
# Midwest Regional Carbon Sequestration Partnership

*DOE/NETL Cooperative Agreement # DE-FC26-0NT42589*

*Neeraj Gupta, Battelle (gupta@battelle.org)*

*Carbon Storage R&D Review Meeting*

*Transforming Technology through Integration and Collaboration*

*August 18-20, 2015*

NETL Battelle The Business of Innovation

## MRCSP Presentation Outline

- Program Overview
- Large-Scale Test in Michigan
  - Site Overview
  - Injection operations and accounting
  - Late-stage reef injection, monitoring, modeling
  - New EOR Reef injection and monitoring
- Characterizing storage and utilization across MRCSP
- Outreach and Technology Transfer
- Summary

2 NETL Battelle The Business of Innovation

## Project Overview: Goals and Objectives

- Primary goal: To execute a large-scale scale $CO_2$ injection test to evaluate best practices and technologies required to implement carbon sequestration
- Objectives are to advance operational, monitoring, and modeling techniques needed to:
  - Develop and validate reservoir models useful for commercial scale applications
  - Address public concerns such as leakage and storage security
  - Address other topics such as cost effectiveness and CCUS practicability



## MRCSP Supports DOE Program Goals

| DOE Program Goal | MRCSP Approach/Benefit |
|---|---|
| Predict $CO_2$ storage capacity in geologic formations to within ±30% | Geologic and reservoir characterization and models correlated with field monitoring combined with MRCSP regional mapping. |
| Demonstrate that 99% of $CO_2$ remains in the injection zones | Operational accounting for $CO_2$ during EOR Monitoring options to track and image plume, and monitor $CO_2$ storage and retention |
| Improve reservoir storage efficiency while ensuring containment effectiveness | Test in EOR fields in various stages of their life cycle and examine strategies for utilizing the pore space created by the oil production |
| Development of Best Practices Manuals (BPMs) | Contribute to BPMs through large-scale test and regional analysis across MRCSP |

## RCSP Goals and MRCSP Program

| 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 reservoir pressures<br>• Pressure analysis and modeling used to evaluate capacity |
| ***Goal 2** – Prove Storage Permanence* | • Site selection to include good caprock, geologic structure<br>• Seismic and well data used to evaluate storage mechanisms and containment<br>• Monitoring wells used to measure containment over time within the reef and immediate caprock |
| ***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 |

## RCSP Goals and MRCSP Program

| RCSP Goal | MRCSP Approach and Success Criteria |
|---|---|
| ***Goal 4** – Develop Risk Assessment Strategies* | • Risk assessment for events, pathways, and mitigation planning<br>• 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.<br>• 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 |

## MRCSP Scope of Work Structured Around Six Tasks

| | |
|---|---|
| Task 1 | Regional Characterization: Develop a detailed actionable picture of the region's geologic sequestration resource base |
| Task 2 | Outreach: Raise awareness of regional sequestration opportunities and provide stakeholders with information about $CO_2$ storage |
| Task 3 | Field Laboratory Using Depleted 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 |
| Task 6 | Program Management |

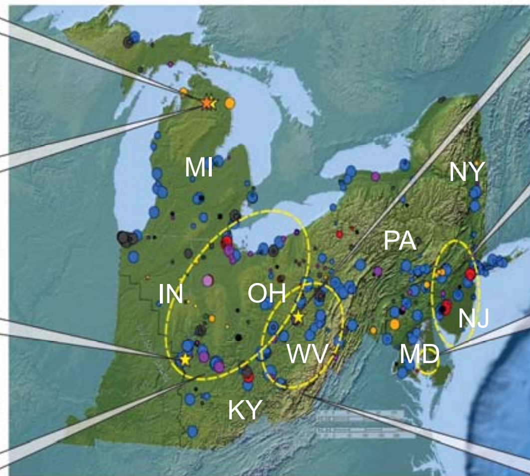
7

## Accomplishments to Date

- Completed baseline monitoring and site preparation
- ~244,000 metric tonnes injected in late state reef
- >150,000 metric tonnes net $CO_2$ in active EOR reefs
- Operational and subsurface monitoring underway
- Reservoir analysis shows closed reservoir conditions
- Phase changes and compressibility affect pressure response
- Initial static and reservoir models prepared
- INSAR monitoring shows no change in elevation
- Injection in one more new EOR reefs likely to start in late 2015
- Regional mapping/characterization across nine states
- Assessment of storage and EOR in Appalachian Basin

8

# MRCSP Area and Field Sites

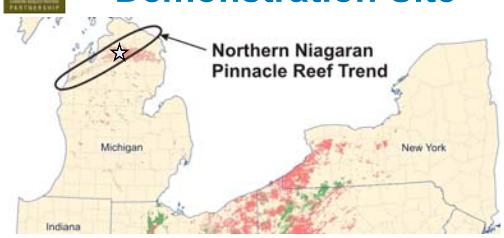


**MRCSP Region – Economic Drivers**

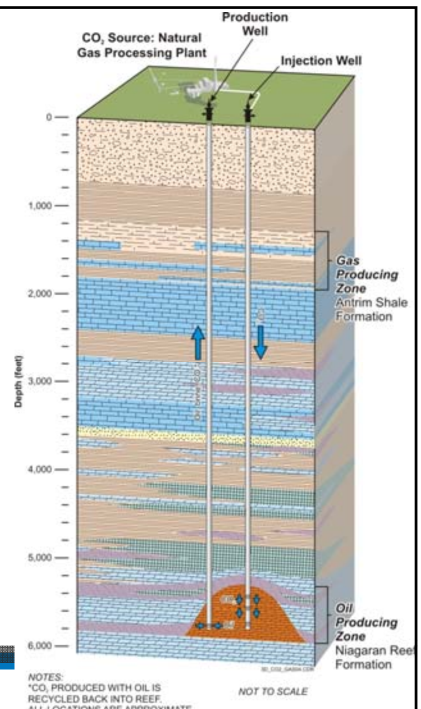
- Population: 80.4 million (26% of the U.S. population)
- Gross Regional Product: $3.1 trillion (27% of the U.S. economy)
- 26.3% of all electricity generated in the US
- 75% of electricity generated in the region is generated by coal

9 NETL Battelle The Business of Innovation

# Large Scale Demonstration Site

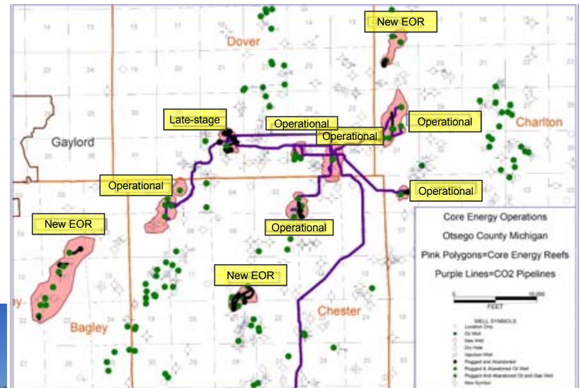



- **Location:** Otsego County, Michigan
- **Source of $CO_2$:**
  - Local Natural Gas Processing Plant (Antrim Shale Gas ~15% $CO_2$ content)
- **Reservoir Type:**
  - Closely-spaced, highly compartmentalized oil & gas fields located in the Northern Michigan's Niagaran Reef Trend




