Darrell Paul, Program Mgr
Neeraj Gupta, Technical Mgr
Srikanta Mishra, Modeling

MRCSP
MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

Midwest Regional Carbon Sequestration Partnership

Carbon Storage R&D Review Meeting, Pittsburgh, PA

August 12-14, 2014

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

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MRCSP Presentation Outline

- Program Overview
- Technical Discussion
  - Injection operations
  - Site characterization
  - Baseline monitoring
  - Reservoir pressure analysis
  - Static modeling
  - Dynamic modeling

MRCSP: 10 Years of Achievements... and Going Strong

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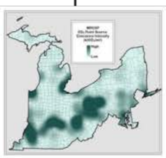
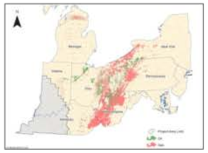
2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018

Phase I
Characterization





Phase II
Small Scale Validation

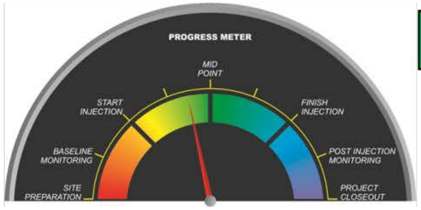
Phase III
Large Scale Development Project

Site Selection, Permitting, Site Characterization, Site Preparation, and Baseline Monitoring

OH Site | MI Saline | MI EOR Fields

MI Injection Operations (multiple fields)

Post Injection Monitoring



Project updates and results can be found at www.mrcsp.org

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Contributions From Partners Have Helped Make MRCSP Successful

AEP
AMP OHIO
ArcelorMittal
Battelle The Business of Innovation
B&W thebabcock&wilcoxcompany
bp
CEED CENTER FOR ENERGY AND ECONOMIC DEVELOPMENT
Constellation Energy Group
Consumers Energy Count on Us
CORE ENERGY, LLC
CONSOL ENERGY
Dominion It all starts here.
DTE Energy
Duke Energy.
FirstEnergy
Indiana Geological Survey 1837 Indiana University
OUCC Indiana Office of Utility Consumer Counselor
Kentucky Geological Survey UNIVERSITY OF KENTUCKY
THE Keystone CENTER
Leland Stanford Junior University 1891
DEPARTMENT OF NATURAL RESOURCES MARYLAND GEOLOGICAL SURVEY
Michigan Basin Core Research Laboratory WESTERN MICHIGAN UNIVERSITY 1903 - 2003
National Rural Electric Cooperative Association A Touchstone Energy Cooperative
NYSERDA New York State Energy Research and Development Authority
New York State Museum
NiSource
MAKING OHIO COAL THE CLEAN CHOICE
ODNR Geological Survey
Ohio Development Services Agency
O·H·I·O ENVIRONMENTAL COUNCIL KEEP WATCH, TAKE ACTION, MAKE CHANGE
THE OHIO STATE UNIVERSITY
Pacific Northwest National Laboratory Operated by Battelle for the U.S. Department of Energy
Pennsylvania Geological Survey EST. 1836
PRAXAIR
RUTGERS THE STATE UNIVERSITY OF NEW JERSEY
RWE
University of Maryland 1856
WADE
財團法人中興工程顧問社
WVGES West Virginia Geological and Economic Survey
West Virginia University. Where Greatness is Learned

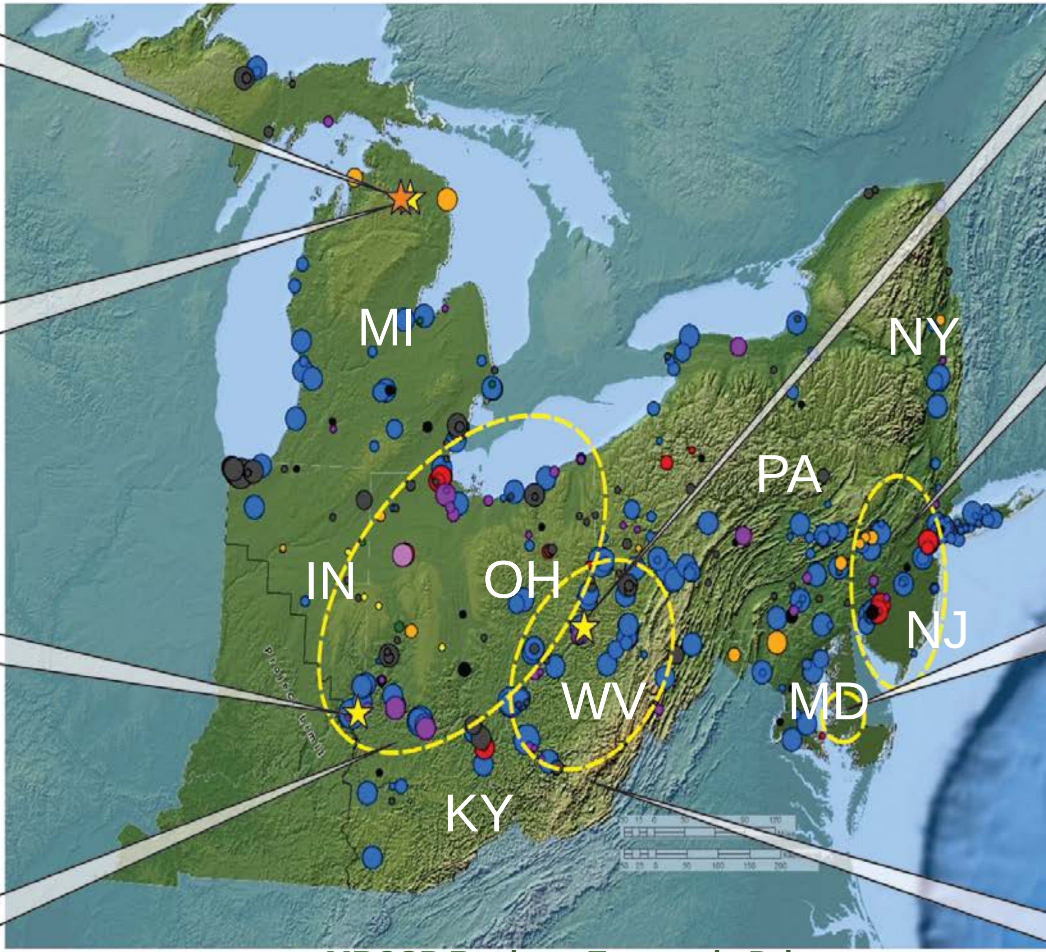
MRCSP Field Test Sites

Phase III EOR Fields
Core Energy

Michigan Basin
DTE Energy

Cincinnaty Arch
Duke Energy
East Bend Station

Croplands



Appalachian Basin
First Energy
R.E. Burger Plant

Forested Wetlands

Tidal Marshlands

Reclaimed Mineland

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**

Regional Characterization Critical for Developing Implementation Plans

Nine State Geo Teams assist in identifying and characterizing reservoirs across state lines

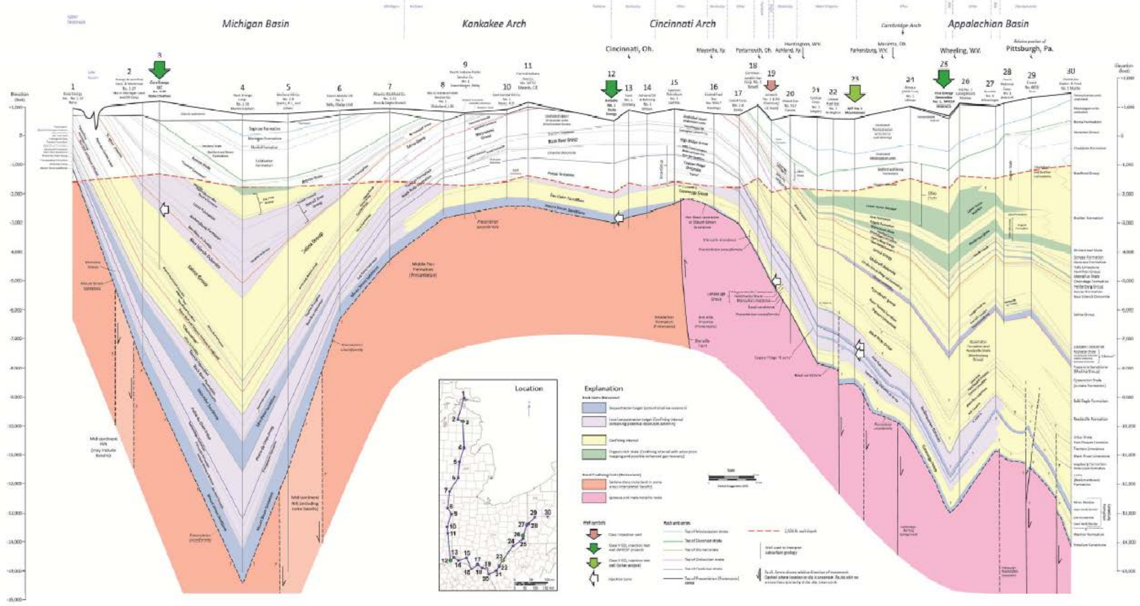
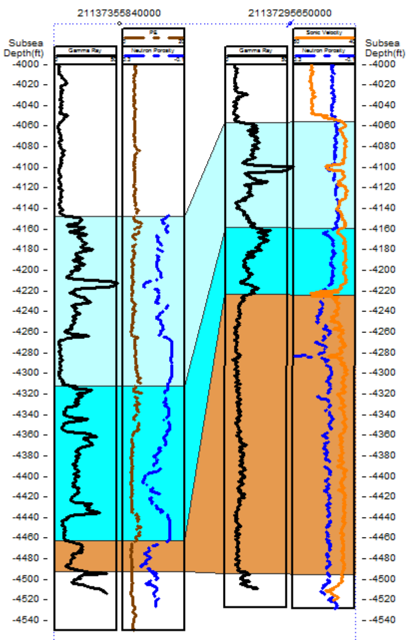


Figure 4. Cross Section of subsurface geology for carbon sequestration for part of the MRCSP region



Piggyback wireline logging, coring, etc. fills gaps in knowledge base, and stretches research funds

Ohio Coal Development Office strong supporter of geological characterization efforts through cofunding of activities.

