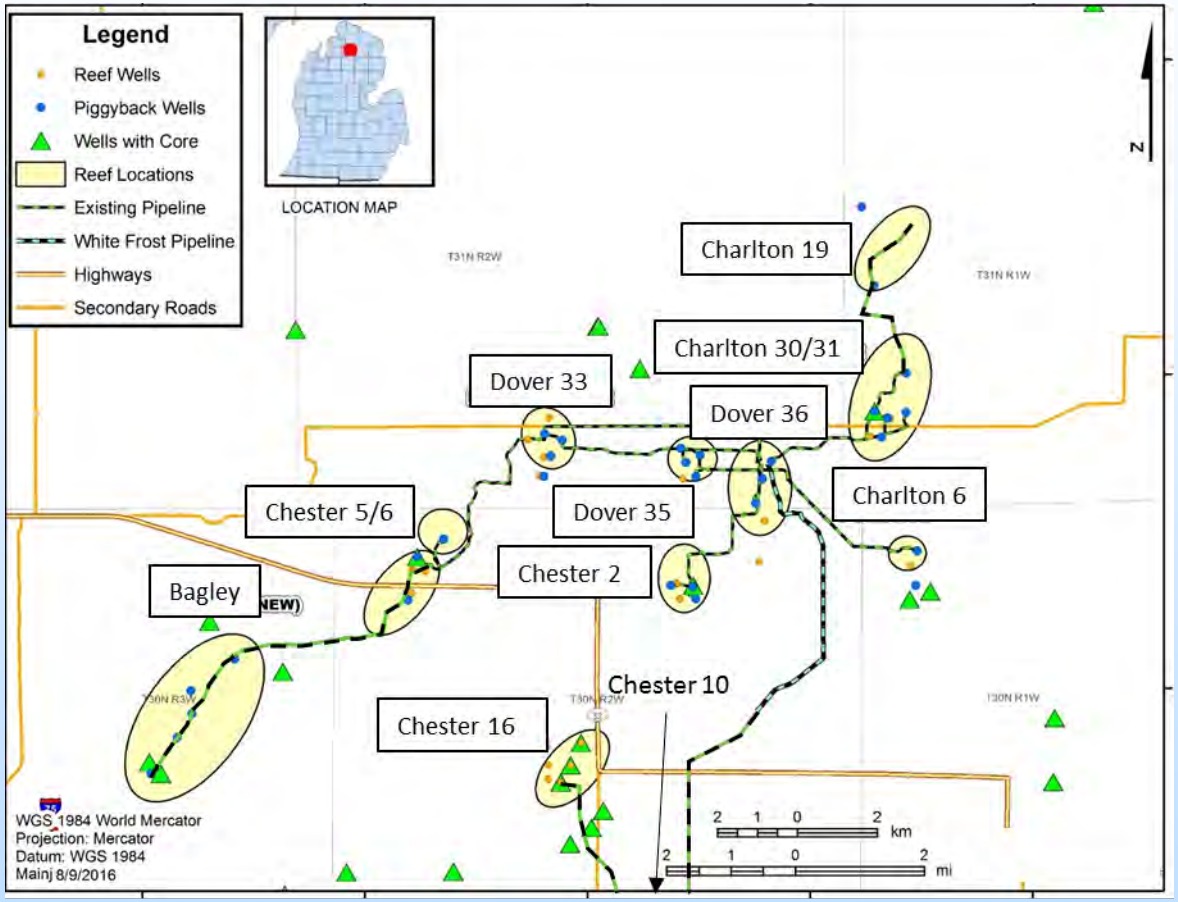
Black is pore space; granular and splinter materials are secondary minerals



Microanalysis of individual crystals with SEM (EDX) reveals sylvite (KCl), calcium chloride, anhydrite ($CaSO_4$), and barite ($BaSO_4$). In addition, a low-Mg-Ca carbonate is observed in SEM as a pore-filling material.

Monitoring, Reporting & Verification (MRV) Plan

Reef	Date Initiated
Dover 33	1996
Dover 36	1996
Dover 35	2004
Charlton 30/31	2006
Charlton 6	2008
Chester 2	2009
Chester 5	2011
Charlton 19	2015
Bagley 11-14-23	2015
Chester 16	2017