10 NETL

# MRCSP Large-Scale Test Site – Leveraging $CO_2$-EOR Infrastructure



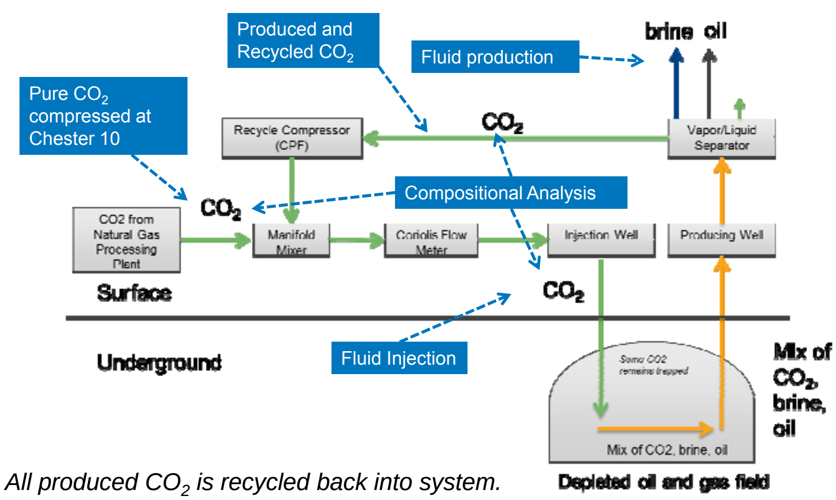



NETL

Battelle
The Business of Innovation

# Diagram of Closed Loop $CO_2$ EOR Cycle

## Monitoring and Accounting for the $CO_2$



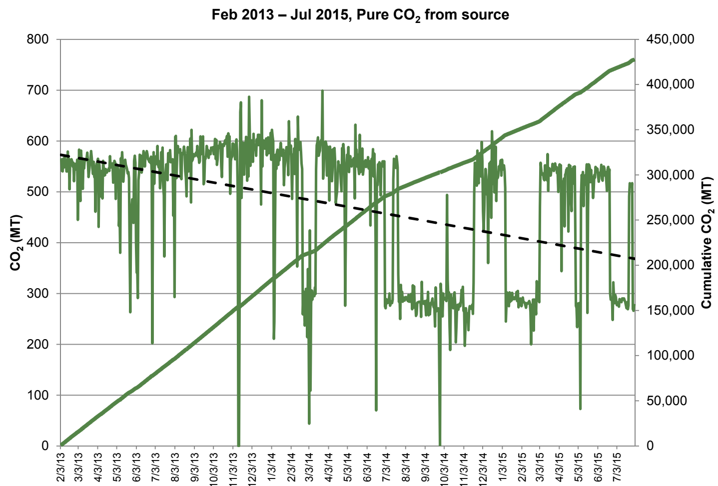

*All produced $CO_2$ is recycled back into system.*



NETL

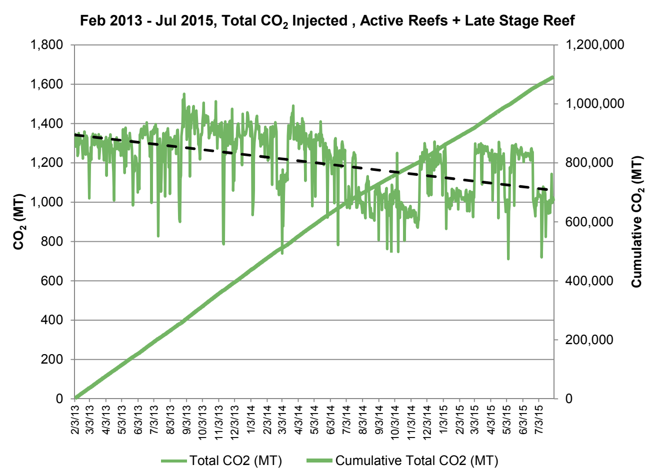
Battelle
The Business of Innovation

# Fresh $CO_2$ Supply Trends from Compression Facility towards EOR





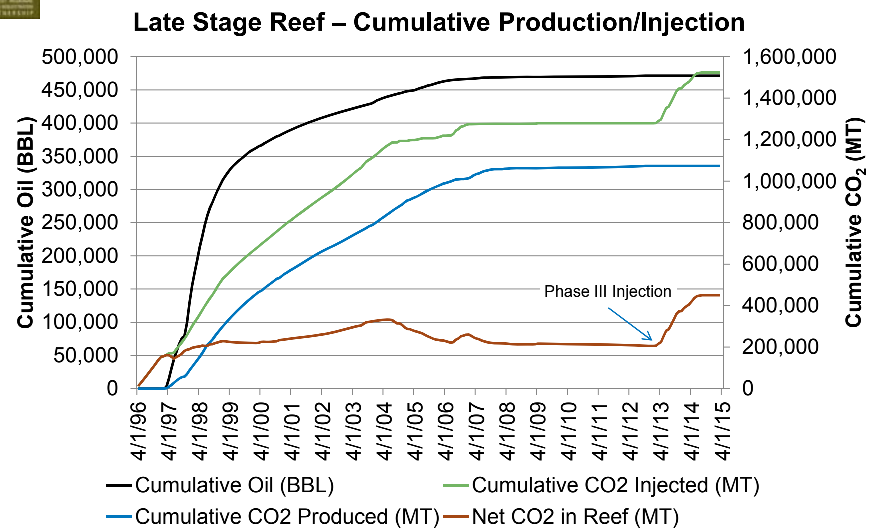

# Total $CO_2$ Injection Trends Across All Reefs



MRCSP

# Historical and Recent $CO_2$ Injection Data

Late Stage Reef EOR Operations

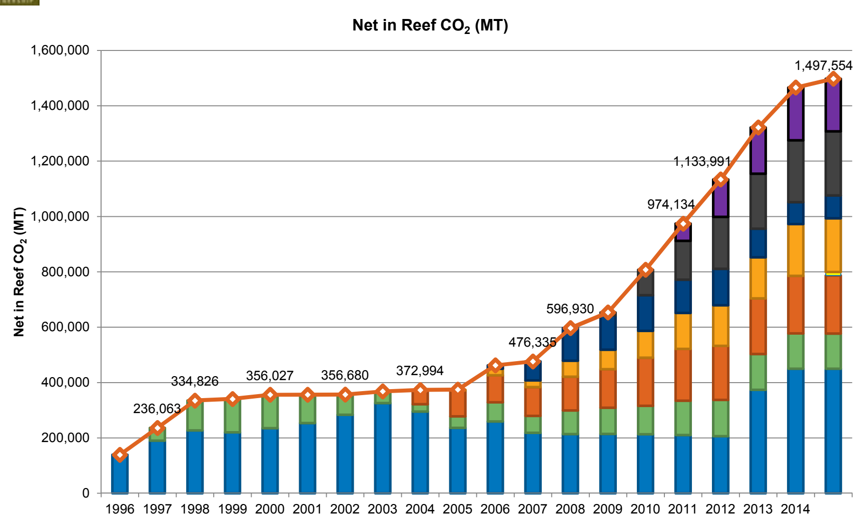



15 NETL Battelle The Business of Innovation

MRCSP

# Net $CO_2$ Stored in All Reefs Over Time

~1.5M metric tonnes retained since 1996

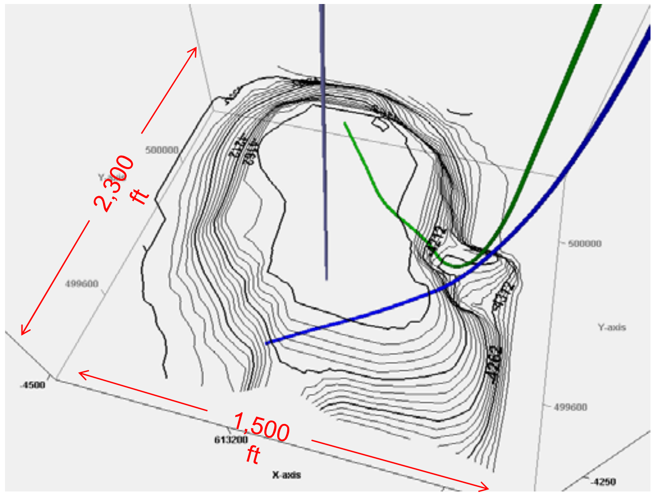



16 NETL Battelle The Business of Innovation

# Late-Stage Reef Structure and Wells

**Surface of A-1 Carbonate Showing Reef Structure**

- 1 Injection well
- 2 Production or monitoring wells




17

# Monitoring Status for Late Stage Reef

A portfolio of technologies is being tested

| Activity | Before Injection | Early Injection | Mid Injection | Late Injection | After Injection |
|---|---|---|---|---|---|
| $CO_2$ flow | | X | X | X | |
| Pressure and temperature | | X | X | X | X |
| Wireline logging | X | | X | | X |
| Borehole gravity | X | | | | X |
| Fluid sampling | X | | X | | X |
| Vertical seismic profile | X | | | | X |
| Microseismic | X | | | Under planning | |
| Satellite radar | X | X | X | X | X |

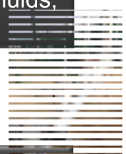
*Lessons learned will be applied to design the MVA plan for the newly targeted field*

18

## Fieldwork Safety Considerations

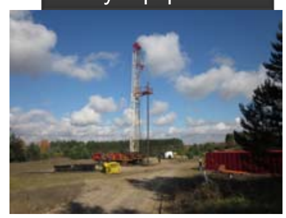
- Wide variety of work – wide range of safety considerations
- All work completed safely to date!

Fluid Sampling and Reservoir Testing – high pressure fluids, well work

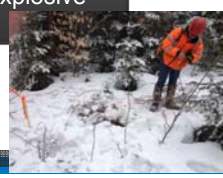


InSar ACRs – heavy equipment operation

Well Workovers – well control, overhead hazards, heavy equipment



Seismic Activities – well work, explosive hazards



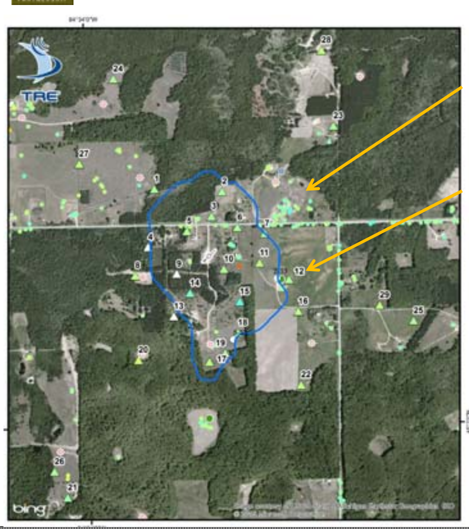
Wireline Logging – well work, radiologic hazards



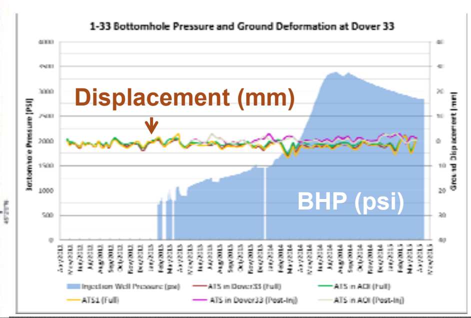
Battelle
The Business of Innovation

## INSAR Monitoring for Surface Changes:

No perceptible change Seen due to injection



- Vegetation and snow are challenging for radar, but there were a reasonable number of natural reflectors
- Artificial reflectors augmented the data for injection monitoring

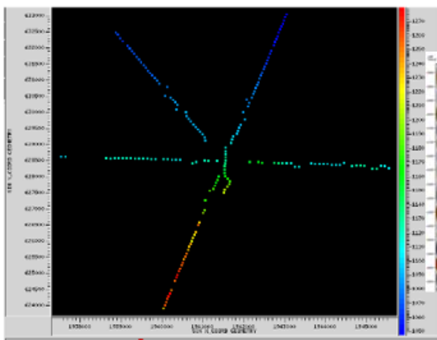




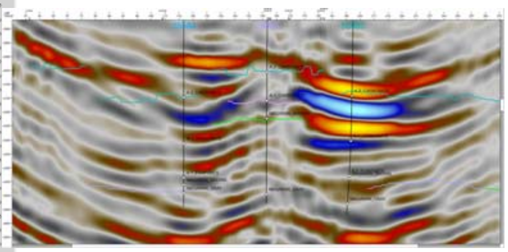

Battelle
The Business of Innovation

# Vertical Seismic Profile – Late Stage Reef

- Five walk-away lines centered around injection well
- Processed data shows increase in resolution, relative to surface seismic
- VSP will be repeated during 2016 after injection is completed



Receiver Locations



VSP Showing Reef Structure

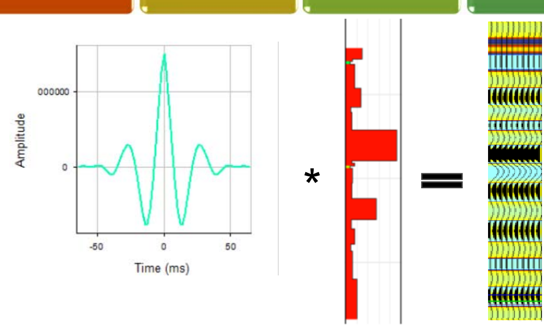


NETL

Battelle
The Business of Innovation

# Wavelet Analysis to Evaluate Velocity Change Detectable by VSP

- Extract phase wavelet from VSP
- Generate synthetic seismogram using wireline logs and wavelet
- Incrementally change velocity of reservoir rock
- Generate new synthetic with new velocity model