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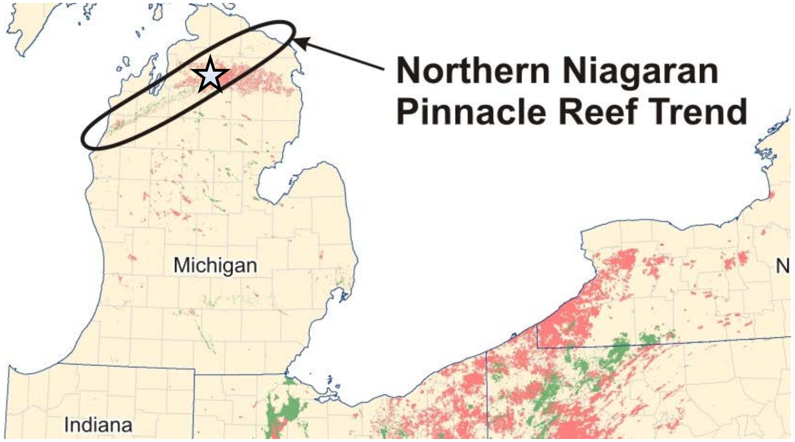
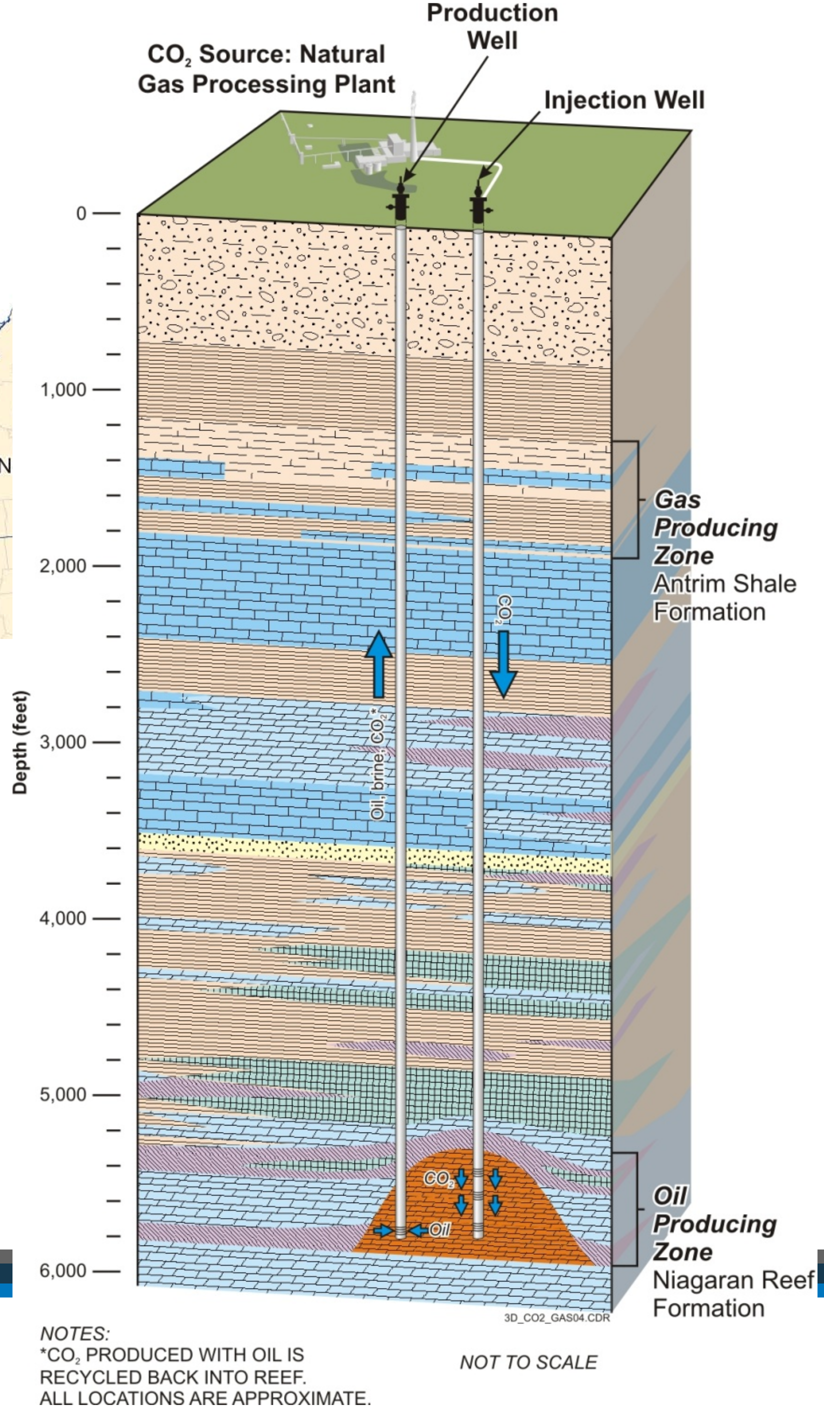
Large Scale Demonstration Site



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



Outreach and Education Critical to Success of the Program

- DOE/NETL Best Practices Manuals
- NATCARB Database and Publications
- EPA Guidelines Requests for Comments
- Industry Mtgs & Conferences
- Trade Associations

<u>Proactive Approach</u>

- Communication Plan
- Annual Partner's Meetings
- Site Visits
- Community Relations
- Outreach Materials
- Website

Acknowledgements

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

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

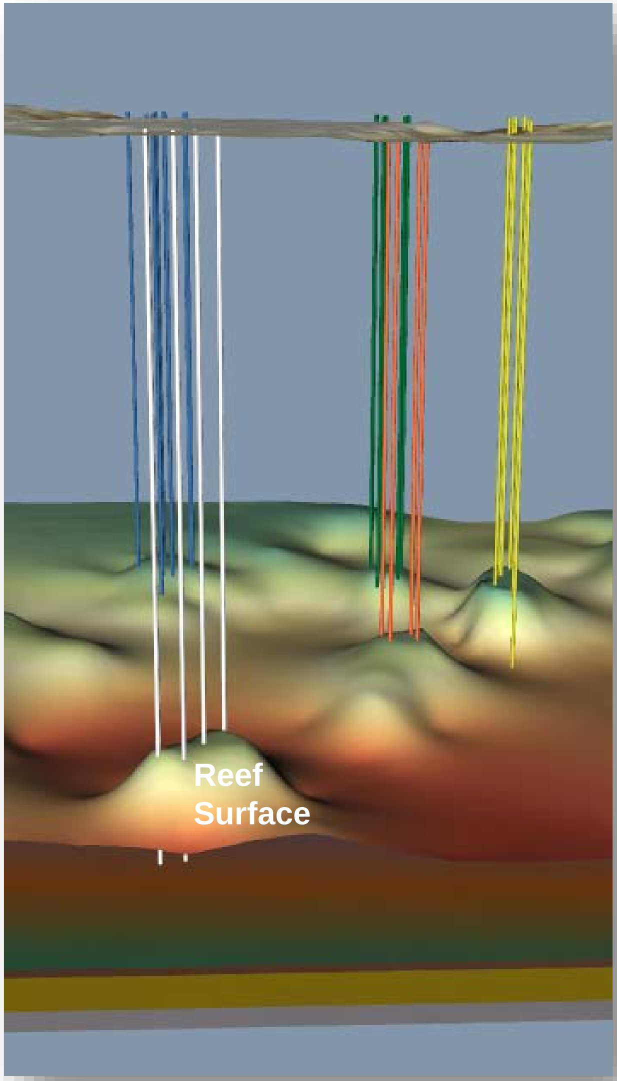
The nine state **Geology Surveys and Universities** have been essential in expanding the results into regional implementation plans.

Battelle's MRCSP team members for work shown here

EOR Field Evaluation Across Life Cycle Stages

Oil fields in various production stages

- **Late-Stage EOR Reefs (Task 3)**
  Highly depleted with extensive primary and secondary oil recovery.
- **Active EOR Reefs (Task 4)**
  Completed primary oil recovery and secondary oil recovery is under way
- **Pre-EOR Reefs (Task 5)**
  Undergone primary oil recovery but no secondary oil recovery is attempted