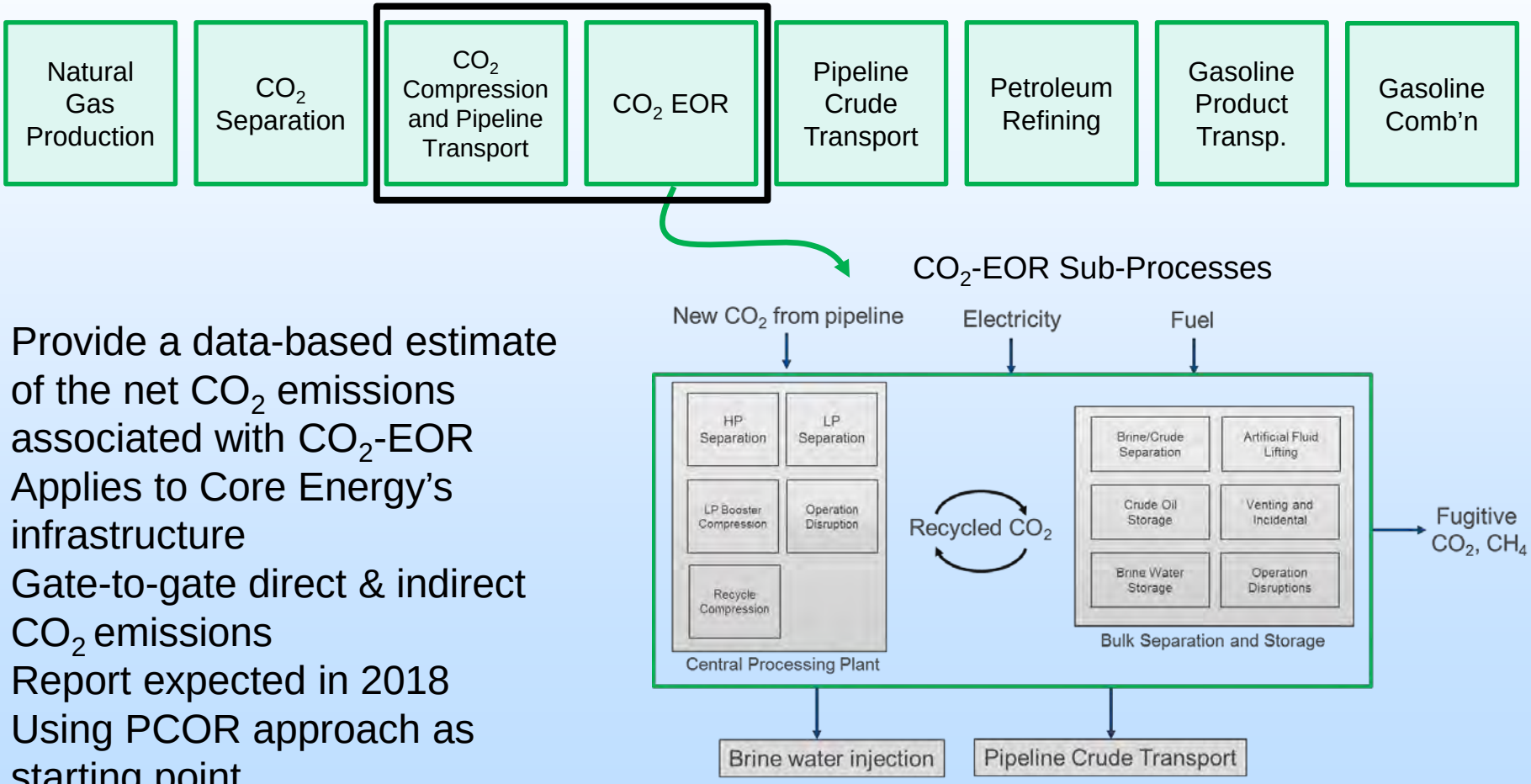


Draft MRV Plan (Subpart RR, EPA):

- Project Description
- Delineation of Active & Maximum Monitoring Area
- Evaluation of Leakage Pathways
- Monitoring Baselines
- EPA Mass Balance Equations

Life Cycle Assessment of CO_2-EOR

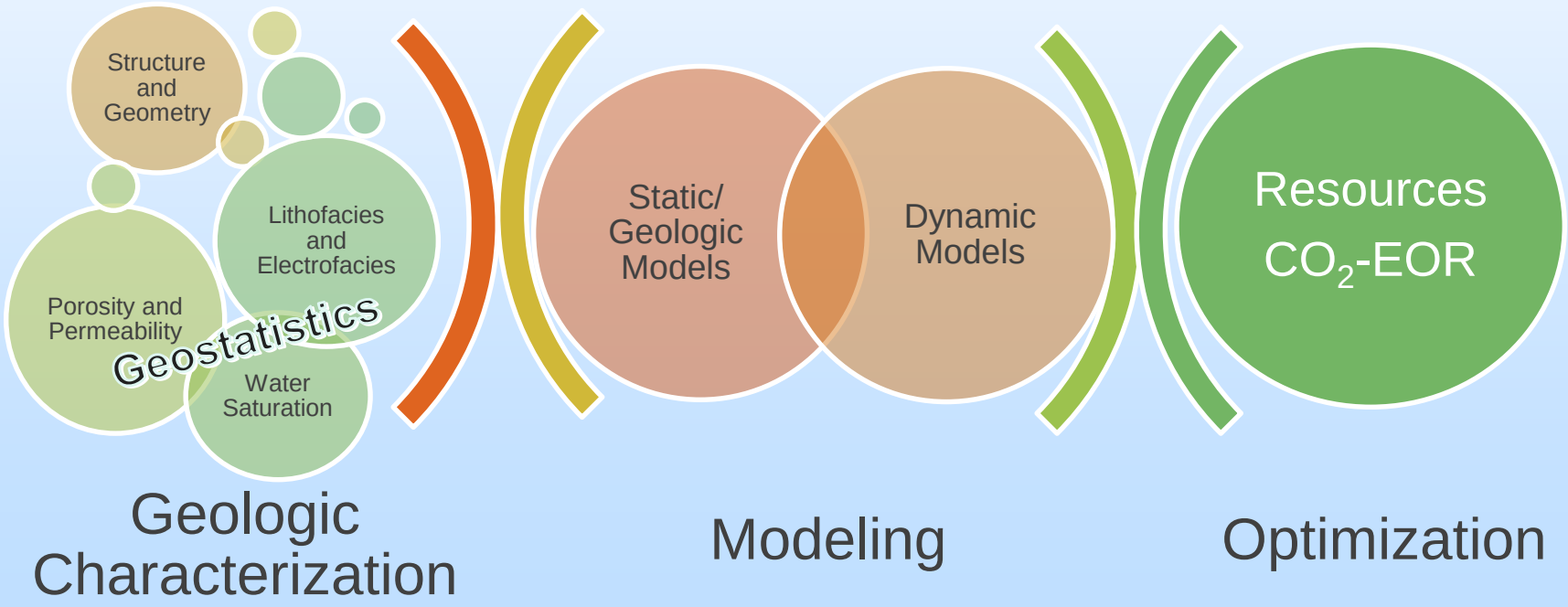
Full "cradle to grave" representation of CO_2-EOR



- Provide a data-based estimate of the net CO_2 emissions associated with CO_2-EOR
- Applies to Core Energy's infrastructure
- Gate-to-gate direct & indirect CO_2 emissions
- Report expected in 2018
- Using PCOR approach as starting point

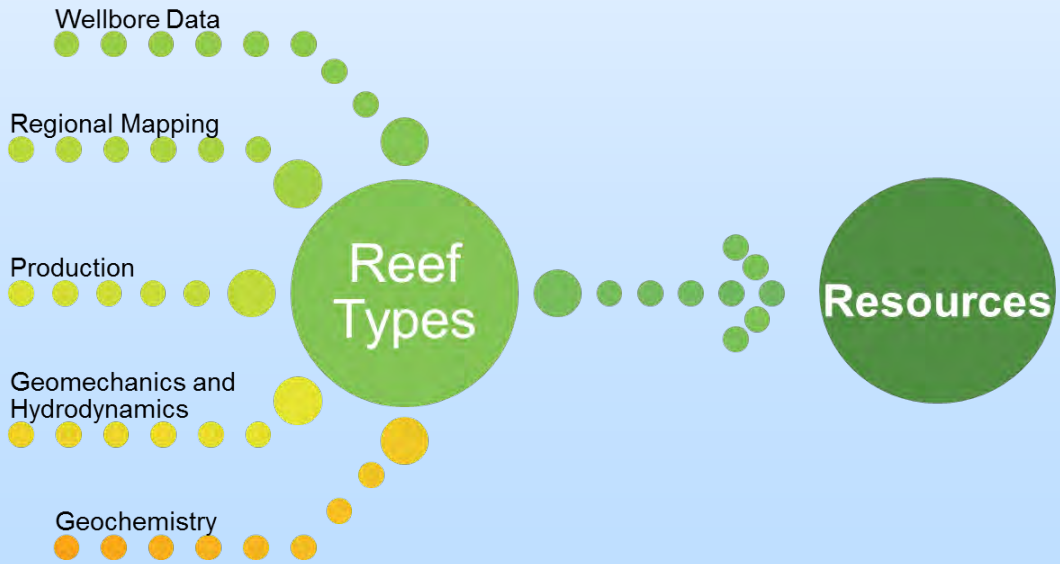
Improving Workflows for Reliable Geologic Modeling