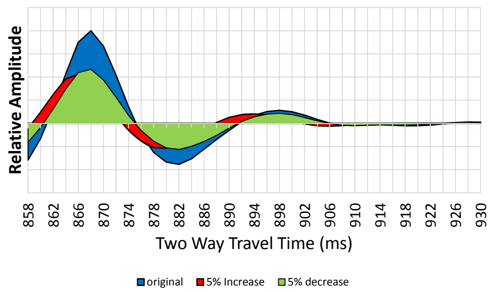



NETL

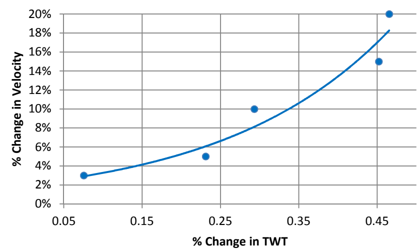
Battelle
The Business of Innovation

# Evaluating VSP Velocity Change Sensitivity to Determine Repeat Feasibility

Comparison of Synthetics with a 5% Velocity Change to the Original Synthetic




TWT Response to Velocity Change

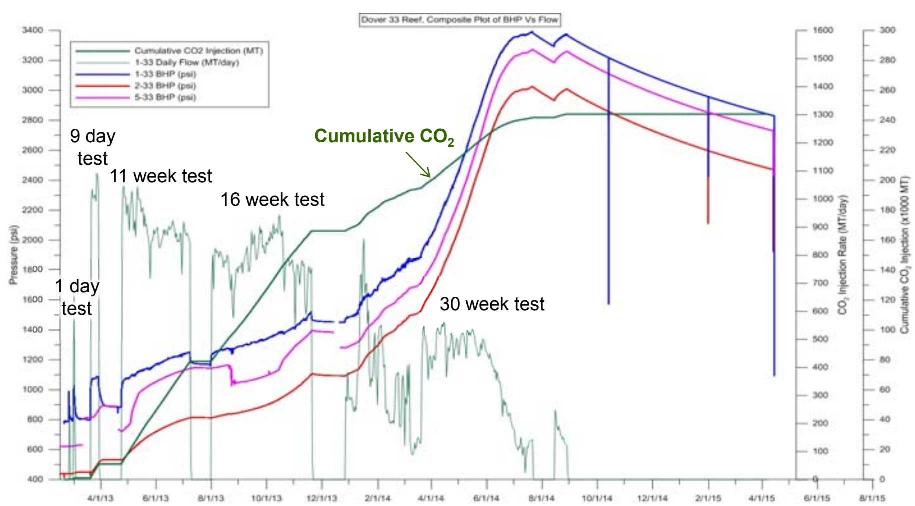



- Notice the arrival of the positive signature for a 5% increase (red) is slightly sooner than the original (blue) and the arrival for the 5% decrease is slightly later
- The VSP can detect 3% velocity changes

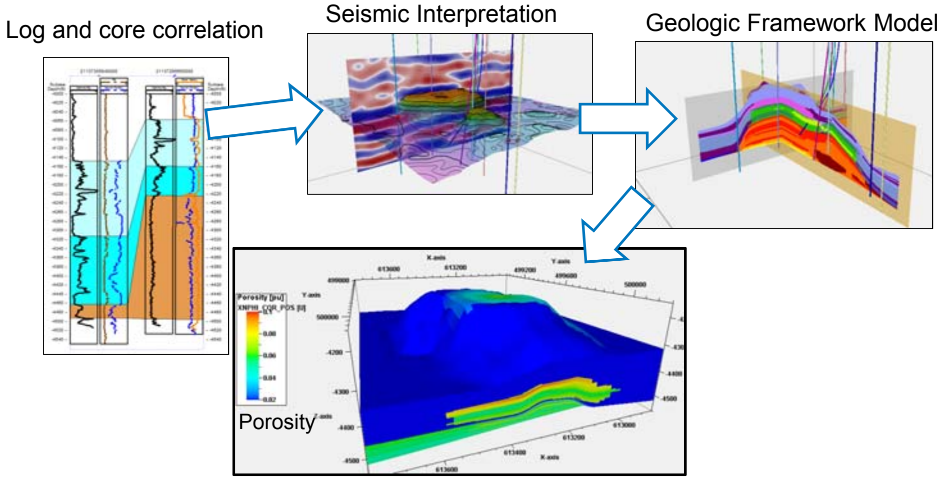


# Pressure Monitoring in Late-Stage Reef

Slow, long-term decline 9 months after injection



## Geologic and Reservoir Model Development



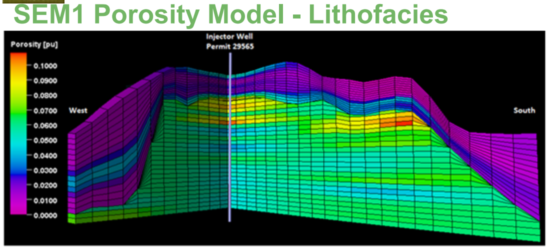

**Final Geologic Model**



## Modeling Reef Geologic Complexity

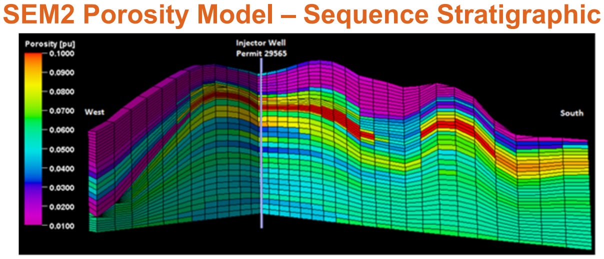
Static earth models built in various levels of geologic detail

**SEM1 Porosity Model - Lithofacies**



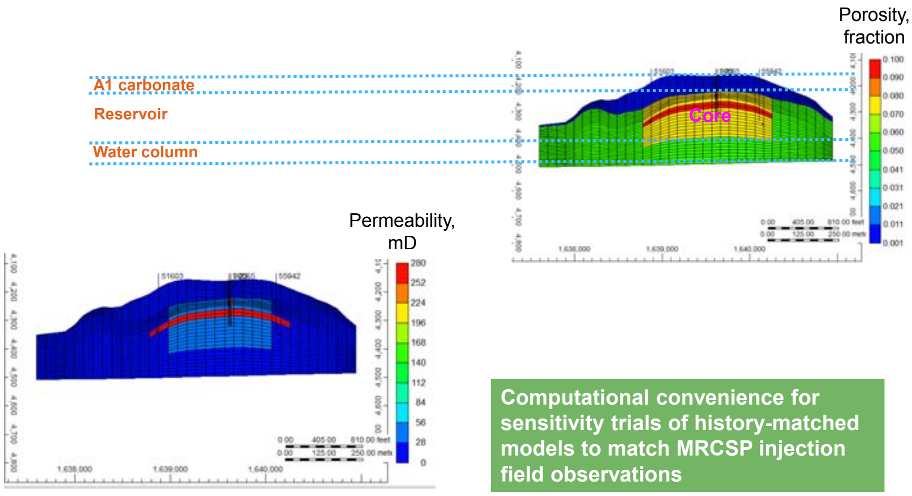

- Limited data available in late-stage reef (few wells and no core data)
- Heterogeneous geology
- Internal architechure difficult to model precisely

**SEM2 Porosity Model – Sequence Stratigraphic**



# Simplified Compositional Model

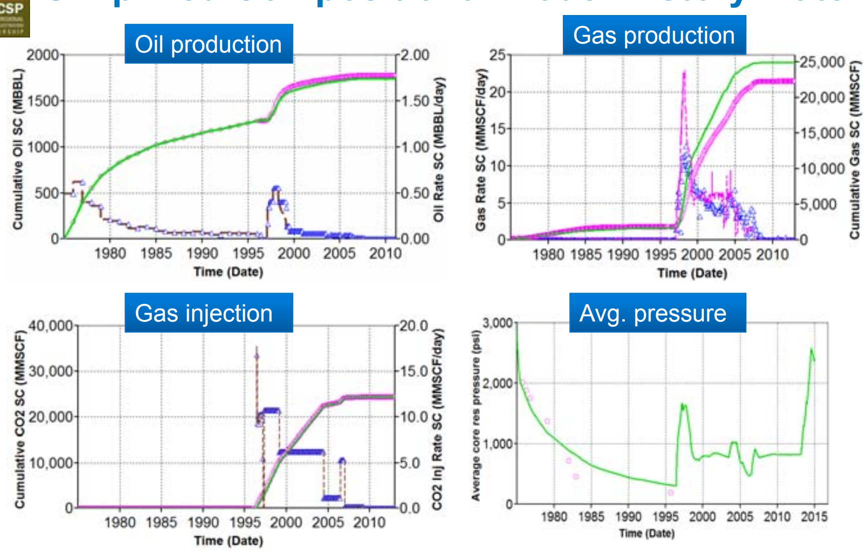
## Equivalent Homogeneous Reservoir Model




**Computational convenience for sensitivity trials of history-matched models to match MRCSP injection field observations**

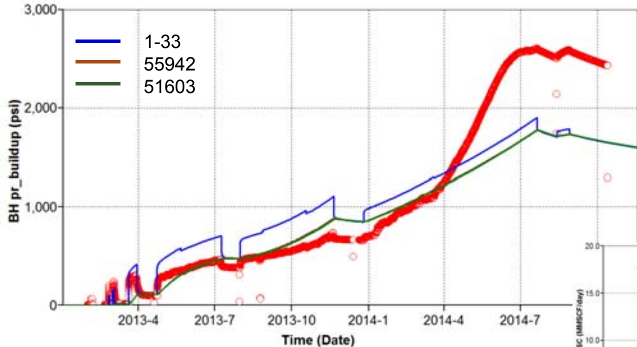


# Simplified Compositional Model History-Match

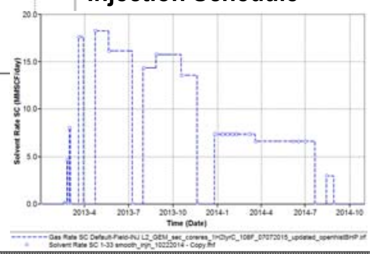


# Modeling Pressure Response

Equivalent Homogeneous Compositional Reservoir Model
MRCSP Injection Response Validation




Injection Schedule



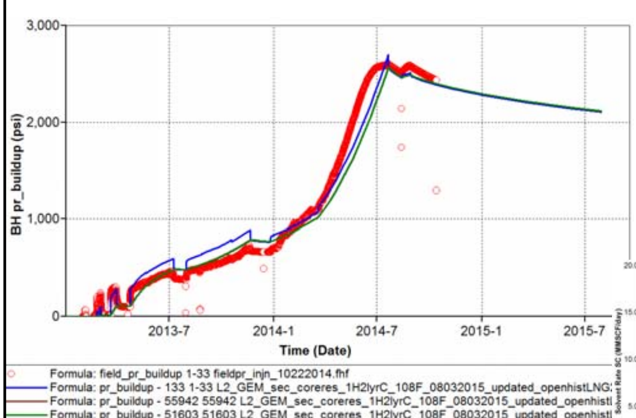
Reasonable match except near the end of injection

Further model calibration is in progress

29

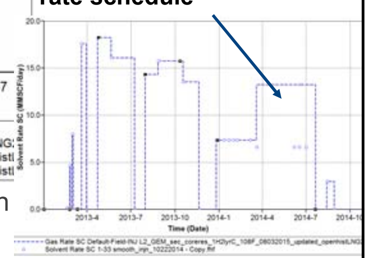
# Modeling Pressure Scenarios

Sensitivity to injection rates




**Hypothetical "what-if" higher injection scenario**

Modified MRCSP Injection rate schedule



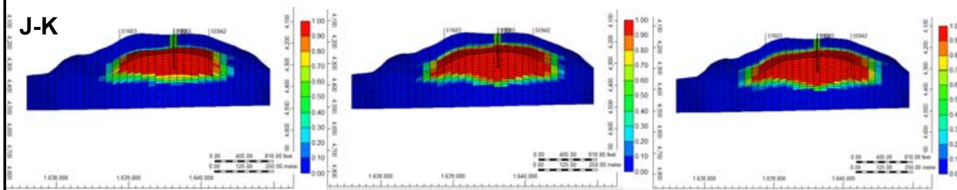
- Small injection increase leads to a better match
- Current model within range of uncertainty?