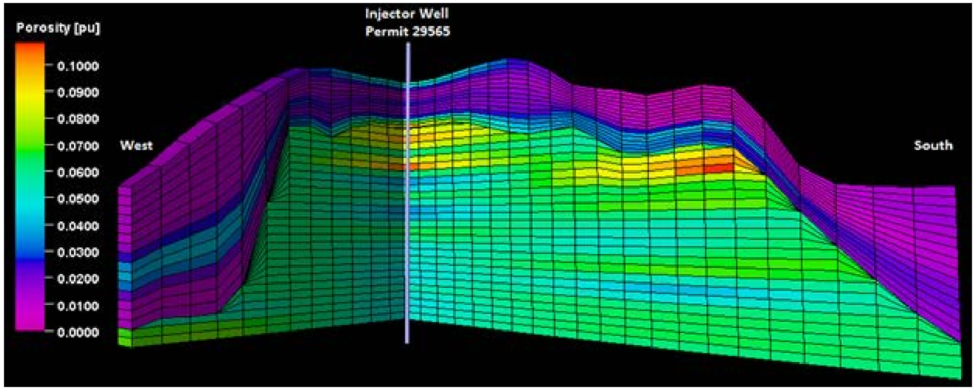


Summary of Progress

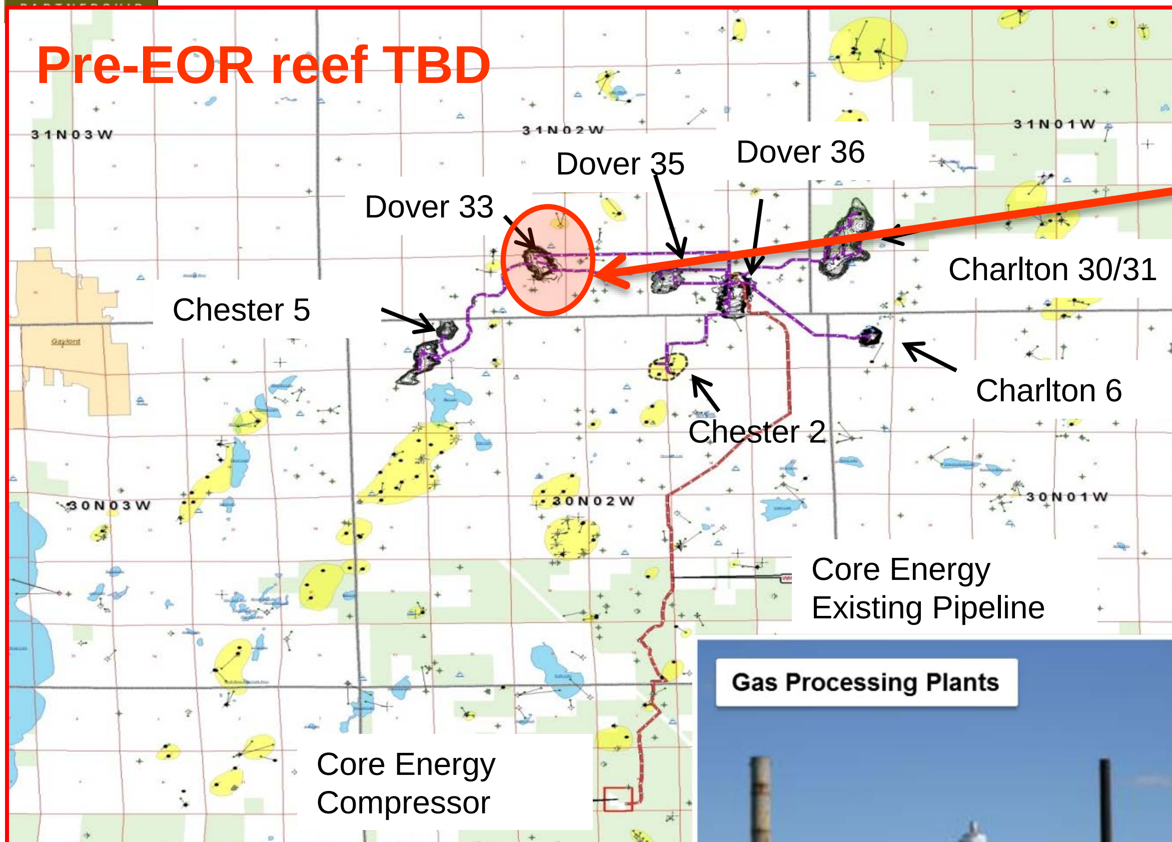
- Completed baseline monitoring and site preparation
- ~240,000 metric tonnes injected in late state reef
- >25,000 metric tonnes net CO_2 in active EOR reefs
- Operational and subsurface monitoring underway
- Reservoir analysis shows closed reservoir conditions
- Phase chance and compressibility affect pressure
- Initial static and reservoir models prepared
- Injection in new EOR reefs likely to start in early 2015
- Regional mapping/characterization across nine states

Many Operational and geological factors affect CO_2 injection and storage in EOR Fields

- Production history for each reef needs to be known, including:
  - Original estimates of fluids (oil, gas, brine)
  - Primary production history
  - Secondary recovery, CO_2 injection and retention
- Current operational constraints determine how much CO_2 is stored within each reef at a given time
- Geologic factors such as:
  - Size of the reservoir
  - Configuration of the wells
  - Relative permeability
  - Solubility of CO_2 in brine and oil
  - Reservoir temperature and pressure