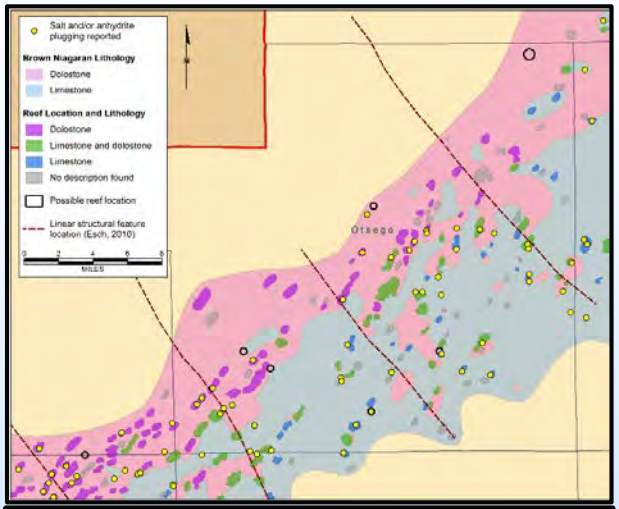
- Robust integrated workflow to better characterize pore space
- Higher confidence in CO_2 storage estimates and potential migration pathways

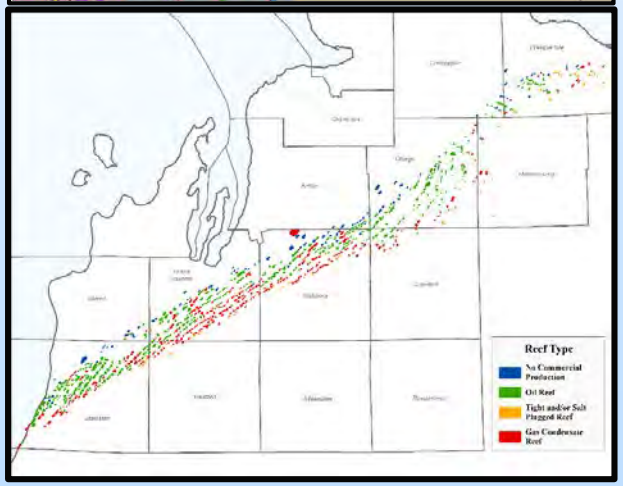


Expanding Geologic Characterization to Entire NPRT

- Building off of individual reef characterizations to >800 reefs in NPRT
- Comprehensive database of reefs, wireline logs, core, production, etc.
- Develop reef types to better estimate resources and feasibility in the region





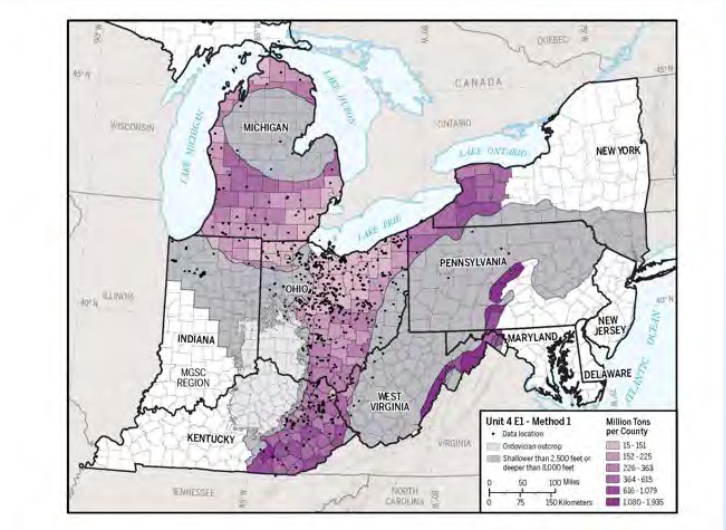


NPRT = Northern Pinnacle Reef Trend

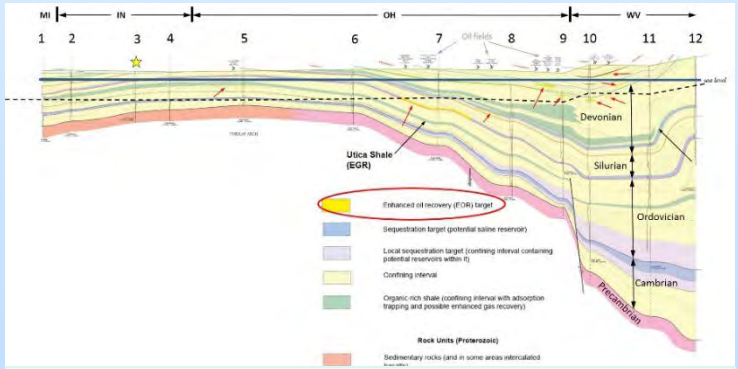
Overall Strategy of Regional Characterization– Demonstrate Geological Storage Potential

Establish fundamentals for CO_2 storage within the ten-state region and to qualify what volumes, how and where

- Assess the potential reservoirs and seals in the region, including offshore
- Determine the type of storage (saline, EOR or EGR reservoirs)
- Quantify the potential storage resources
- Generate products essential for siting, performance modeling, MVA



Storage resource estimate map



Regional cross section

Regional Characterization Task

- Establish fundamentals for CO_2 storage within the ten-state MRCSP region and to qualify what volumes, how and where
- Assess the potential reservoirs and seals in the region, including offshore
- Determine the type of storage (saline, EOR or EGR reservoirs)
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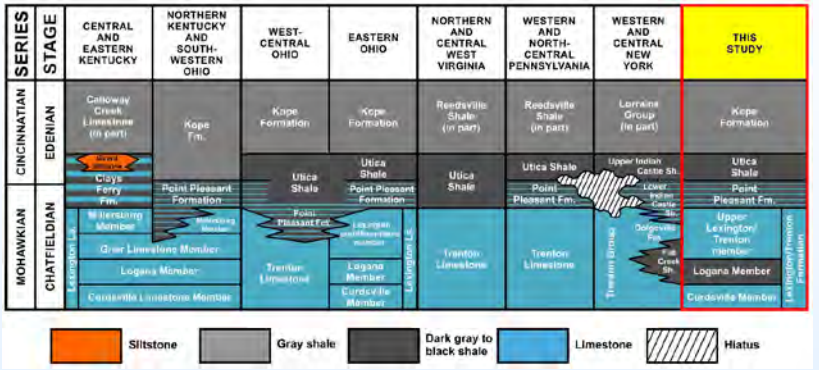
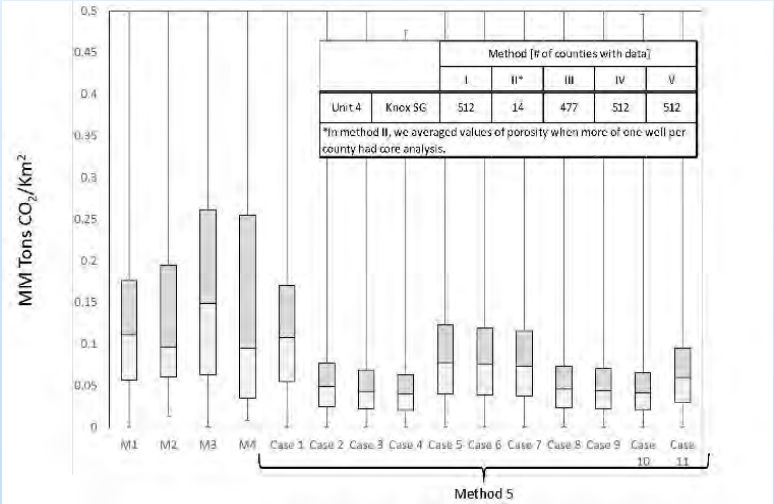