30

# Simulated $CO_2$ Distribution within the Reef

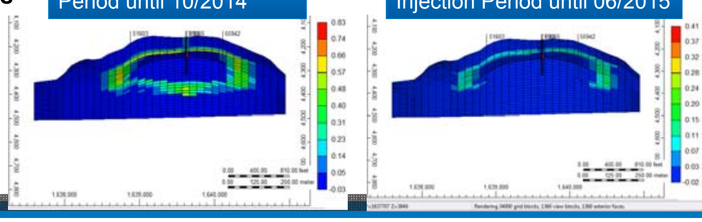
## Migration into reef flanks over time

At beginning of MRCSP Injection | At end of MRCSP Injection @10/2014 | Post-MRCSP Injection @06/2015




**Difference Maps**

For MRCSP Injection Period until 10/2014 | Fall-off post MRCSP Injection Period until 06/2015



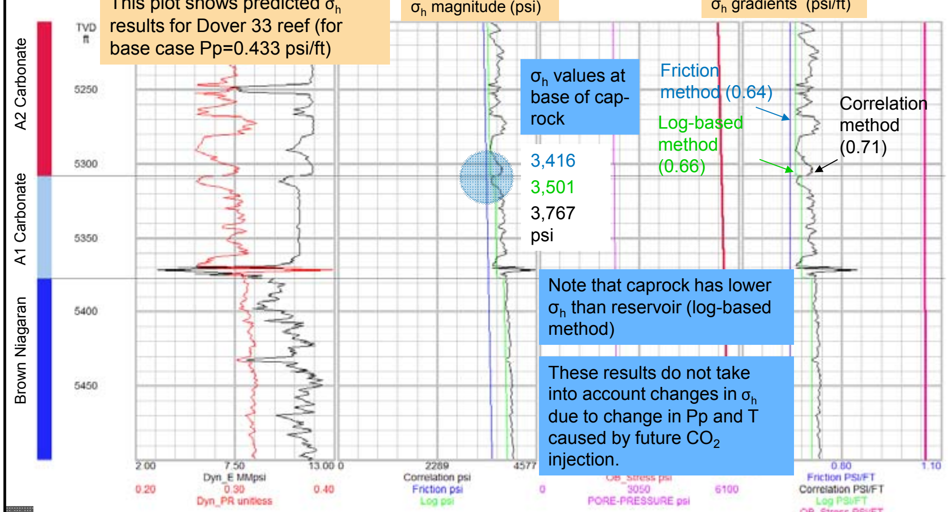
31

# Estimating Safe Injection Pressure with Log Data – Baseline $\sigma_h$ Values

This plot shows predicted $\sigma_h$ results for Dover 33 reef (for base case Pp=0.433 psi/ft)

$\sigma_h$ magnitude (psi)

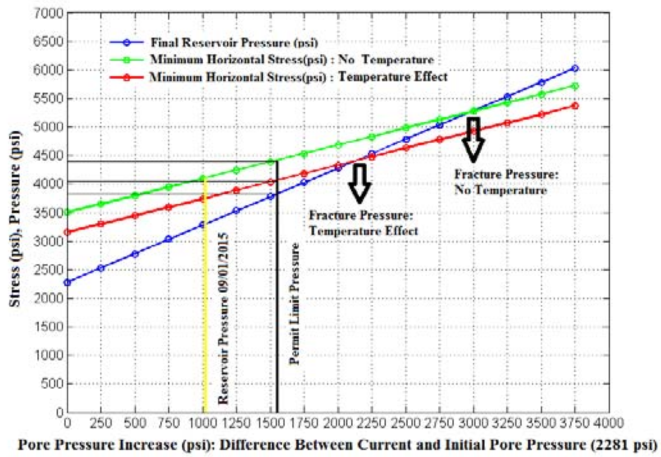
$\sigma_h$ gradients (psi/ft)




32

## Late-Stage Reef – Fracture Pressure Analysis from Log-Based Method

- Minimum horizontal Stress (fracture pressure) estimated using log-based method
- Poro-elastic and thermo-elastic effects included
- Likely pressure increase from injection remains below fracture pressure




33

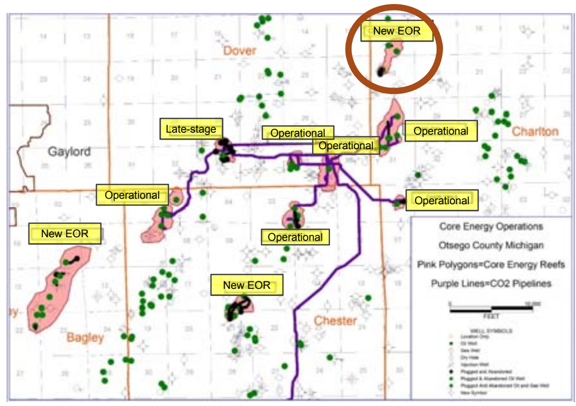
## Late Stage Reef – What's Next

- Complete injection – with a booster pump utilization
- Complete post injection monitoring
  - Pressure, PNC logs, gravity, microseismic, VSP, fluid sampling
- Calibrate, optimize static and dynamic models
- ***Drill and characterize in a validation well*** (subject to final review and approval)
  - Logging, coring, fluid analysis, and maybe ROZ characterization
  - Incorporate into models and validate
- Incorporate lessons learned into future reef assessments

34

## Starting Injection in a New Reef

- Field appears to have two partly connected lobes
- 1 injection well
- 1 monitoring well
- 1 old well plugged

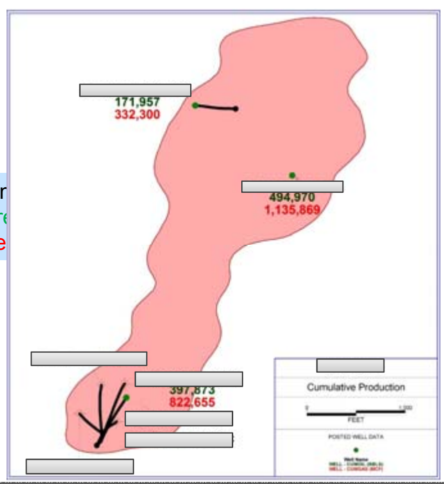


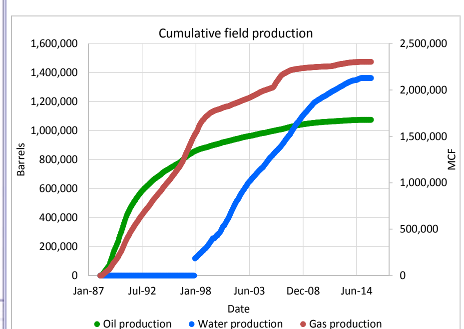



## New EOR Reef Layout and Production History

- Initial saturation (oil, water, gas) = 88.65%, 11.35%, 0% (no initial gas cap)
- Original Oil In Place = 2.634 MMSTB

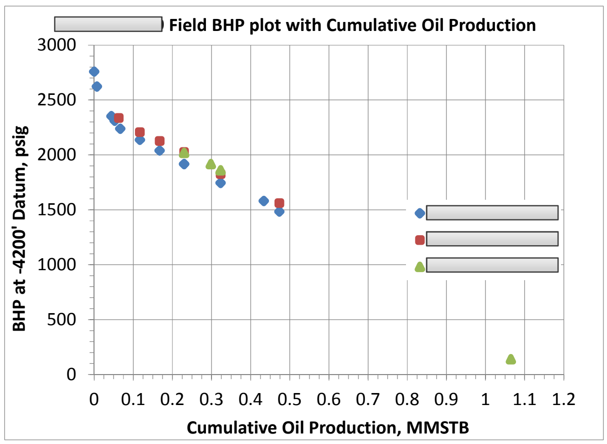
Cur
(Gre
(Re




Cumulative Production
- 1.074 MMSTB oil (40.7% of OOIP)
- 2303 MMSCF gas

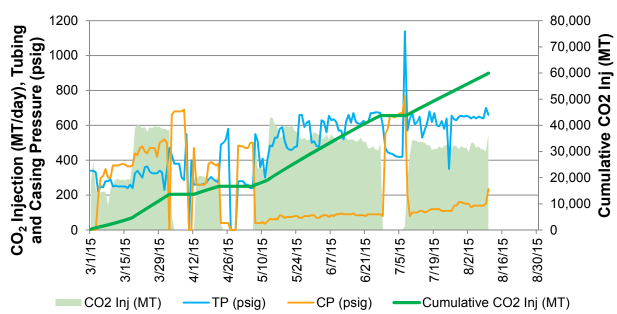
# Reservoir Pressure (Primary Production)




- Initial discovery pressure = 2774 psi
- Pressure at end of primary production ~155 psi
- Initial reservoir pressure is greater than the oil bubble point pressure (estimated to be 2400 psia); therefore, all gas present was in the dissolved state (i.e., solution gas)