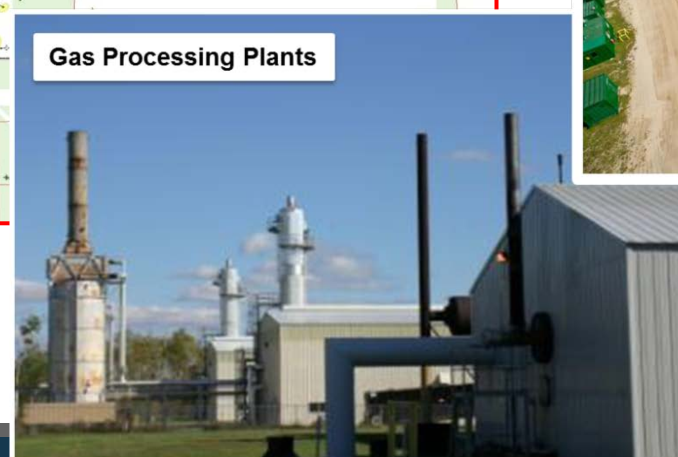


Core Energy's EOR Infrastructure used for Testing CO_2 Storage



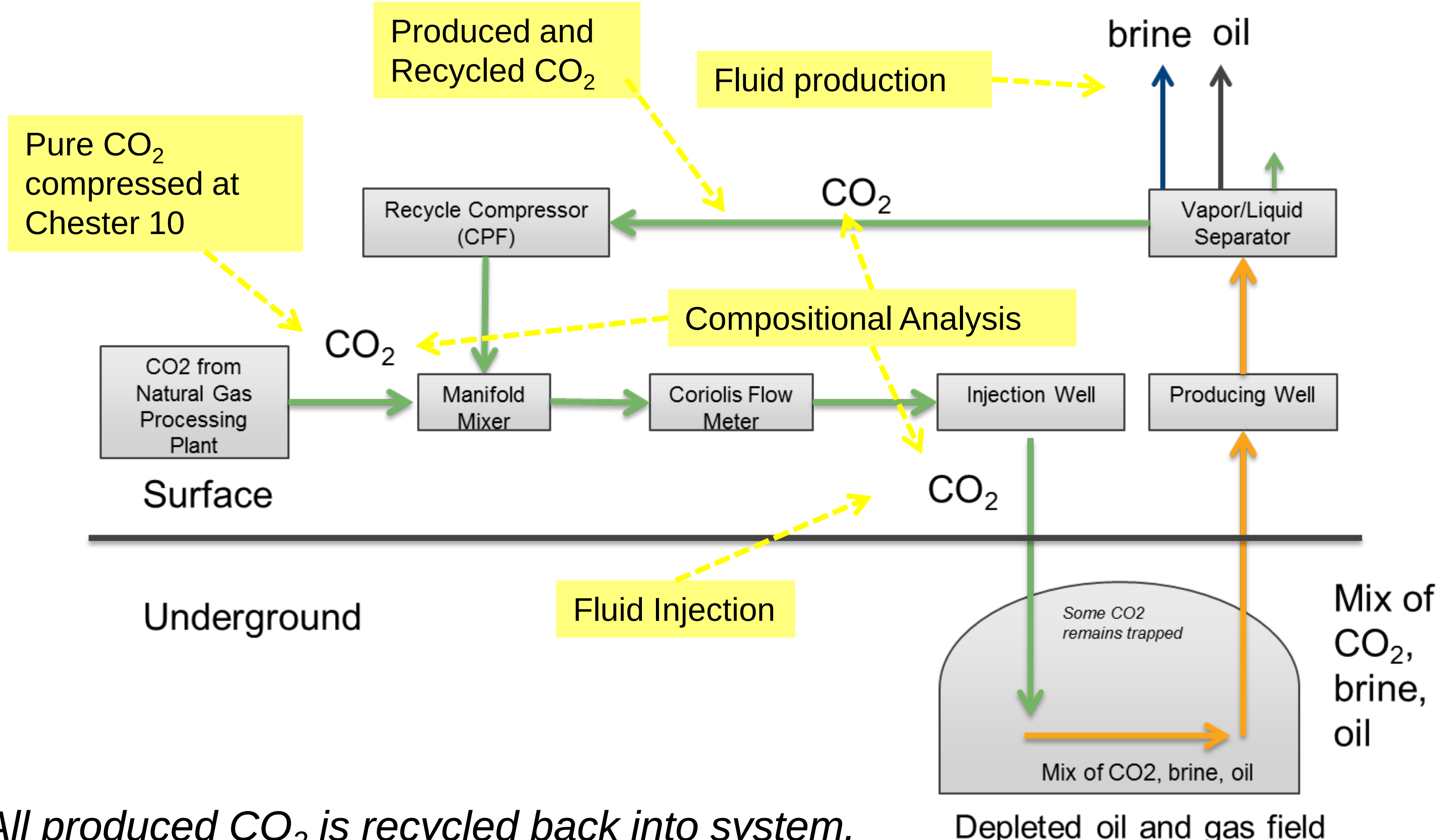
Dover 33 is the main test bed

Active reefs also being monitored



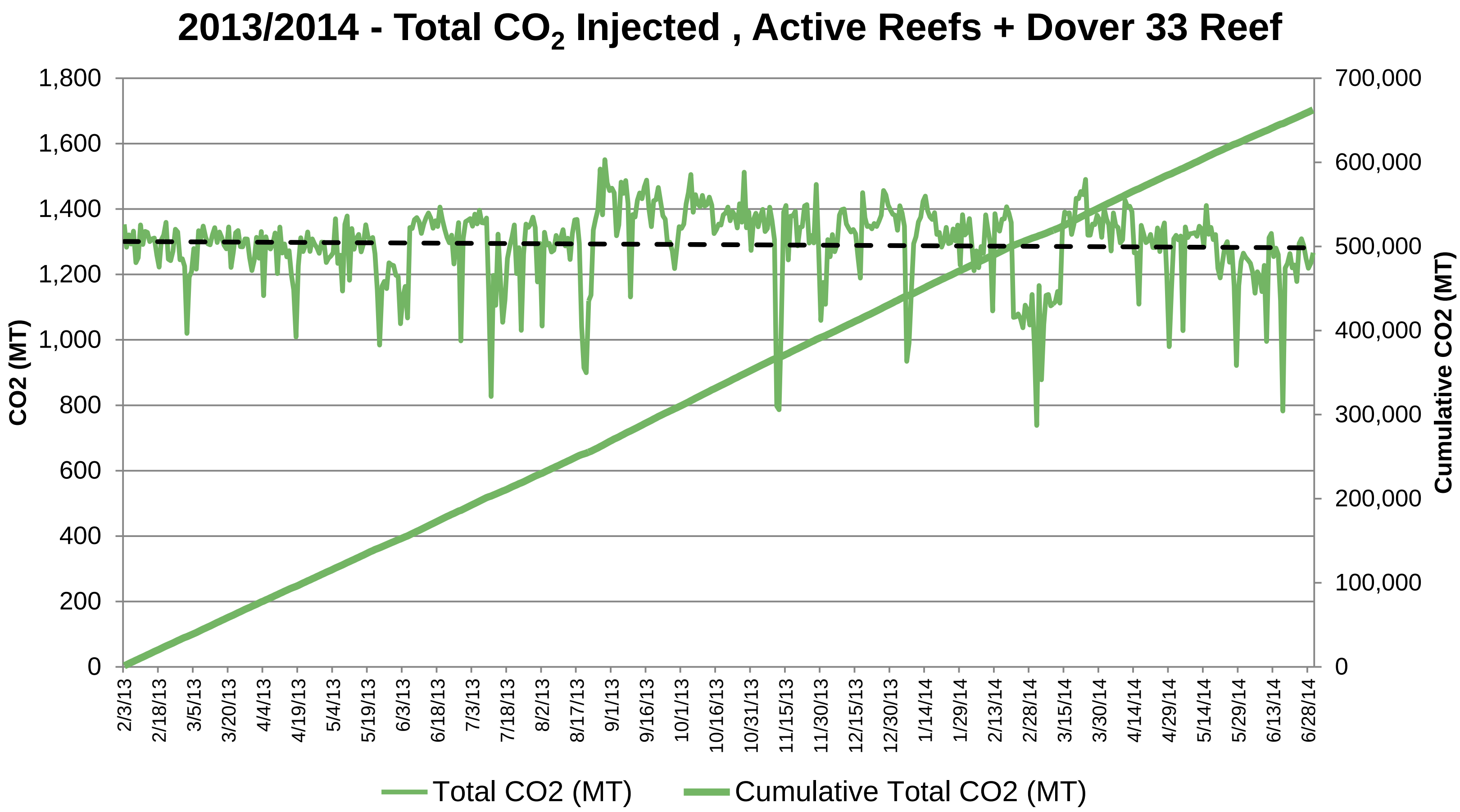
Natural gas processing provides the CO_2

CO_2 Flow System

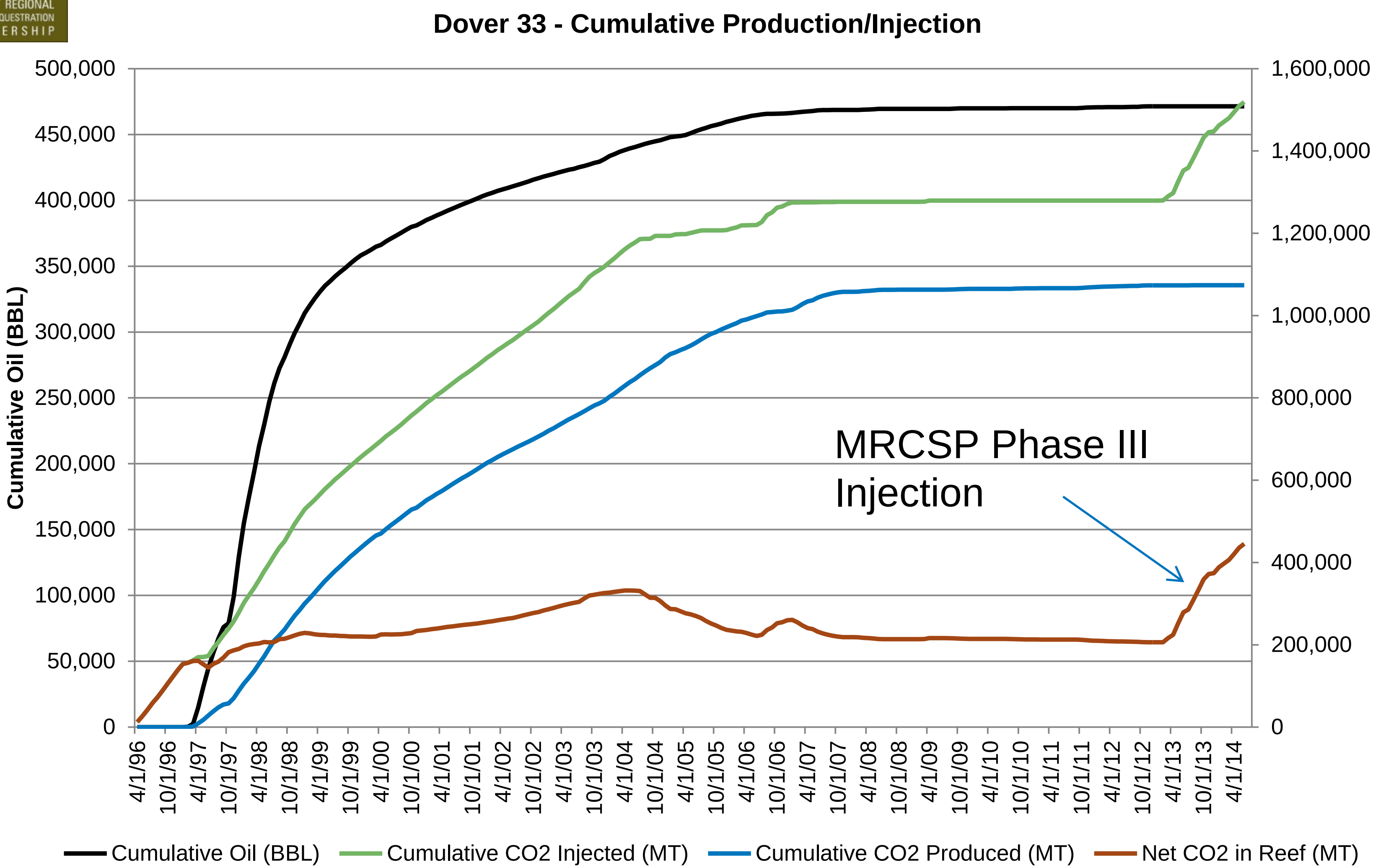


All produced CO_2 is recycled back into system.

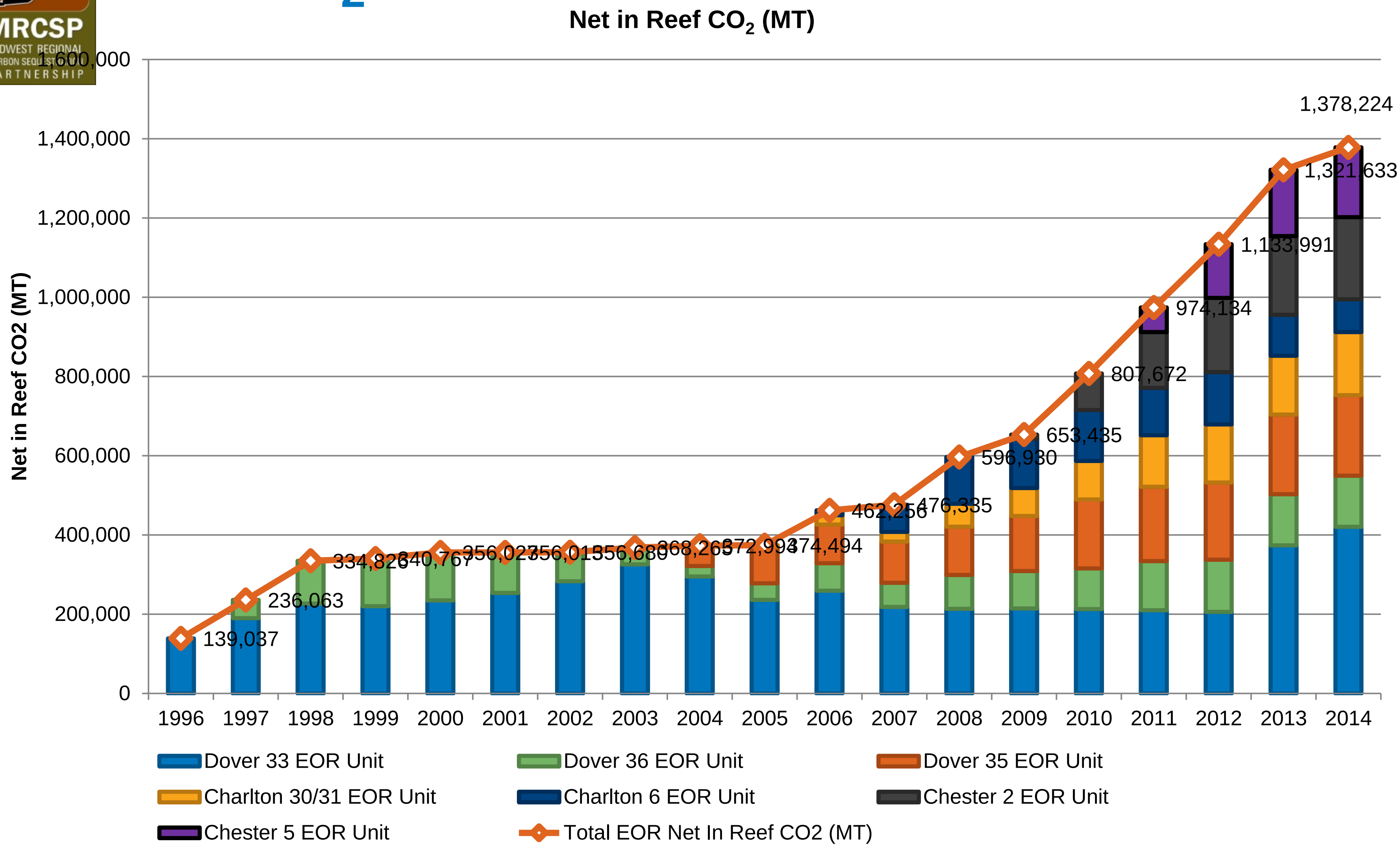
Injected CO_2 (includes pure CO_2 from Chester 10 + produced/recycled CO_2)