Modeling of Ordovician Utica Shale

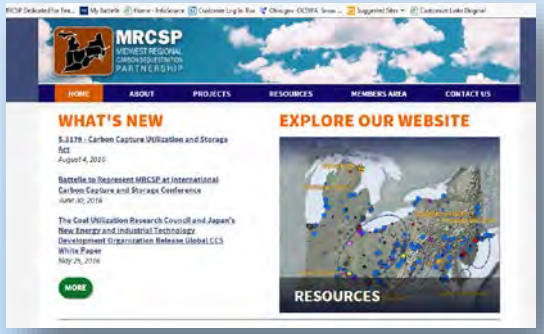


Box plots for differing SRE methods

MRCSP Outreach

Sharing Lessons Learned to Foster CCUS Development

Stakeholder Meetings



www.mrcsp.org

Factsheets and BPMs

Conferences and Papers

Message Mapping

MRCSP Outreach

FY2018 Highlights

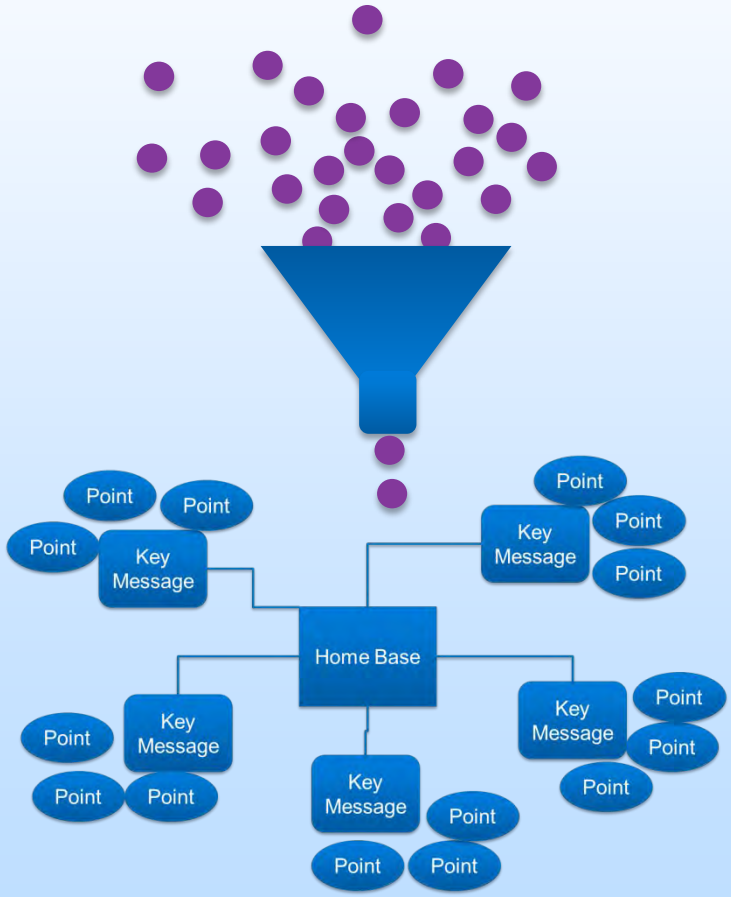
- Highly attended MRCSP Annual Meeting in Washington DC
- Participated in major conferences and workshops
  - Mexico EOR Conference
  - AIChE Conf. on regional carbon storage resource assessment
  - Harrisburg Univ. of Science and Technology CCUS meeting
  - Joint IEA/KAPSARC meeting on CO_2 EOR
  - CO_2 GeoNet program workshops and Tech Savvy conference
  - 3rd International Workshop on Offshore Geologic CO_2 Storage
  - IEAGHG Modelling and Risk Management Network Meeting
  - SPE/AAPG Regional Meetings
- Provided input into Permitting and Standards
  - DOE/EPA UIC meeting about permitting under MRCSP and related projects.
  - International Standards Organization (ISO) meetings
  - SPE SRMS System and Guidance Document

MRCSP Outreach

Next steps

MRCSP 2018 Meeting and Offshore Workshop, Annapolis, Nov 14-15

- Complete monitoring, including DAS-VSP and DAS-cross well surveys
- Final report – document lessons learned
- Series of topical reports and papers
- Outreach summary for policy makers
- Information sharing meetings with stakeholders
- Develop an extensive bibliography of papers and materials
- Facilitate public access to technical and scientific information using DOE's EDX and/or other tools
  - Phase II data already loaded on EDX



Accomplishments to Date

All Critical Milestones and Objectives On Track

- >1,100,000 metric tons net stored under MRCSP monitoring
- >2.4 M metric tons stored since start of EOR in 1996
- Completed injection at main test bed in late-stage reef
  - Performed microseismic monitoring in final injection stage
  - Post-injection PNC, microgravity, and VSP completed
  - Post-injection test well drilled and characterized
  - Returned to normal EOR operations, with continued accounting and pressure monitoring
- Added new EOR reefs with complex geology to monitoring
- Drilled new wells and initiated advanced fiber-optic monitoring
- Advancements in static and numeric modeling processes
- Developed performance metrics to assess storage capacity

Project Summary

- MRCSP Large-Scale Test >80% completed with diverse EOR field setting and variety of monitoring options
- Multiple monitoring options are being tested
- Both monitoring and modeling are essential for understanding performance – imperative to be able to do much with limited data
- Regional characterization helping identify new storage zones and estimate storage resources – setting stage for commercial scale CCS
- Results will contribute to developing standards and best practices, NRAP tools, CO_2 capacity estimation tools