37

# $CO_2$ Injection in a New EOR Flood

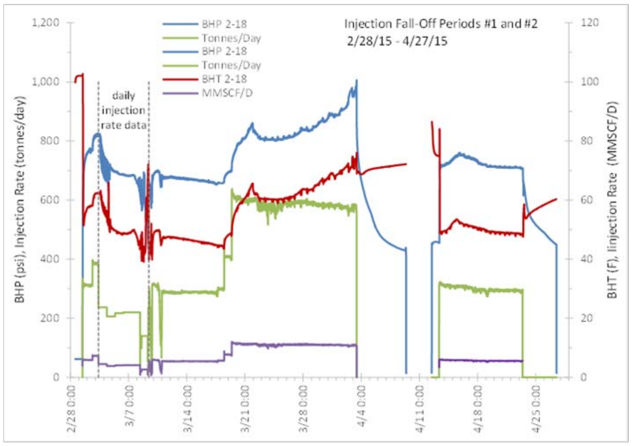



Daily and Cumulative $CO_2$ Injection at a new EOR Reef March to August, 2015

- $CO_2$ injection began on March 1st, 2015
- ~60K metric tons of $CO_2$ injected to date
- Rates ranged from 150 to 645 MT/day
- Two operational interruptions used to obtain pressure fall-off data for analysis

38

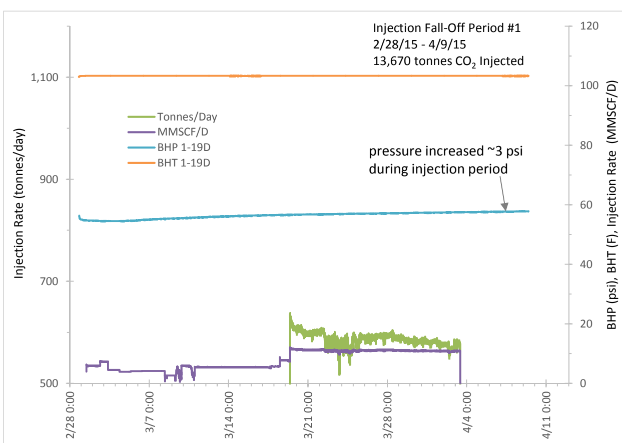
## New EOR Reef – Injection Well Pressure/Temperature Response




- Pressure increases by several hundred PSI
- Temperature appears to follow pressure trend (gauge issue?)
- Two fall-offs conducted

39

## New EOR Reef – Monitoring Well Pressure Response)



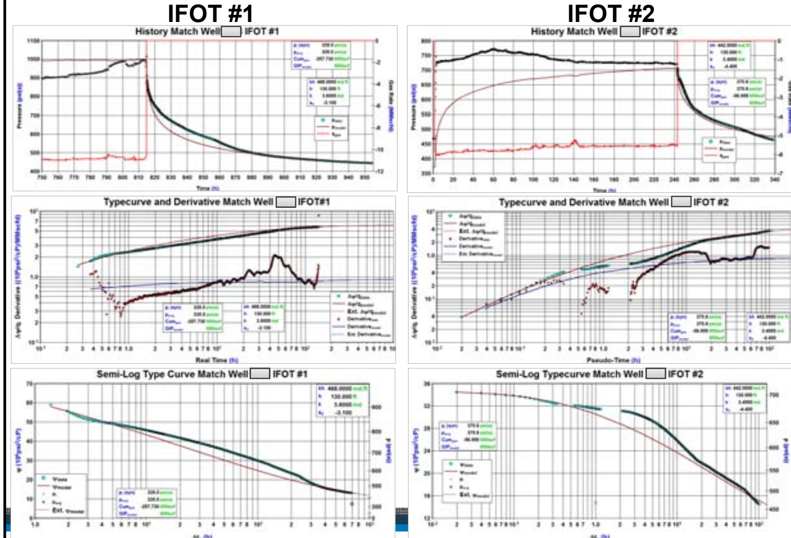

- Well is only partly connected to main reef lobe
- Only a small pressure response observed (~3psi)
- Demonstrates a slight hydraulic connection between the north and south parts of the reef

40

## New EOR Reef Pressure Fall-Off Analysis

### Low Permeability but Reasonable Injection Rates

**IFOT #1** **IFOT #2**




IFOT #1
kh=468 md-ft
h=130 ft
k = 3.6 md
s=-3.1

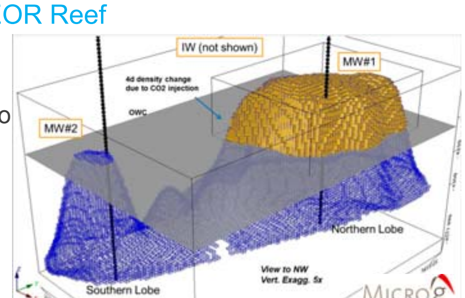
IFOT #2
kh=442 md-ft
h=130 ft
k = 3.4 md
s= -4.4

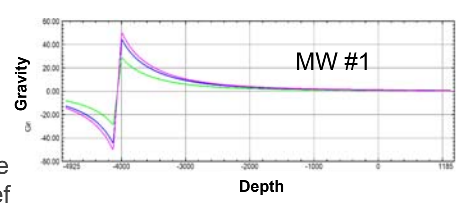


## Borehole Gravity Meter Survey Assessment

### Modeling exercise for the New EOR Reef

- Battelle provided well logs, formation top picks, and structure contour grids to Micro-g LaCoste
- Built 3D reservoir model (in Oasis Montaj) and profile (2-½D) reservoir model
- Modeling methods estimated total change in formation density for 3 injection scenarios
- Preliminary modeling predicted detectable signal response in north/center of new EOR reef but low response in MW#2
- Since, MW#1 had to be plugged, so the gravity survey not performed in this reef

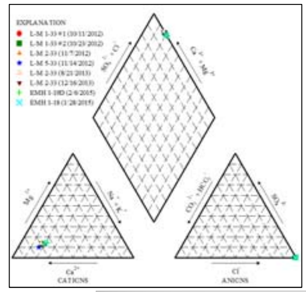


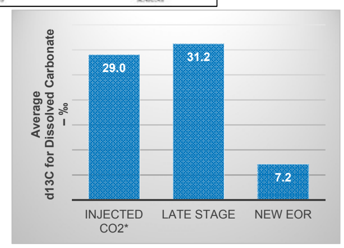



## Geochemical Studies: Stable Isotope as Tracers

Late-Stage reef shows impact of $CO_2$ relative to new reef

- Collected gas and brine samples from a new EOR reef, which has not received $CO_2$.
- General brine chemistry is similar between new EOR reef and late-stage reef with very high TDS.
- Isotopically, the brines are different. Differences in the $\delta^{13}C$ for dissolved carbonate suggest the brine chemistry is altered by the injection of $CO_2$.
- Note: the $\delta^{13}C$ value has been corrected for fractionation resulting from dissolution and dissociation.





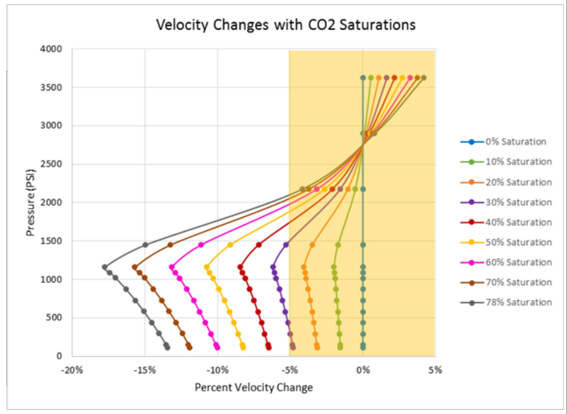

## Baseline Sonic Log in New Reef

- Other field studies (Nagaoka Project in Japan and Frio Project in Texas) have had success using sonic logging to monitor the migration of $CO_2$
  - At Nagaoka, velocity decreased by 23% across the injection zone and reached a maximum velocity change once the rock was 20% saturated with $CO_2$
- Therefore, an analysis was conducted to estimate the change in the velocity ($V_p$) that could be expected under different pressure conditions as the initial fluid in the reservoir is replaced with $CO_2$
  - The objective was to assess feasibility of using sonic logging for tracking $CO_2$

# Evaluating Sonic Logging Feasibility

## Predicted Velocity Changes in Reef due to $CO_2$ Injection

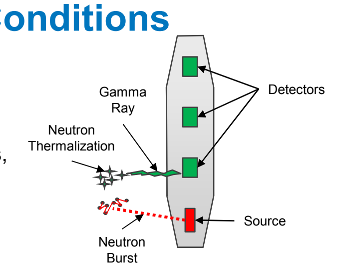
- Initial fluid was 22% brine+ 78% methane mixture
- Increasing pressure considered
- Velocity changes > +/- 5% are assumed to be detectable
- Results suggest 30% $CO_2$ saturation is needed to detect a pressure < 1500 psi
- Above 1500 psi, >30% saturation is required



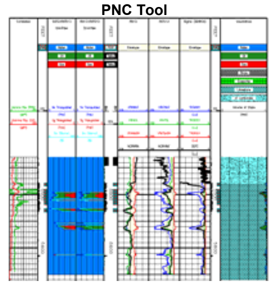



# PNC Logging for Monitoring Saturation Levels and Wellbore Conditions

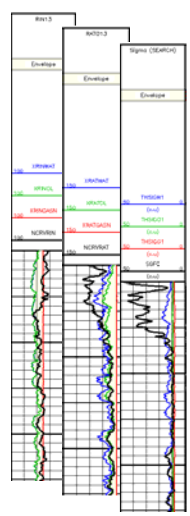
- Pulsed Neutron Capture (PNC) logging for verifying saturations in the near wellbore environment
  - Provides monitoring of oil, gas, and water saturation
  - $CO_2$ saturation evaluations
  - It is inexpensive to deploy?
- Operation and Output of PNC
  - Tool source bombards the formation with a high energy neutron burst
  - Time lapsed inelastic and thermal-neutron scattering responses are measured at the detectors
  - Time lapsed responses are translated and digitized as RIN13, RATO13, and Sigma measurements




PNC Tool



PNC Log



RIN13, RATO13, and Sigma Curves

## Various Data Needed prior to Logging and during PNC Data Analysis

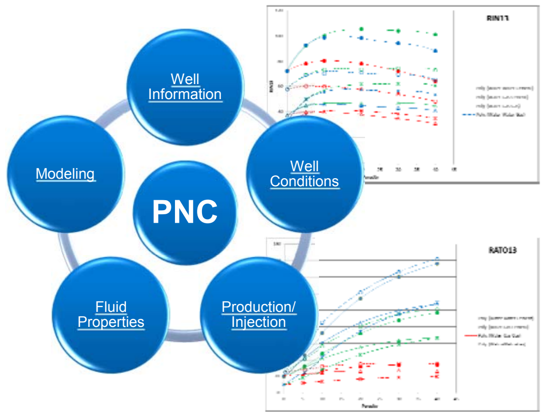
**Well Information**
- Open Hole LAS Data (Wireline Data)
- Lithology Type