Dover 33 Reef EOR Operations

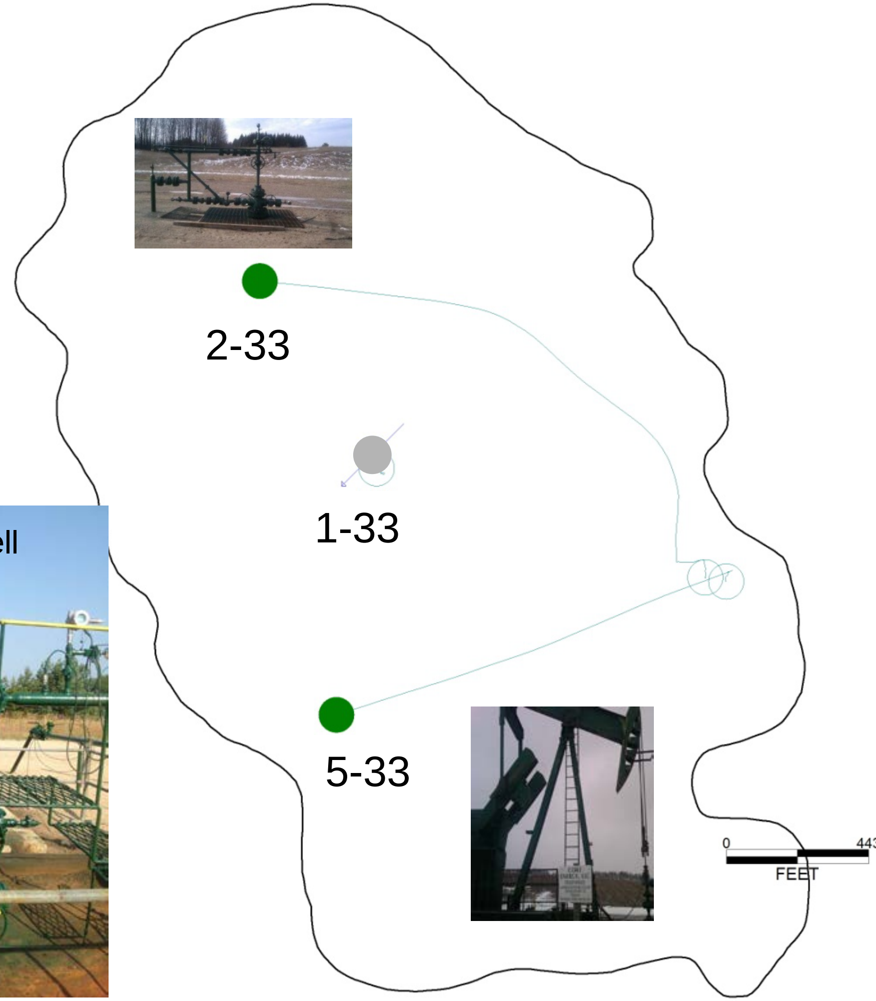


Net CO_2 in reefs increases over time



Dover 33 Reef Wells

- 3 active wells
- Well 1-33 (vertical well) is the CO_2 Injection well.
- Well 2-33 (horizontal well) is a former production well that was used as a monitoring well. This well is an open borehole.
- Well 5-33 (high angle well) is a former production well that was used as a monitoring well.



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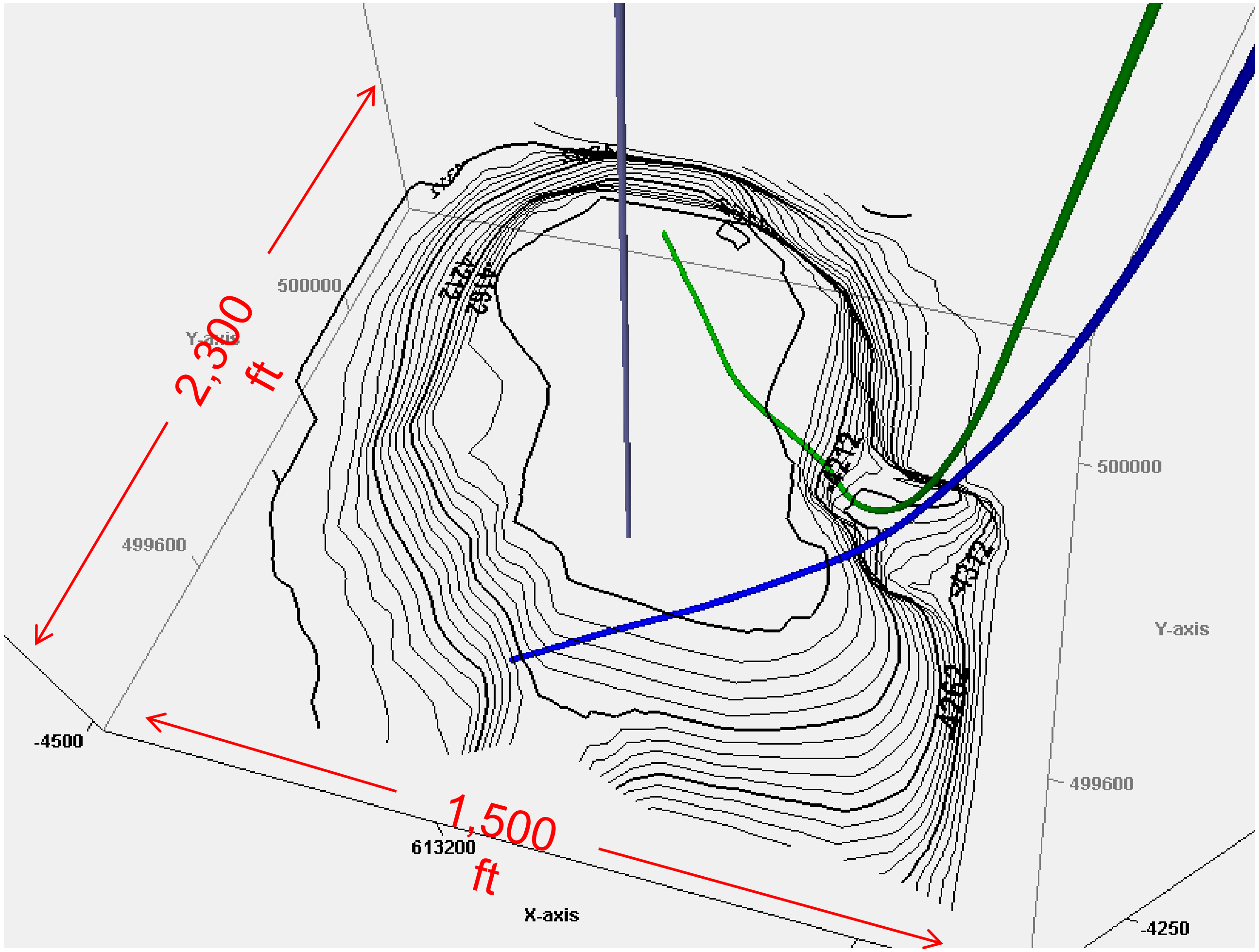
Dover 33 Reef Showing Well Traces

Surface of A-1 Carbonate Showing Reef Structure



A portfolio of technologies is being tested at the Dover 33 late stage reef

Activity	Before Injection	Early Injection	Mid Injection	Late Injection	After Injection
CO_2 flow		X	X	X	
Pressure and temperature	X	X	X	X	X
Wireline logging	X		X		X
Borehole gravity	X				X
Fluid sampling	X		X		X
VSP	X				X
Microseismic	X			Maybe	
Satellite radar	X	X	X	X	X

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

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Baseline monitoring activities

2012			2013											
Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Baseline Characterization							Long-Term Injection Operations							

Apr

InSAR

Baseline Geochemical Sampling

Well Workovers and Wireline Logging

Gravity Survey

Vertical Seismic Profiling

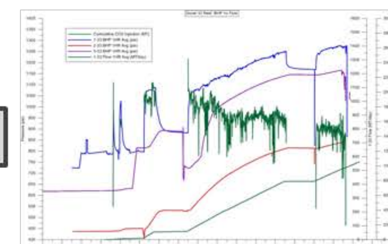
Reservoir Testing and Microseismic Testing

Start of Long-Term Injection – April 23

Repeat Geochemical Sampling

Pressure Fall Off Testing

Repeat Geochemical Sampling



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MRCSP Midwest Regional Carbon Sequestration Partnership

Safety Considerations for MRCSP Fieldwork

- 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

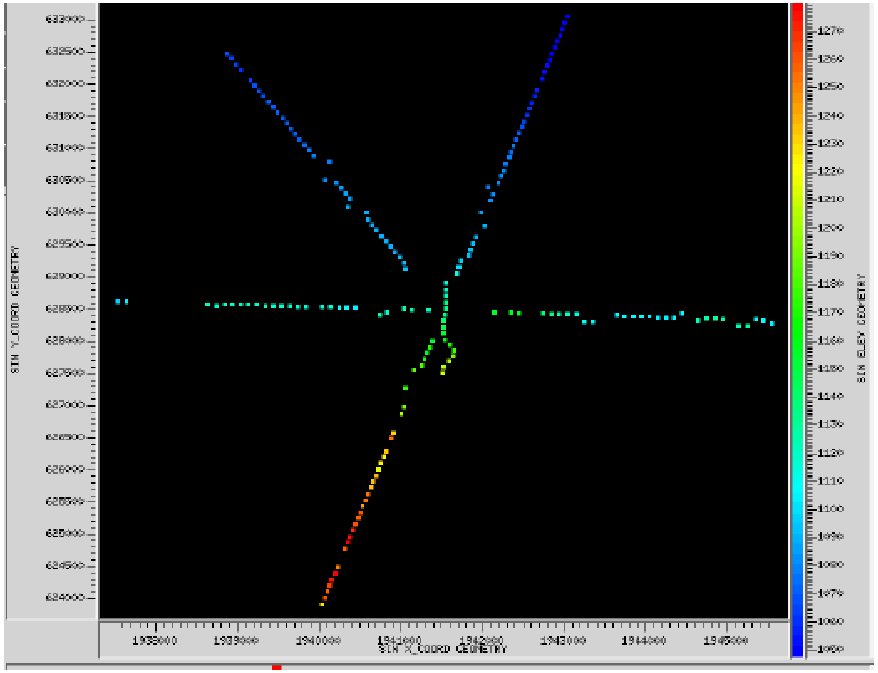
Well Workovers – well control, overhead hazards, heavy equipment