Lessons Learned

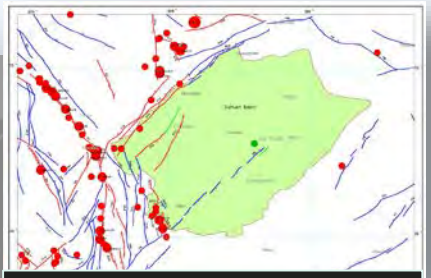
- CO_2 measurement/accounting can be performed with high level of confidence in an inter-connected multi-field EOR complex
- Storage potential in closed reservoirs evaluated, after active EOR ends – EOR to storage transition
- Geologic complexity within and across reefs affects CO_2 injection, migration, and storage
- Pressure monitoring remains the mainstay for managing injection operations and monitoring reservoir response
- Advanced monitoring technologies still require testing/validation for confident assessment of plume development
- Characterization-monitoring-modeling loop requires more research for cross-validation over the life-cycle
- A well developed CO_2-EOR regulatory/policy framework with financial incentives essential for enhanced associated storage

Synergy Opportunities

- Geomechanical Stress Assessment (FOA1829)
- CarbonSafe Phase I (Ohio, Michigan, Nebraska) and Phase II (Nebraska, Kansas) projects
- Mid-Atlantic Offshore storage assessment
- Well integrity and risk management
- Brine disposal and induced seismicity research
- Knowledge share with RCSPs on monitoring and modeling
- Testing NRAP models and CO_2 Screen tools
- Collaboration with international projects - South Africa, China, Mexico, Indonesia, Spain
- IEAGHG monitoring/Modeling Networks
- Input to DOE Best Practices Manuals

International Capacity Building – Extending MRCSP's Value

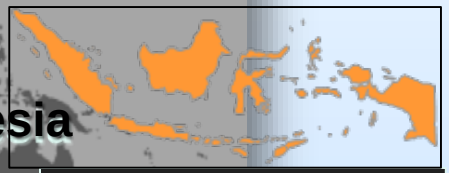
Mid-Atlantic Offshore Storage Capacity



China

Mexico

China



Indonesia

Indonesia – ADB Pilots

South Africa

South Africa Pilot CO_2 Storage Project

MRCSP experience used in local capacity building in international CCS projects with multilateral funding

Acknowledgements

Battelle's MRCSP Current Contributors – Mark Kelley, Srikanta Mishra, Matt Place, Lydia Cumming, Sanjay Mawalkar, Charlotte Sullivan, Priya Ravi Ganesh, Autumn Haagsma, Samin Raziperchikolaee, Amber Conner, Glen Larsen, Joel Main, Jacob Markiewicz, Isis Fukai, Ashwin Pasumarti, Manoj Kumar Valluri, Andrew Burchwell, Jackie Gerst, Rod Osborne, and others

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Ohio Development Services Agency's **Ohio Coal Development Office**

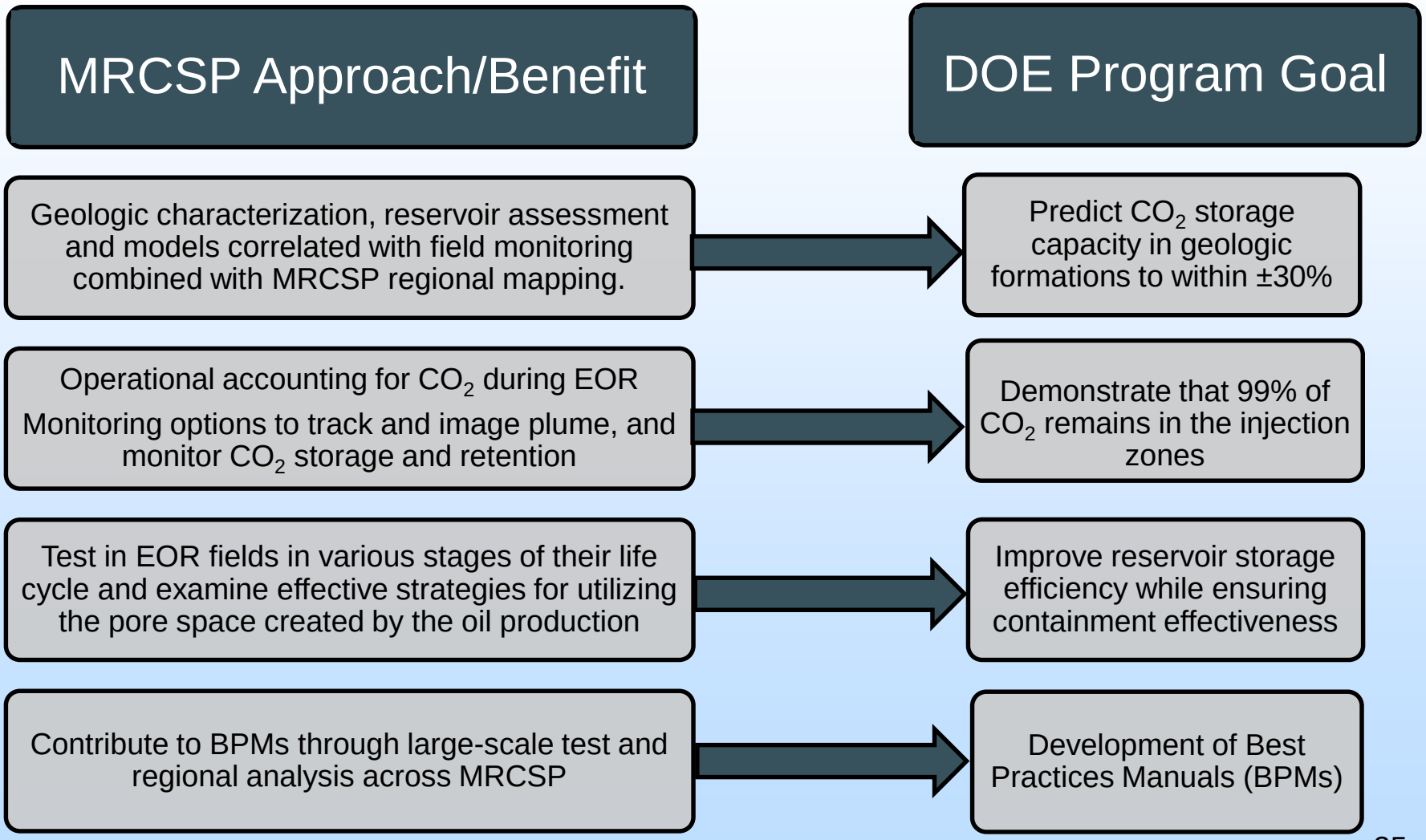
MRCSP's technical **partners, sponsors, and host sites since 2003**