**Well Conditions**
- Cement Conditions
- Casing/Tubing Size

**Production/Injection**
- Recent Production Rates
- Water/Gas/Oil Rates
- Downhole Pressures

**Fluid Properties**
- Water Salinity (ppm-NaCl)
- Downhole Gas Density (g/cc)
- Gas ($CH_4$/$CO_2$)
- Gas Specific Gravity (s.g)

**Modeling**
- Monte Carlo Predictive Algorithm
- Calibration of Data to Wireline Data



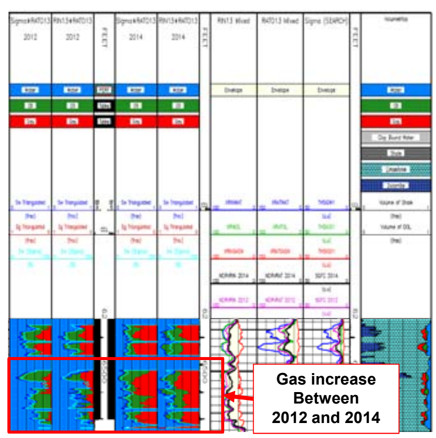

Extensive data collection and implementation is required for PNC analysis



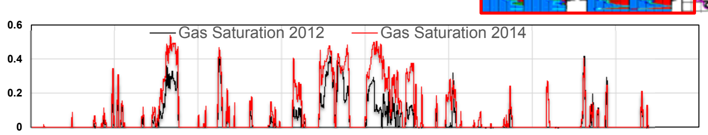
## PNC Monitoring of Production Well

### Example from an Active Reef

- **March 2012 Logging**
  - Oil dominates in high porosity intervals
  - Majority of gas and oil above perforations
  - Gas and oil intervals due to possible vugular porosity
- **March 2014 Logging**
  - Gas dominate in high porosity intervals
- **Repeat runs (2012 and 2014) yield increase in gas saturation due to pushing oil**
  - Multiple logging runs are key to monitoring reservoir conditions




PNC Log

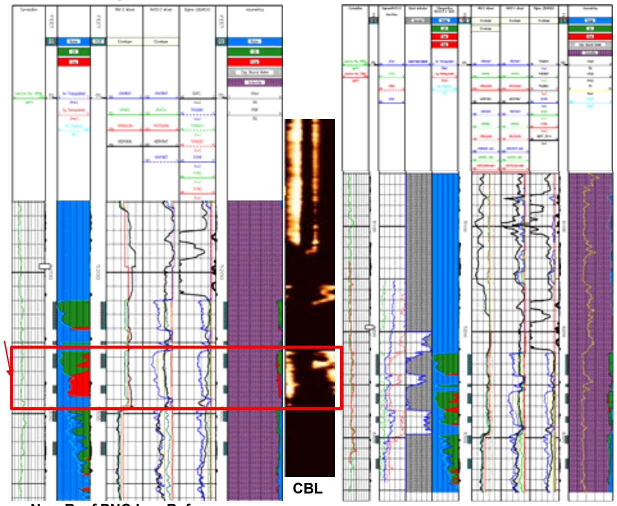



Gas saturation increased between 2012 to 2014

## Unfavorable Well Conditions Present Challenges for Analysis

- **New Reef Example**
  - Poor cement quality creates gas anomaly at approximately 5,258 to 5,289 ft
  - Attenuation over poor cement intervals incorporated in new PNC model


Cement quality causing gas artifact




New Reef PNC Log Before Cement Modeling

New Reef PNC Log After Cement Modeling

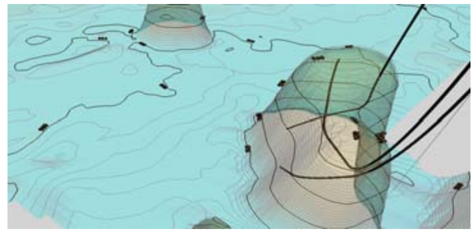


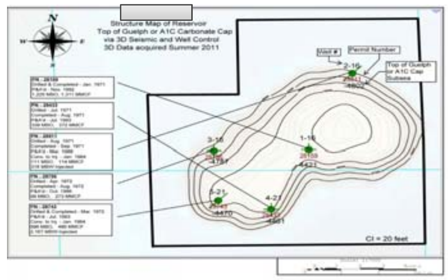
## Active and New Reefs – What's Next

- Continue injection and monitoring in multiple reefs towards 1 million tonnes goal
- Prepare 1-2 additional new EOR Reefs
  - Drill 1 injection and 1 monitoring well (2015-16)
  - Baseline characterization with logging, coring, and seismic
  - Develop geologic and reservoir models
  - Start injection during late 2015
  - Monitoring

## What's Next - New EOR Field

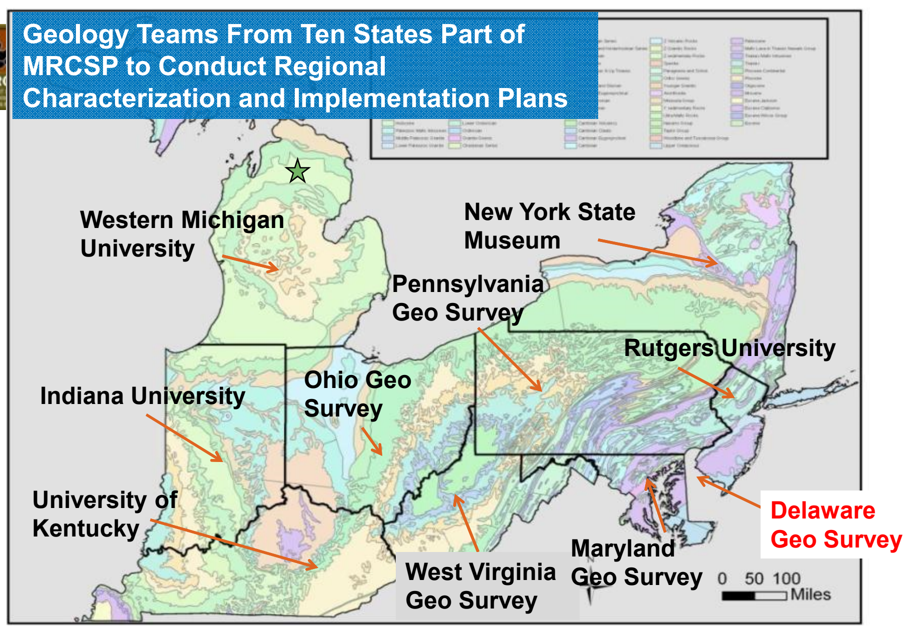
- Innovative design
- 1 injection well, 2 monitoring wells
- MRCSP to support drilling one well with logging and coring
- Detailed modeling and monitoring to be planned
- Possible collaboration with EPRI and LBNL



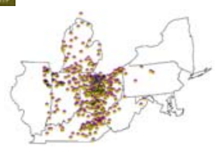





## Geology Teams From Ten States Part of MRCSP to Conduct Regional Characterization and Implementation Plans

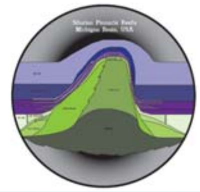


## Selected Regional Geology Team Activities

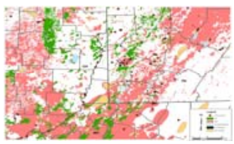


Cambro-Ordovician Storage Potential
*Led by Indiana*

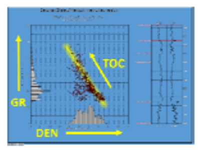
East Coast Offshore and Onshore Storage Targets
*Led by Rutgers*



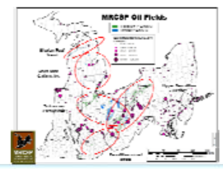
Silurian Pinnacle Reef Reservoirs
*Led by W. Michigan University*



CCUS Opportunities in Appalachian Basin
*Led by Pennsylvania*



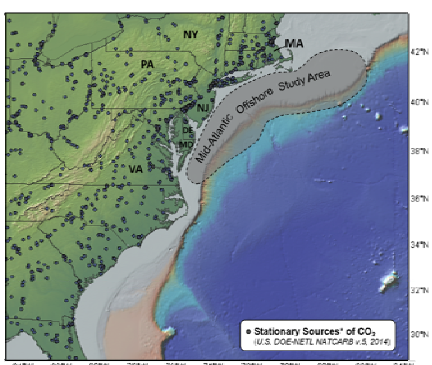

Storage and Enhanced Gas Recovery for Organic Shale
*Led by Kentucky*




Reservoirs for $CO_2$-EOR, EGR, and other Commercial Uses
*Led by West Virginia*

53

## Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment Project
## New Project (FOA 1246)



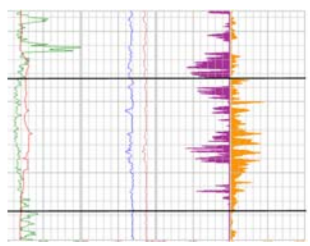

- Project Team includes Battelle; geological surveys of MD, DE, and PA; USGS; Rutgers; Harvard; and Columbia


**Example of existing core material, COST G2 well**

54

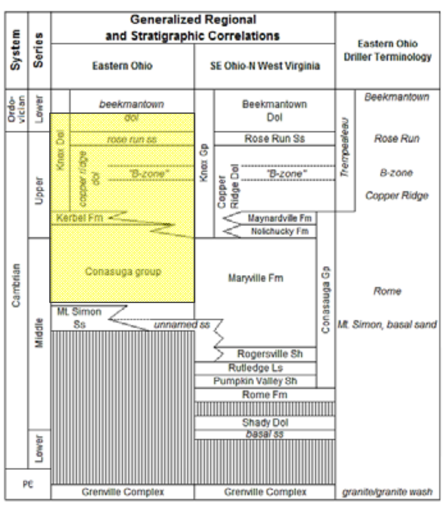
## Defining $CO_2$ Storage in Upper Ohio River Valley

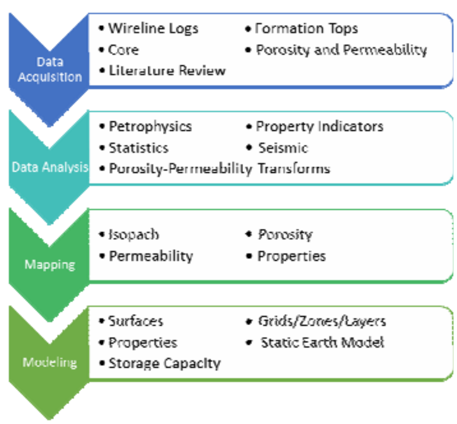
- Create "Road Map" for $CO_2$ sequestration in saline reservoirs in the Upper Ohio River Valley area.
  - Determine extent of potential reservoirs, such as the Copper Ridge and Conasauga/Rome
  - Characterize potential caprocks, both in terms of petrophysical and geomechanical properties
  - Map relevant parameters: porosity, kh, injectivity, capacity
  - Continue gathering new data through piggyback opportunities