Seismic Activities – well work, explosive hazards

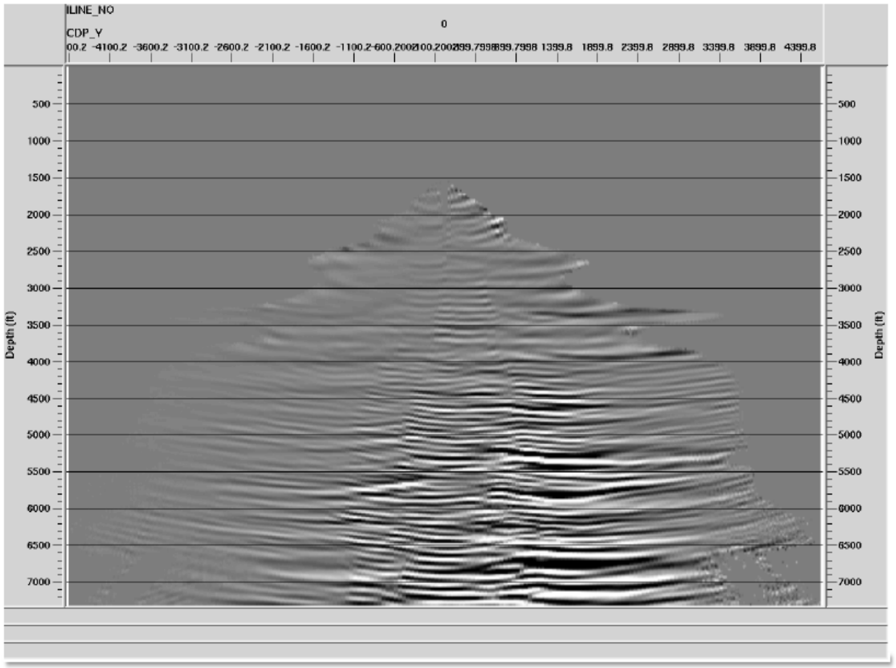
Wireline Logging – well work, radiologic hazards

Vertical Seismic Profile

- Five walk-away lines centered around 1-33 injection well
- Processed data shows increase in resolution, though questions remain regarding potential migration errors
- VSP will be repeated after injection is completed



Receiver Locations



North-South Line

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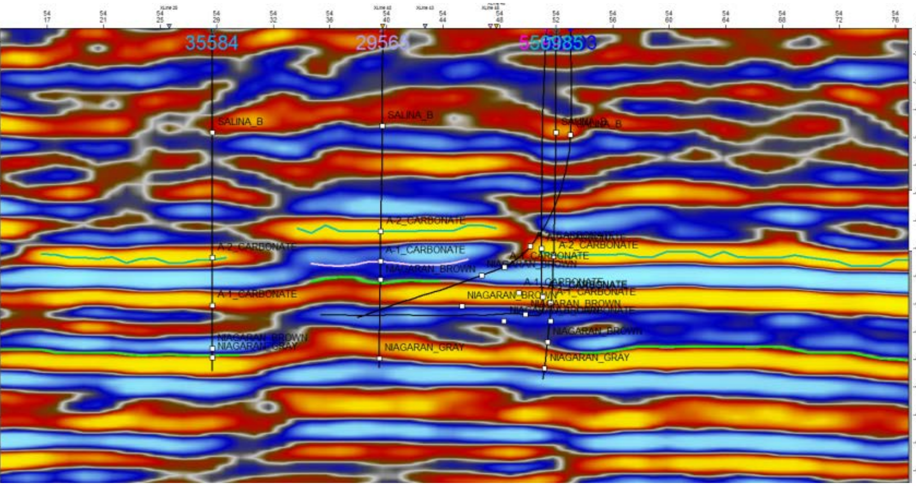
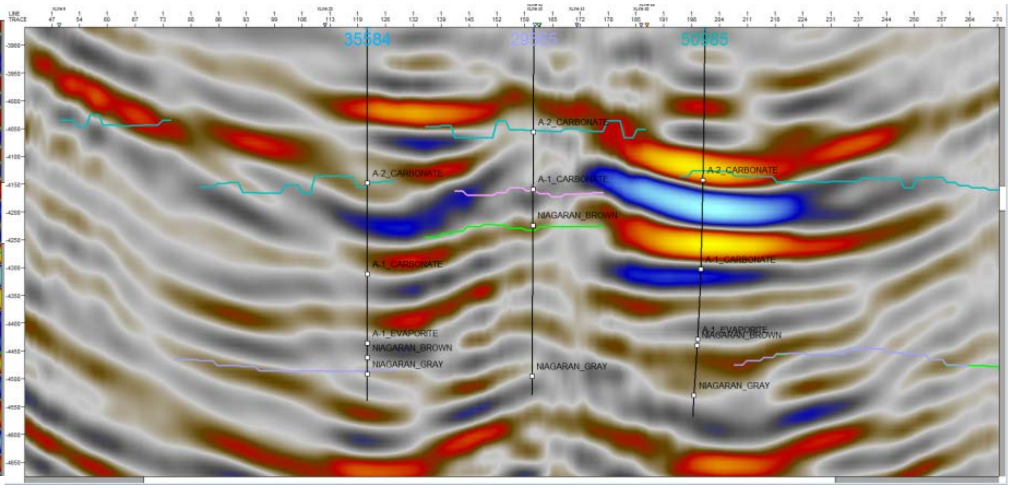
Comparison of Surface and Borehole Seismic Data

- 3D Data

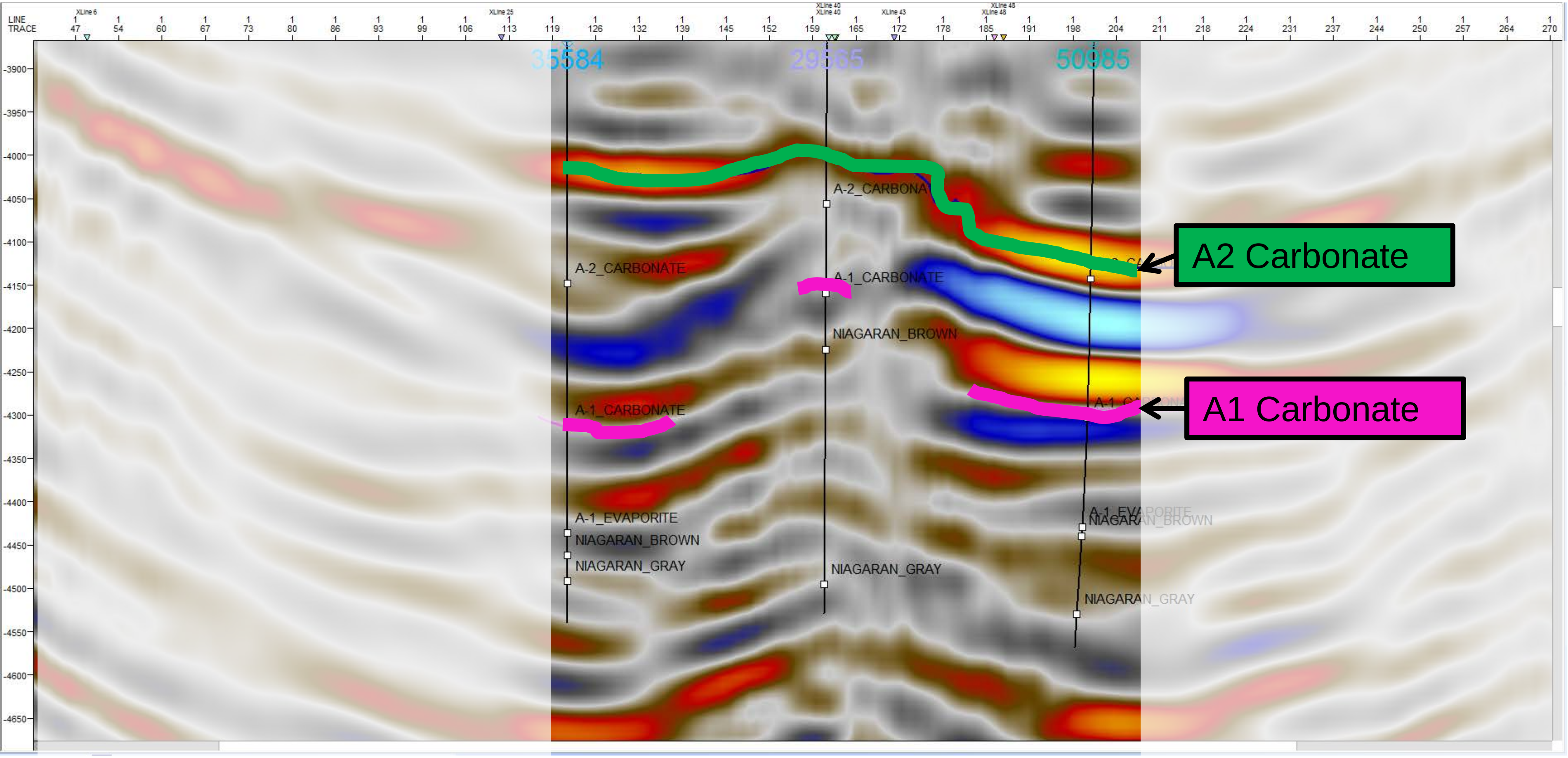


- VSP



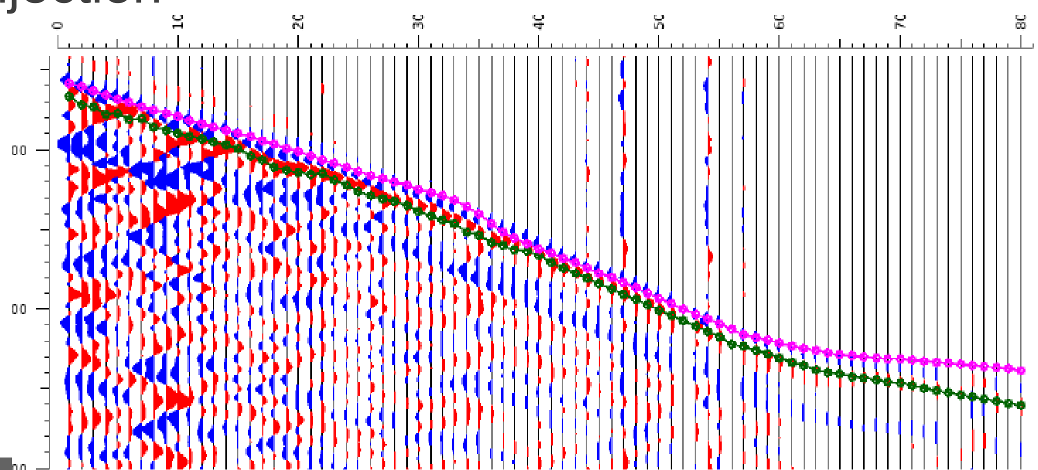
- The two images show nearly the same geologic slice
- The VSP shows higher resolution and more internal reef character
- Curvature seen on the edges of the image is a processing artifact