The MRCSP Region's State **Geology Survey and University team members**

Partners over 15 years have helped make MRCSP successful

Appendix

Benefit to the Program



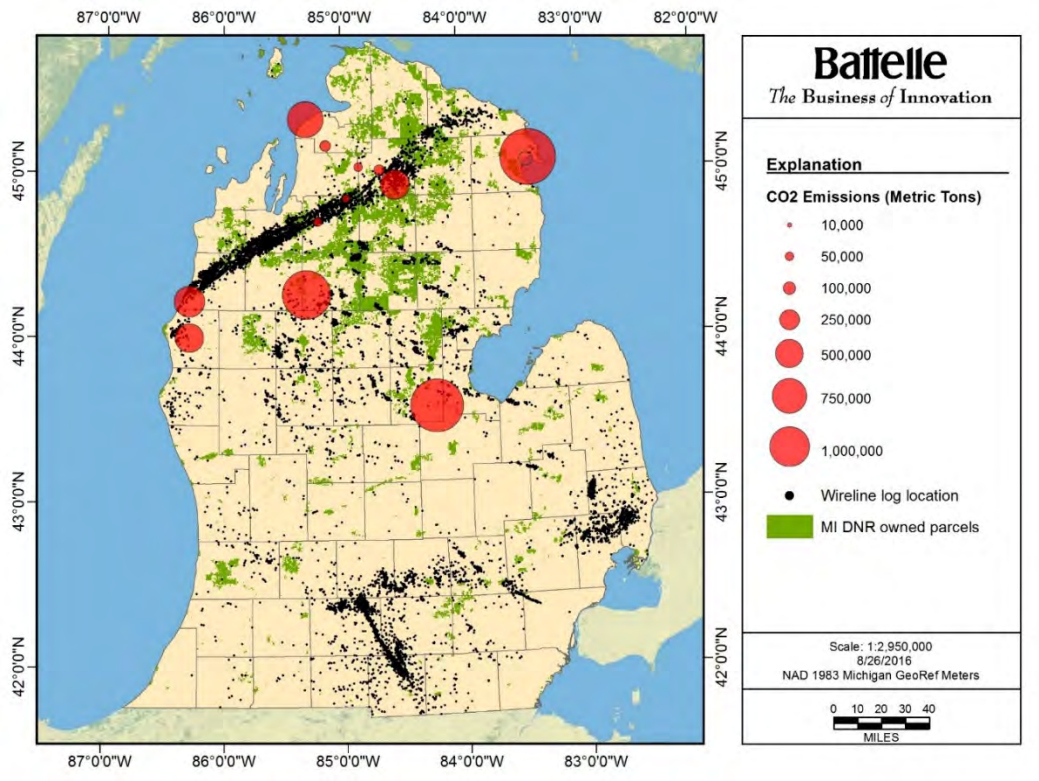
Project Overview

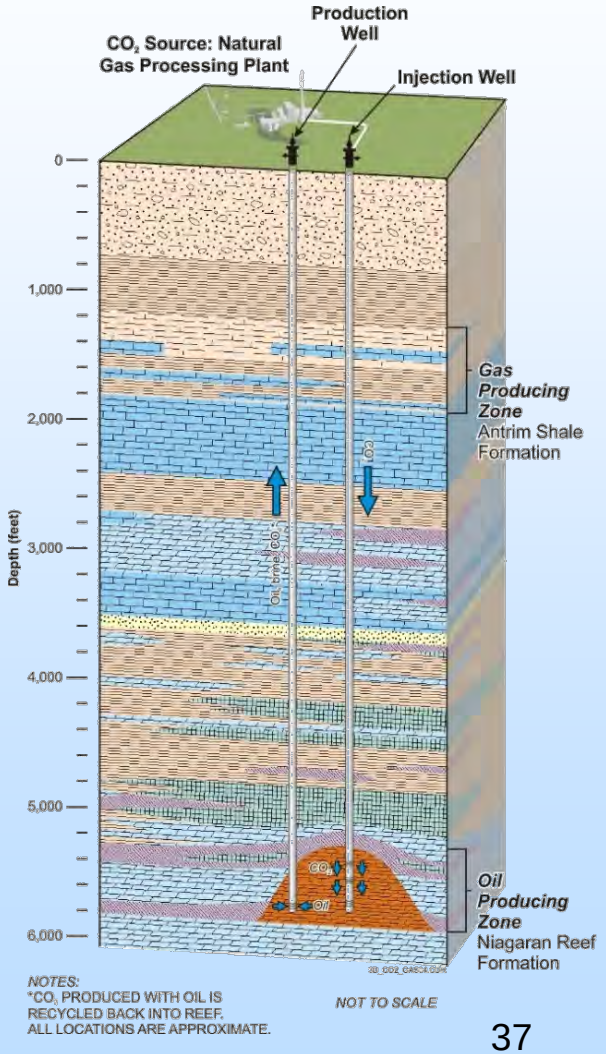
Goals and Objectives

- Describe the project goals and objectives in the Statement of Project Objectives.
  - How the project goals and objectives relate to the program goals and objectives.
  - Identify the success criteria for determining if a goal or objective has been met. These generally are discrete metrics to assess the progress of the project and used as decision points throughout the project.

MRCSP Basin Large-Scale Injection

- Objective – Inject/monitor 1 million metric tons of CO_2 in collaboration with EOR operations.
- Evaluate CO_2 injectivity, migration, containment