55 Co-Funded by ODSA/OCDO

## Geo-characterization in Appalachian Basin




Workflow applied to Rose Run, "B" zone, Lower Copper Ridge, and Conasauga group

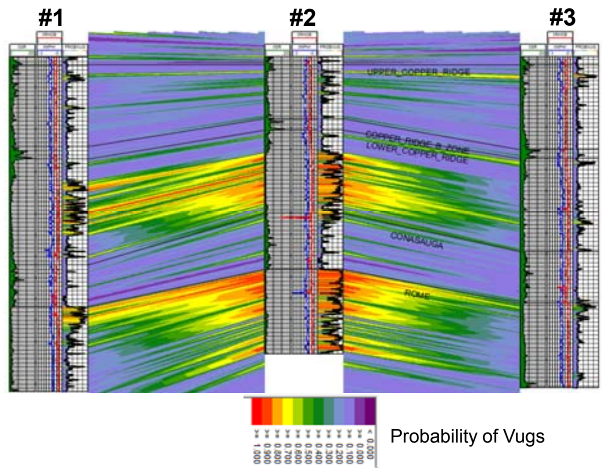
56

# Characterizing Storage Zones

## Learning from Brine Injection Wells

Vug Probability in Lower Copper Ridge and Rome Dolomites

- Local view of vug probability across three closely spaced wells
- There is better probability of vugs and potential connectivity between Wells 1 and 2
- Properties improve understanding of fluid flow

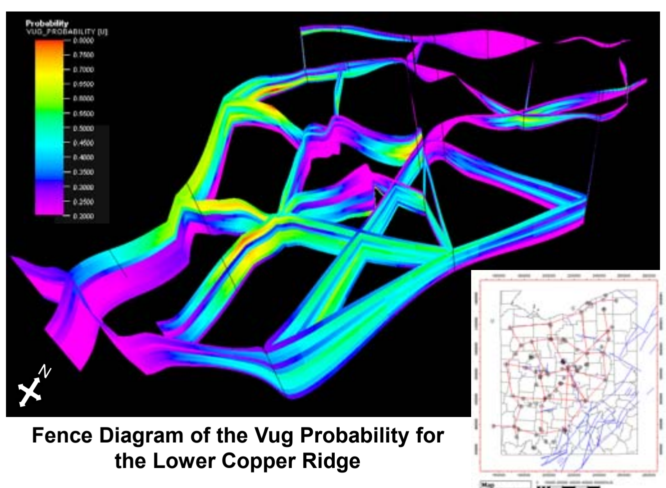



57

# Characterizing New Storage Candidates

## Vuggy Dolomite Probability Mapping in Copper Ridge

- Apply methods to a regional scale
- Identify areas of high probability of vug development
- Identify areas of best reservoir potential

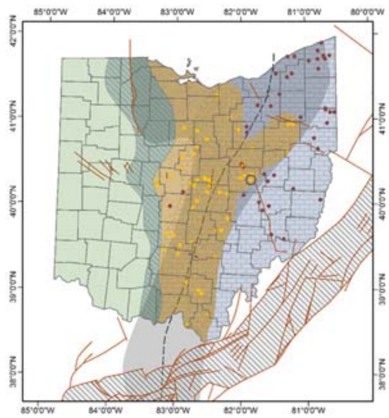



Fence Diagram of the Vug Probability for the Lower Copper Ridge

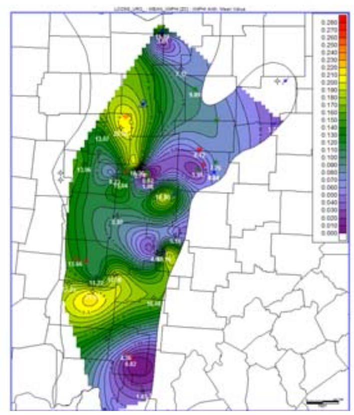
58

## Regional Mapping of Storage Targets

### Sandy Facies Map for Conasauga Group



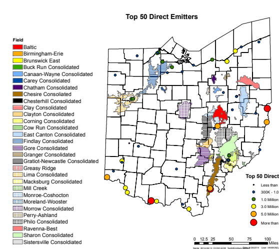
Extent of the sandy facies in the Conasauga (orange) and how it relates to known structure



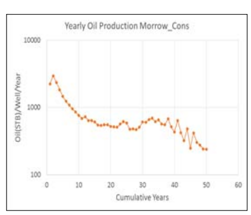
Porosity map of the sandy facies showing high porosity (yellow) in the center.

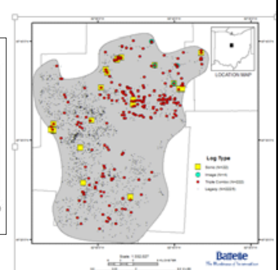
59

## $CO_2$ Utilization for EOR and Geologic Storage in Ohio's Depleted Oil Fields




- **Research goals**
  - Develop process understanding and evaluate technical and economic feasibility of $CO_2$ utilization and storage in Ohio's depleted oil fields
  - Focus on Clinton sandstone and Knox dolomite formations (under-pressured, low permeability reservoirs with poor primary recovery)
- **Current focus**
  - Source-sink matching
  - Production history assessment
  - Geologic model development
  - Fluid property characterization
  - Reservoir simulation



60

Co-Funded by ODSA/OCDO

MRCSP

# $CO_2$-EOR/Storage Assessment

## Fluid Property Prediction Tool for oil-gas-water-$CO_2$ Systems

**Inputs:**

*Shadding Indicates Needed Input*

| Input Bubble Point Property | | |
|---|---|---|
| Select Known Bubble Point Property : | Pressure | |
| Pressure, pB | 2017.0 | psia |

| Additional Reservoir Properties | | |
|---|---|---|
| Oil gravity, $\gamma_{API}$ | 43.6 | API |
| Gas gravity, $\gamma_g$ | 0.76 | - |
| Reservoir Temperature, T | 108 | °F |

| Single Point Pressure of Interest<br>Evaluation at right | | |
|---|---|---|
| Pressure, p | 1250 | psia |

| Pressure Range of Interest<br>See next sheets for tables and plots | | |
|---|---|---|
| Maximum Pressure | 2894 | psia |
| Min Pressure | 15 | psia |

| Brine-Gas Calculations | | |
|---|---|---|
| Calculate Brine-Gas Properties? | Yes | |
| If Yes, Salinity = | 1.2 | Weight % Solids |

| $CO_2$ Calculations | | |
|---|---|---|
| Calculate Pure $CO_2$, $CO_2$-Oil and $CO_2$-Brine Properties? | Yes | |
| *Pure CO2 properties only available for 100psia ≤ p ≤ 3600psia and 0°F ≤ T ≤ 350°F | | |
| *CO2-Oil and $CO_2$-Brine Calculations assume dead oil | | |
| If Yes, Avg. Oil Molecular Weight (MW) = | 220 | lb/lbmol |
| If Yes, Salinity = | 1.5 | Weight % Solids |

**Outputs at Single Point of Pressure:**

| | | | |
|---|---|---|---|
| At: | Pressure, p | 1250 | psia |
| | Bubble Point Pressure, $p_B$ | 2017 | psia |
| | Solution Gas Oil Ratio at Bubble Pt, $R_{soB}$ | 774 | SCF/BBL |
| Oil-Gas | Formation Volume Factor, $B_o$ | 1.21 | RB/STB |
| | Solution Gas Oil Ratio, $R_{so}$ | 439.2 | SCF/BBL |
| | Viscosity, $\mu_o$ | 0.466 | cP |
| | Compressibility, $c_o$ | 3.41E-04 | 1/psi |
| | Density, $\rho_o$ | 45.2 | lbm/ft3 |
| Gas | Formation Volume Factor, $B_g$ | 0.0103 | ft3/SCF |
| | deviation factor, Z | 0.802 | - |
| | Viscosity, $\mu_g$ | 0.014 | cP |
| | Compressibility, $c_g$ | 9.57E-04 | 1/psi |
| | Density, $\rho_g$ | 5.64 | lbm/ft3 |
| Brine-Gas | Formation Volume Factor, $B_w$ | 1.0097 | RB/STB |
| | Solution Gas Water Ratio, $R_{sw}$ | 15.31 | SCF/BBL |
| | Viscosity, $\mu_w$ | 0.64 | cP |
| | Compressibility, $c_w$ | 5.04E-05 | 1/psi |
| | Density, $\rho_w$ | 62.29 | lbm/ft3 |
| Pure $CO_2$ | Formation Volume Factor, $B_{CO2}$ | 0.01 | ft3/SCF |
| | Viscosity, $\mu_{CO2}$ | 0.03 | cp |
| | Density, $\rho_{CO2}$ | 21.88 | lbm/ft3 |
| | Compressibility Factor, $Z_{CO2}$ | 0.43 | - |
| $CO_2$ - Oil | $CO_2$-Oil Solubility, Sol | 0.60 | mole fraction |
| | Solution CO2 Oil Ratio, $R_{so\text{-}CO2}$ | 740.8 | SCF/STB |
| | $CO_2$-Oil Swelling, SF | 1.29 | - |
| | $CO_2$-Oil Viscosity Ratio, $\mu_{oCO2}/\mu_{oi}$ | 0.23 | - |
| $CO_2$-Brine | Solution $CO_2$-Water Ratio, $R_{sw\text{-}CO2}$ | 142.3 | SCF/STB |