East-West VSP Line Detail

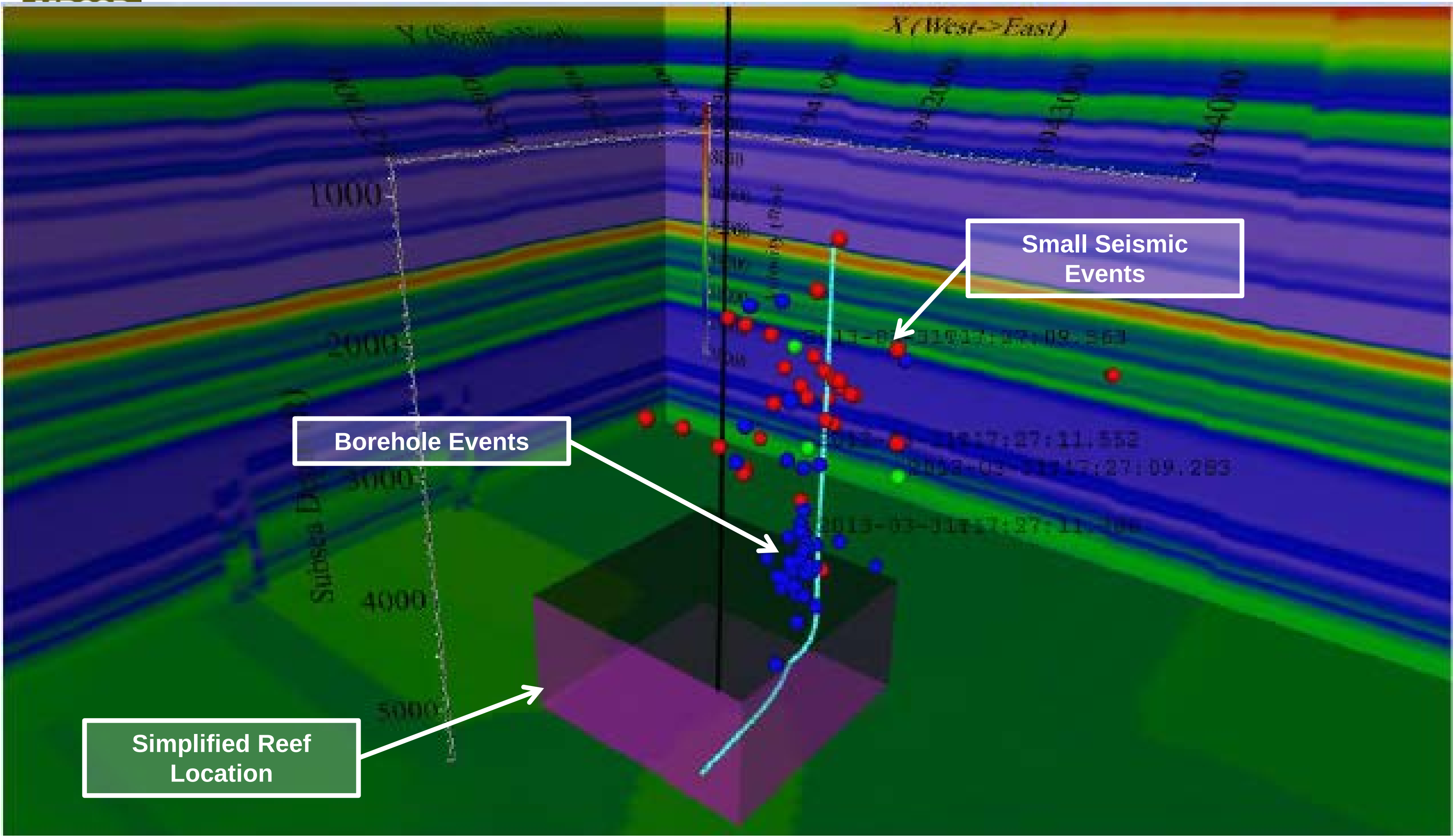


Microseismic Monitoring

- Monitoring in Dover 33 well 5-33 from 3/20/13 - 4/1/13, during and after a short injection test
- Data quality was good for confidence in event picks
- 34 events recorded, but none in the reef
  - Detectable events verify the ability of the array to detect events
  - Events were located using a velocity model created from the available sonic logs in and around the reef
- Maybe repeated after injection



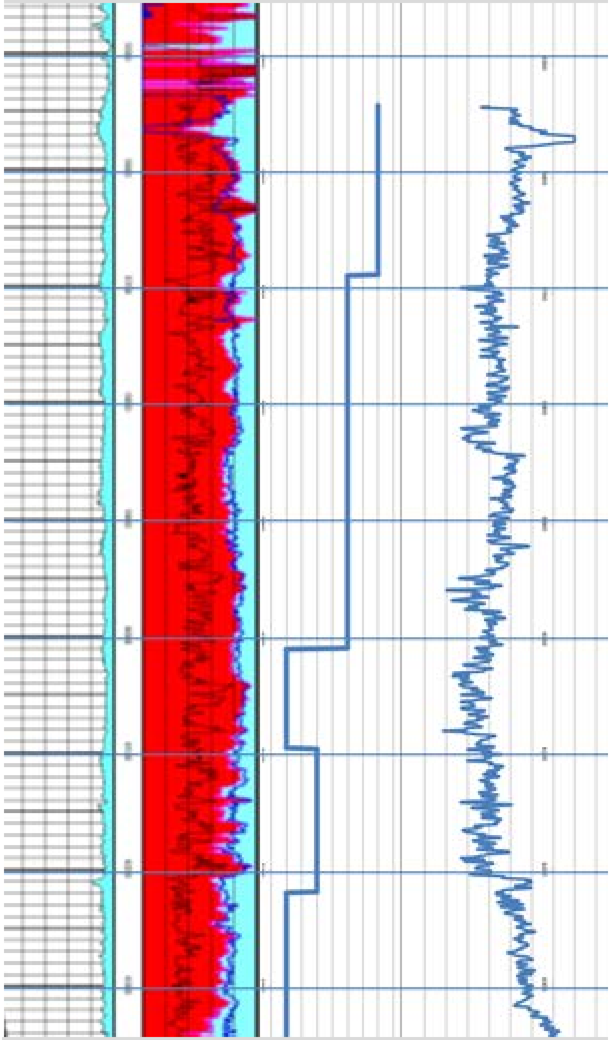
Microseismic Event Locations



Pulsed Neutron Capture

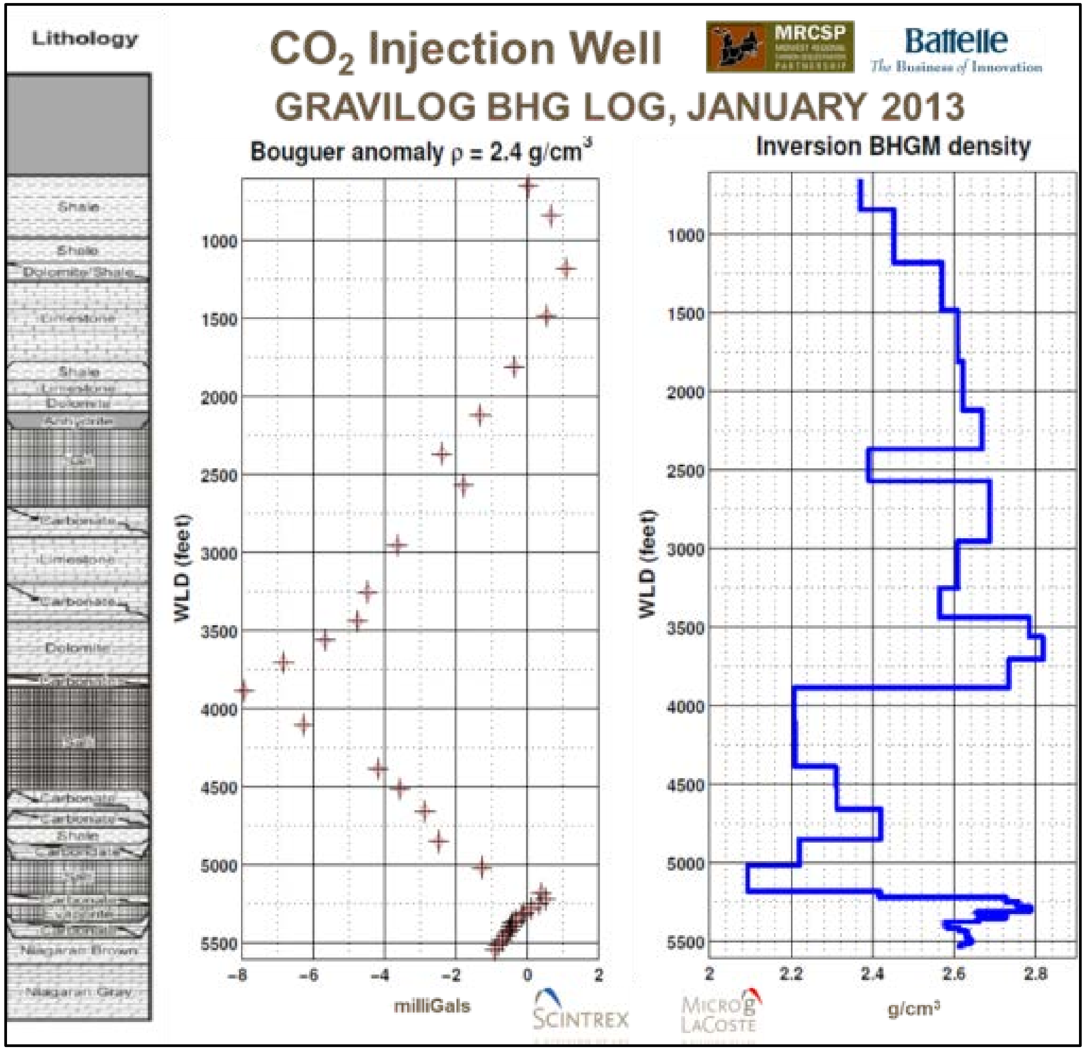
- Completed baseline and repeat logs in two wells (2-33 and 5-33)
- Processing to distinguish liquid (oil/brine) from gas (CO_2/methane) phase
- Additional processing may distinguish between oil and brine
- Initial results show increase in fluid phase constituents and a decrease in gas phase constituents – CH_4 dissolving in oil and CO_2 phase change to supercritical?
- Further logging events may also help distinguish phase behavior from fluid saturations