Project Overview

Goals and Objectives

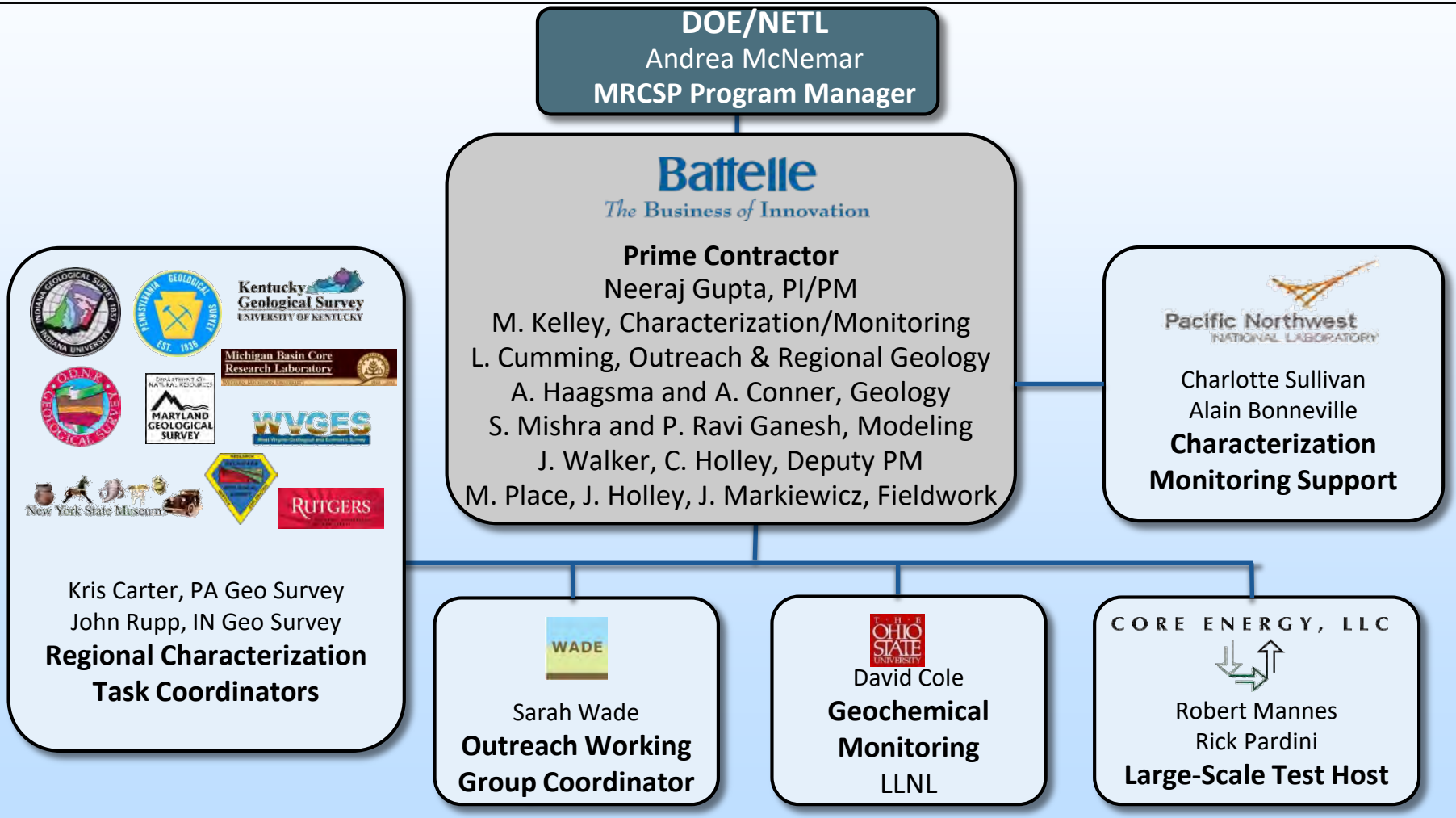
RCSP Goal	MRCSP Success Criteria
Goal 1 – *Prove Adequate Injectivity and Available Capacity*	• Success measured by injecting 1 million tonnes of CO_2 in CO_2-EOR fields within permitted pressures • Pressure analysis and modeling used to evaluate and validate capacity
Goal 2 – *Prove Storage Permanence*	• Seismic and well data used to evaluate storage and containment zones • Monitoring wells used to measure containment over time within the reef and immediate caprock • Reservoir modeling to evaluate storage mechanism
Goal 3 – *Determine Aerial Extent of Plume and Potential Leakage Pathways*	• Monitoring portfolio employed to image and track the lateral and vertical plume migration. Success measured by using monitoring data to compare to and validate plume models

Project Overview

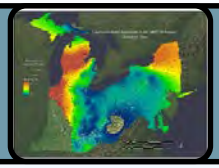
Goals and Objectives

RCSP Goal	MRCSP Success Criteria
Goal 4 – *Develop Risk Assessment Strategies*	• Risk assessment for events, pathways, and mitigation planning • Success will be measured by comparing predicted to actual field experience for all stages of the project
Goal 5 – *Develop Best Practices*	• Phase III builds on Phase II best practices in siting, risk management, modeling, monitoring, etc. • Key emphasis is on operation and monitoring and scale-up to commercial-scale
Goal 6 – *Engage in Public Outreach and Education*	• Extensive outreach efforts for both Phase II and Phase III sites as well as technology transfer and sharing • Phase III lessons learned contribute directly to the RSCP Best Practice Manual updates

Organization Chart



MRCSP Scope of Work Structured Around Six Tasks



Task 1

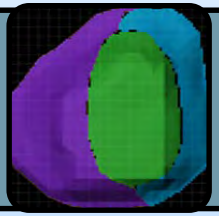
Regional Characterization: *Develop a detailed actionable picture of the region's geologic CO_2 storage resource base*

Task 2

Outreach: *Raise awareness of regional CO_2 storage opportunities and provide stakeholders with information about CO_2 storage*

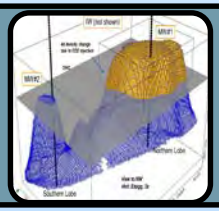
Task 3

Field Laboratory Using Late-Stage EOR Field: *Pressurize a depleted oil field with CO_2 injection to test monitoring technologies and demonstrate storage potential*



Task 4

CO_2 Storage Potential in Active EOR Fields: *Monitor CO_2 Injection and recycling in active EOR operations with different scenarios*



Task 5

CO_2 Injection in New EOR Field(s): *Monitor CO_2 injection into an oil field that has not undergone any CO_2 EOR to test monitoring technologies and demonstrate storage potential*

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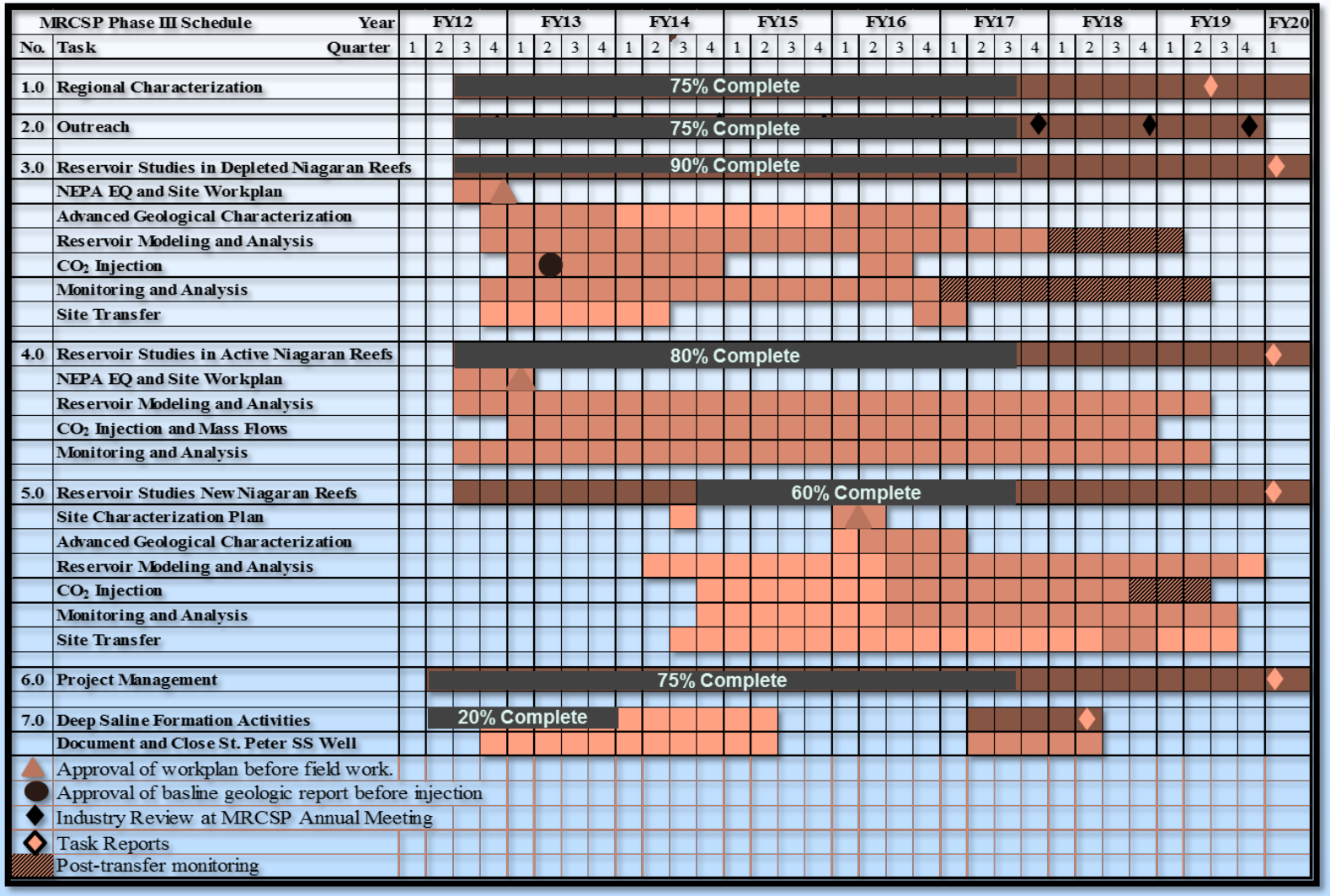
Task 6