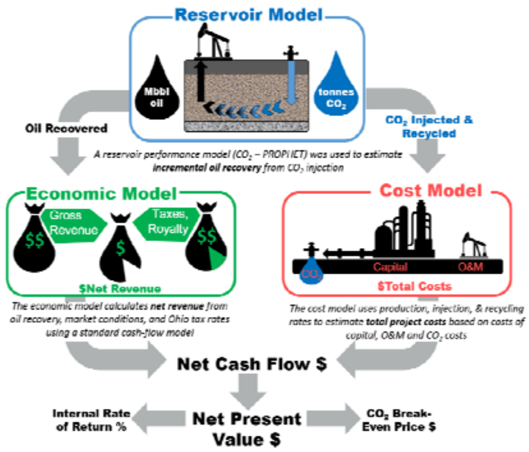
NETL

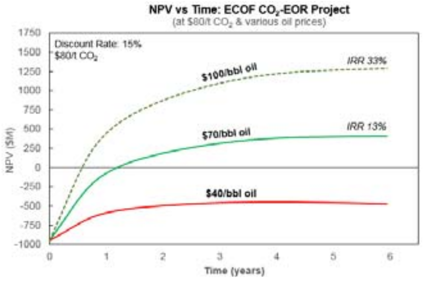
Battelle
The Business of Innovation

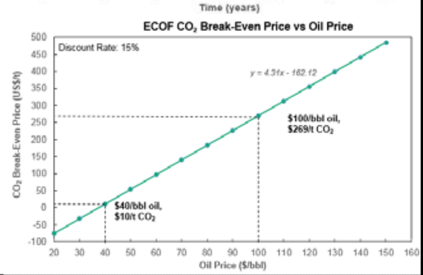
MRCSP

# $CO_2$-EOR/Storage Assessment

## Cost-Benefit Analysis Tools






NETL

Battelle
The Business of Innovation

## MRCSP has four overarching goals for its outreach program:

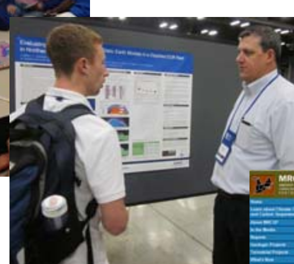
1. Continue to be a neutral and credible source of scientific information on CCUS
2. Improve public understanding of CCUS
3. Support the large-volume $CO_2$ injection test
4. Support other MRCSP research activities, including regional geologic characterization projects



## Communicating the results of the large-scale project to a broad audience is a key focus

- Share technical information and convey key findings (e.g., CCS works, it's safe)

Site Visits, Fact Sheets

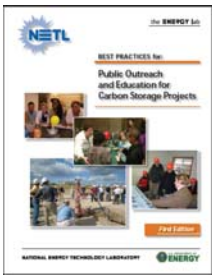


Conferences and Meetings

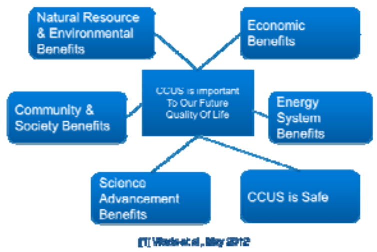

Website

## MRCSP also Convenes and Participates in the Outreach Working Group

A group of outreach coordinators working to better understand and respond to questions about CCS




Best Practices Manual




Message Mapping
(media, outreach materials)


Digital communications



## Synergy Opportunities

- Knowledge share with Plains $CO_2$ Partnership on closed reservoirs modeling and monitoring
- Knowledge share with other RCSPs on monitoring technologies
- Potential for support for DOE SubTER initiatives
- Collaboration with international projects on modeling and $CO_2$ EOR to Storage transitions
- IEAGHG monitoring network presentations
- Input to DOE Best Practices Manuals

## Summary of Recent Progress

- Large-scale Test in Michigan
  - Completed baseline monitoring and site preparation for multiple reefs
  - ~244,000 metric tonnes injected in late state reef
  - >125,000 metric tonnes net $CO_2$ in active EOR reefs
  - Operational and subsurface monitoring underway
  - Reservoir analysis shows closed reservoir conditions
  - Phase changes and compressibility affect pressure
  - Initial static and reservoir models prepared
  - Injection in a second new EOR reef likely to start in late 2015
- Regional mapping/characterization across nine states
- Initiated detailed storage and EOR assessment in Ohio



## Acknowledgements

***Battelle's MRCSP team members for work shown here***

**DOE/NETL** has worked with us and our partners to structure a program that adds to the knowledge base and extends the state-of-the-art.

**Core Energy, LLC** our host site and $CO_2$ supplier for 10 years of collaboration under Phase II and Phase III

The **Ohio Coal Development Office** has provided consistent and significant cofunding for the regional characterization efforts of the MRCSP

MRCSP's **industrial partners and sponsors**

The nine state **Geology Surveys and Universities** have been essential in expanding the results into regional implementation plans.

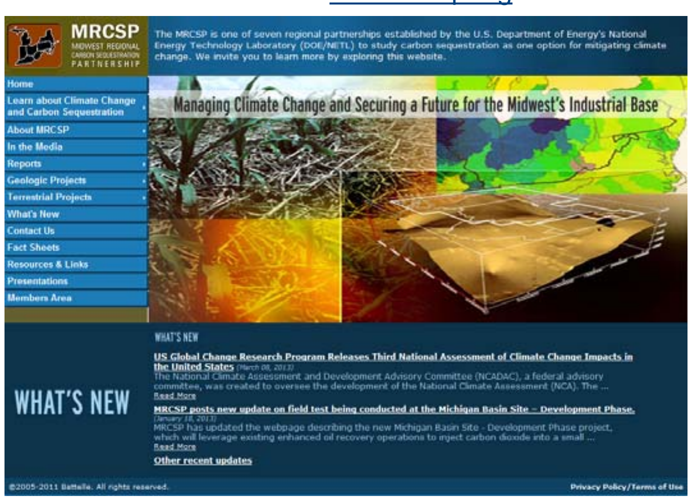
## Contributions From Partners Have Helped Make MRCSP Successful

AEP, AMP Ohio, ArcelorMittal, Battelle The Business of Innovation, B&W, bp, CEED Center for Energy and Economic Development, Constellation Energy Group, Consumers Energy Count on Us, Core Energy, LLC, CONSOL Energy, Dominion, DTE Energy, Duke Energy, FirstEnergy, OUCC, Kentucky Geological Survey University of Kentucky, The Keystone Center, Maryland Geological Survey, Michigan Basin Core Research Laboratory, National Rural Electric Cooperative Association, NYSERDA, New York State Museum, NiSource, Ohio Development Services Agency, Ohio Environmental Council, The Ohio State University, Pacific Northwest National Laboratory, Praxair, Rutgers, RWE, WADE, WVGES, West Virginia University

69 NETL Battelle The Business of Innovation

## Questions?

Please visit www.mrcsp.org




70 NETL Battelle The Business of Innovation

# BACK UP SLIDES
# Midwest Regional Carbon Sequestration Partnership



## Organization Chart

**DOE/NETL**
Andrea McNemar
**MRCSP Program Manager**

Battelle
*The Business of Innovation*
**Prime Contractor**
Neeraj Gupta, PI/PM
M. Kelley, Characterization/Monitoring
L. Cumming, Outreach & Regional Geology
S. Mishra and Ravi Ganesh, Modeling
J. Sminchak, Permitting

Kentucky Geological Survey
Michigan Basin Core Research Laboratory
WVGES
New York State Museum
Rutgers
Kris Carter, PA Geo Survey
John Rupp, IN Geo Survey
**- Regional Characterization Task Coordinators**

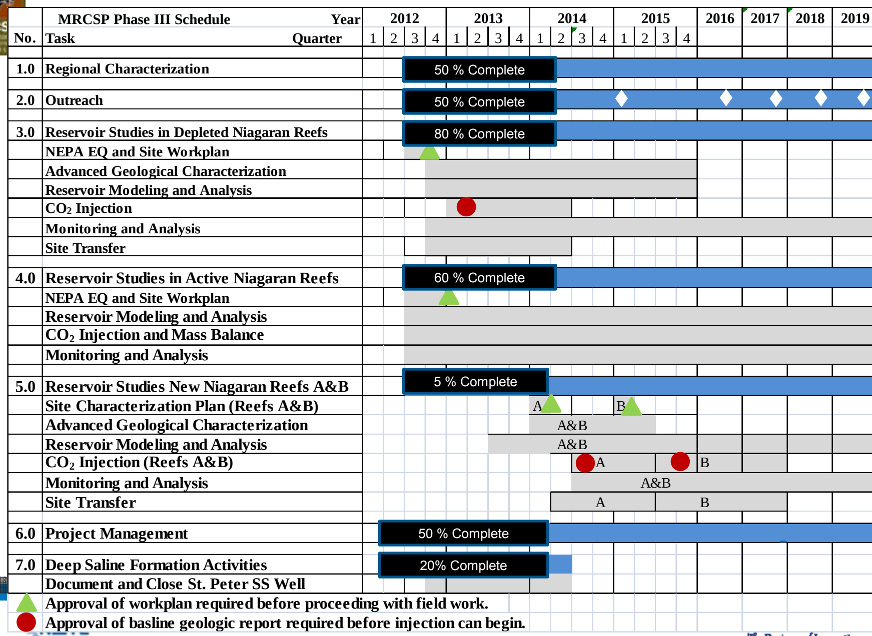
Pacific Northwest National Laboratory
Alain Bonneville
Charlotte Sullivan
**Characterization Monitoring Support**

WADE
Sarah Wade
**Outreach Working Group Coordinator**

Ohio State
David Cole
**Geochemical Monitoring**

CORE ENERGY, LLC
Robert Mannes
Rick Pardini
**Large-Scale Test Host**

# MRCSP Task Schedule




73

# Bibliography


- Kelley, M., Abbaszadeh, M., Mishra, S, Mawalkar, S., Place, M., Gupta, N, Pardini, R., Reservoir Characterization from Pressure Monitoring during CO2 Injection into a Depleted Pinnacle Reef – MRCSP Commercial-scale CCS Demonstration Project, Energy Procedia, Volume 63, 2014, Pages 4937-4964, ISSN 1876-6102
- Gerst, J., Cumming, L., Miller, J., Larsen, G., Gupta, N., Modroo, A. Using baseline monitoring data to strengthen the geological characterization of a Niagaran Pinnacle Reef. Energy Procedia, Vol. 63, 2014 pp. 3923-3934.
- Ravi Ganesh, P., Mishra, S., Mawalkar, S., Gupta, N and Pardini, R. 2014. Assessment of CO2 injectivity and storage capacity in a depleted pinnacle reef oil field in northern Michigan. Energy Procedia, Vol. 63, 2014, pp. 2969-2976.
- Miller, J. , C. Sullivan, G. Larsen, M. Kelley, W. Rike, J. Gerst, N. Gupta, D. Paul, R. Pardini, and A. Modroo. 2014. Alternative conceptual geologic models for CO2 injection in a Niagaran pinnacle reef oil field, Northern Michigan, USA. 12th International Conference on Greenhouse Gas Control Technologies, GHGT-12, Volume 63, 2014, Pages 3685–3701.
- Gupta, N., D. Paul, Lydia Cumming, et al., 2014. "Testing for Large-scale CO2-EOR and Geologic Storage in the Midwestern USA," Energy Procedia, Volume 63, 2014, Pages 6393-6403.
- Gupta, N., L. Cumming, et al. (2013). "Monitoring and Modeling CO2 Behavior in Multiple Oil Bearing Carbonate Reefs for a Large Scale Demonstration in Northern Lower Michigan." Energy Procedia 37(0): 6800-6807.


74