Program Management

Gantt Chart


MRCSP Phase III Schedule
Year
No.
Task
Quarter
FY12
FY13
FY14
FY15
FY16
FY17
FY18
FY19
FY20
1 2 3 4
1.0 Regional Characterization
75% Complete
2.0 Outreach
75% Complete
3.0 Reservoir Studies in Depleted Niagaran Reefs
90% Complete
NEPA EQ and Site Workplan
Advanced Geological Characterization
Reservoir Modeling and Analysis
CO2 Injection
Monitoring and Analysis
Site Transfer
4.0 Reservoir Studies in Active Niagaran Reefs
80% Complete
NEPA EQ and Site Workplan
Reservoir Modeling and Analysis
CO2 Injection and Mass Flows
Monitoring and Analysis
5.0 Reservoir Studies New Niagaran Reefs
60% Complete
Site Characterization Plan
Advanced Geological Characterization
Reservoir Modeling and Analysis
CO2 Injection
Monitoring and Analysis
Site Transfer
6.0 Project Management
75% Complete
7.0 Deep Saline Formation Activities
20% Complete
Document and Close St. Peter SS Well
Approval of workplan before field work.
Approval of basline geologic report before injection
Industry Review at MRCSP Annual Meeting
Task Reports
Post-transfer monitoring

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- McCarren, H, Haagsma, A, Conner, A, Mawalkar, S, Mishra, S, and Gupta, N. 2018. Residual Oil Zone EOR Potential in the Northern Pinnacle Niagaran Reef Trend. 47th Annual AAPG-SPE Eastern Section Joint Meeting, Pittsburgh, PA.
- Haagsma, A., Conner, A., Larsen, G., Scharenberg, M., Goodman, W., Harrison, W., Main, J., Smith, V., Pasumarti, A., Modroo, A., and Gupta, N., Regional characterization of an oil-bearing reef complex for factors affecting assessment of associated CO_2 storage. 47th Annual AAPG-SPE Eastern Section Joint Meeting , Pittsburgh, PA.
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- Haagsma, A., Kelley, M., Gupta, N., Conner, A., Modroo, A., Sullivan, C., Rine, M., and Goodman, W., 2017, Impact of geologic diversity on static earth models in a CO_2-EOR reef complex, Presented at the Carbon Management Technology Conference, Houston, TX.
- Mawalkar, S., Kelley, M., Gupta, N., Place, M., Mansouri, M., Pardini, R., and Shroyer, B., 2017, Distributed Temperature Sensing (DTS) in a CO_2-EOR Complex, Poster Presented at Mastering the Subsurface through Technology, Innovation and Collaboration DOE NETL meeting, Pittsburgh, PA.
- Haagsma, et al., 2017, Regional Variability of Michigan Niagaran Reefs and the Impact on CO_2 Storage Resources, Poster Presented at Mastering the Subsurface through Technology, Innovation and Collaboration DOE NETL meeting, Pittsburgh, PA.
- Cumming, L., Place, M., Hare, J., Black, A., Gupta, N., Modroo, A., and Pardini, R., 2017, Field testing the applicability of borehole gravity for monitoring geologic storage of CO_2 within closed carbonate reef reservoirs, Poster Presented at Mastering the Subsurface through Technology, Innovation and Collaboration DOE NETL meeting, Pittsburgh, PA.
- Kelley, M., Miller, D., Modroo, A., and Gupta, N., 2017, Baseline DAS VSP of the Chester 16 field (reef), Michigan, Poster Presented at Mastering the Subsurface through Technology, Innovation and Collaboration DOE NETL meeting, Pittsburgh, PA.
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- Gupta, N., Osborne, R., Holley, C., Lohner, T., Spitznogle, G., and Usher, M., 2018, 15 Years of CO_2 Storage Research at AEP Mountaineer Power Plant – Stratigraphic Test Well to Site Closure, Oral Presentation to be given at the 14th International Conference on Greenhouse Gas Control Technologies (GHGT-14), Melbourne, Australia.
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- Kelley, M., Mille, D., Modroo, A., and Gupta, N., 2018, Distributed Acoustic Sensing (DAS) Based Vertical Seismic Profiling (VSP) for Monitoring CO_2 Injected into a Pinnacle-Reef Reservoir, Oral Presentation to be given at the 14th International Conference on Greenhouse Gas Control Technologies (GHGT-14), Melbourne, Australia.
- Mawalkar, S., Burchwell, A., Kelley, M., Mishra, S., Gupta, N., Pardini, R., Shroyer, B., and Brock, D., 2018, Where is that CO_2 Flowing? Using the Distributed Temperature Sensing (DTS) Technology for Monitoring Injection of CO_2 into a Depleted Oil Reservoir. Oral Presentation to be given at the 14th International Conference on Greenhouse Gas Control Technologies (GHGT-14), Melbourne, Australia.
- Duguid, A., Glier, J., Heinrichs, M., Hawkins, J., Peterson, R., and Mishra, S., 2018, Practical leakage risk assessment for CO_2 enhanced oil recovery and storage in Ohio's depleted oil fields, Oral Presentation to be given at the 14th International Conference on Greenhouse Gas Control Technologies (GHGT-14), Melbourne, Australia.
- *Along with nine Poster Presentations accepted to be presented at the 14th International Conference on Greenhouse Gas Control Technologies (GHGT-14), Melbourne, Australia.*

Spare slides