Well 5-33 repeated data, showing data from 2012 to 2013



Borehole gravity surveys conducted to measure CO_2 saturation

- Gravity meter takes point measurements along the injection wellbore
- Data is then converted to density
- Repeat surveys indirectly measure the change in CO_2 saturation



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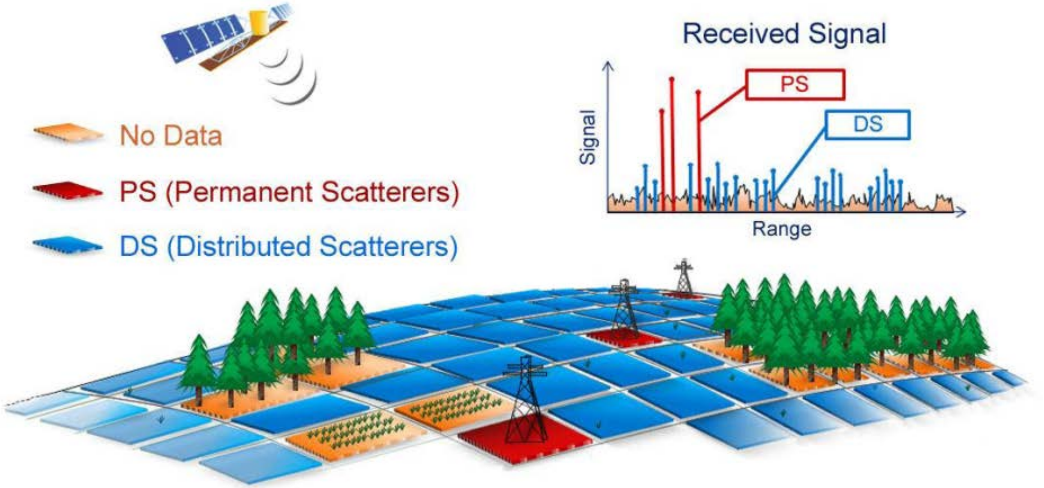
Geochemical sampling and analysis

- Major and trace element in fluids
- Isotopic composition of gas, water, carbon compounds
- Seeking regional core samples to analyze mineralogy, porosity, pore networks
- Integrating results into predictive models to better understand geochemical processes
- In collaboration with Ohio State

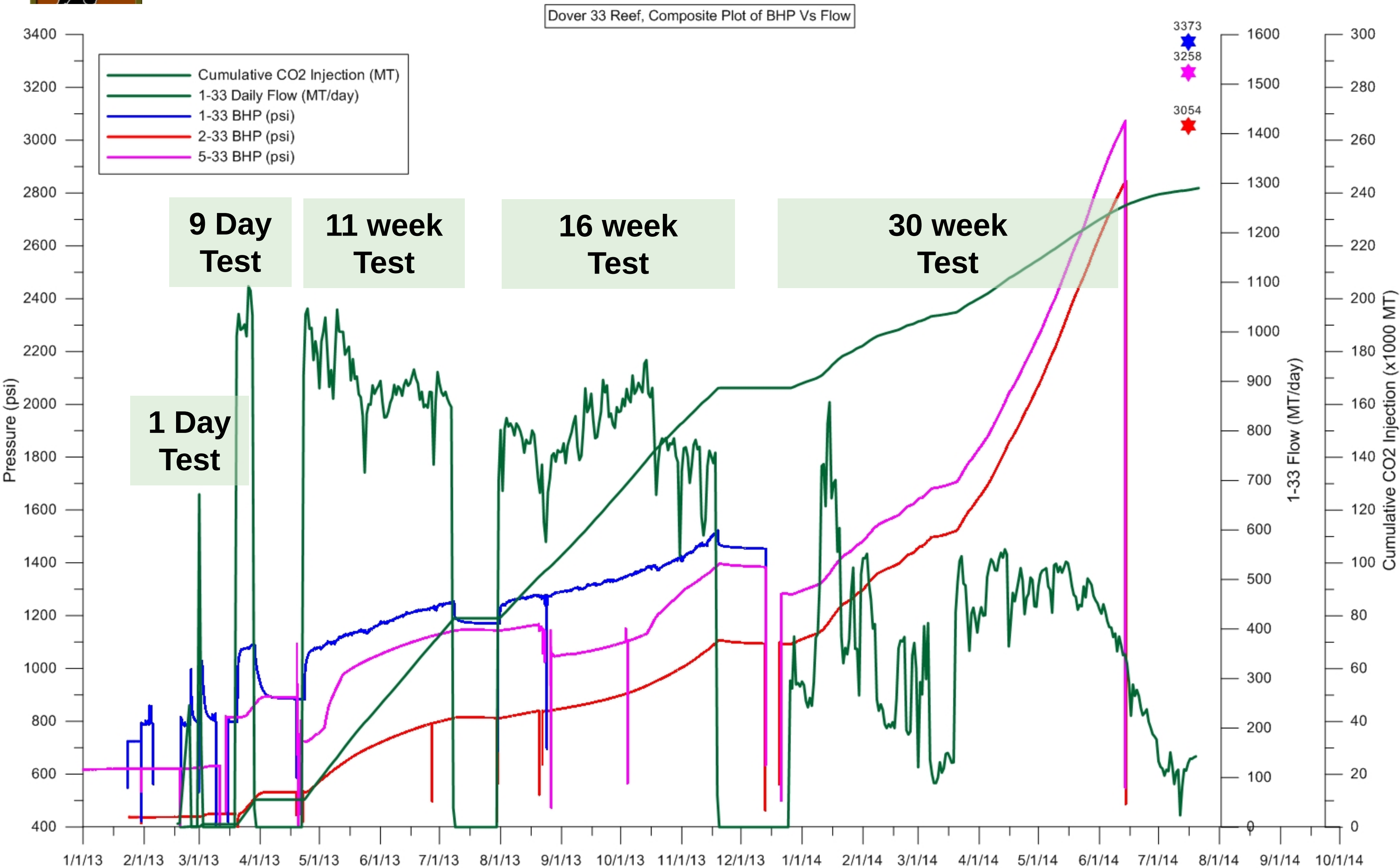
High precision measurements of the ground surface using satellite radar (InSAR)

- Installed reference points (ACRs)
- Completed historic analysis and >one year of operational monitoring
- No significant elevation change detected so far



Source: TRE Canada, Inc.

CO_2 Injection and Pressure Response



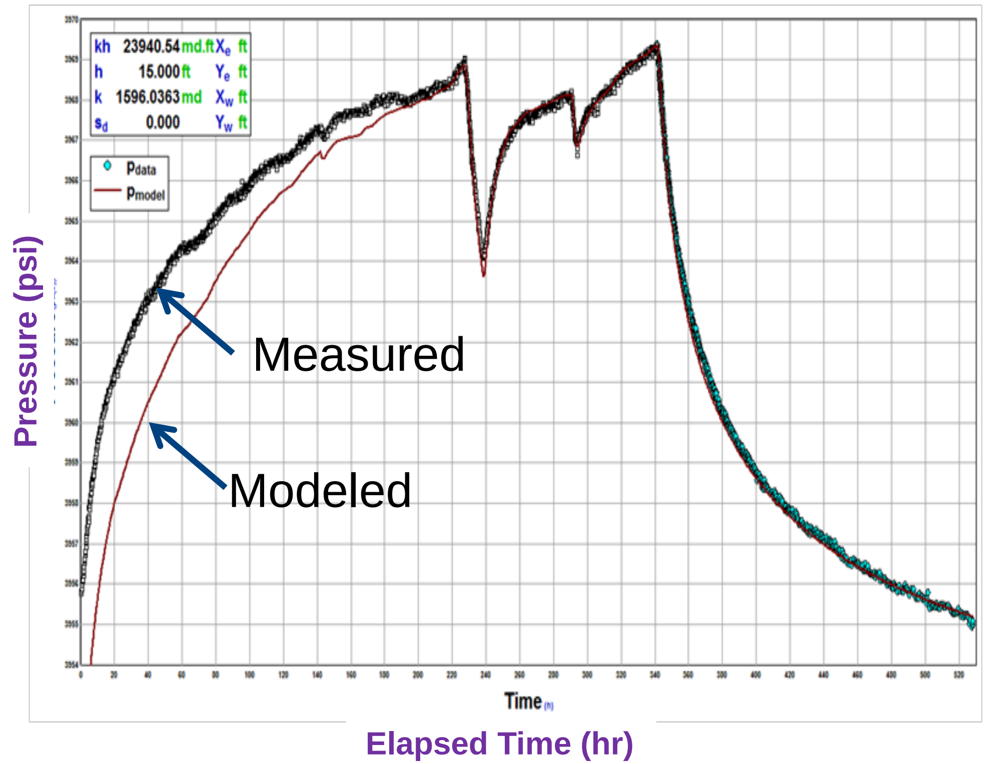
*Pressure in 1-33 injection well available only thru 12-26-13

History Matching Method Was Used for Analyzing Injection-Fall-Off Tests

- History matching was implemented using analytical reservoir model (WellTest™)

- History matching process:
  - Using measured injection record for each CO_2 injection test, simulate pressure response in the injection well and monitoring wells;
  - Adjust model parameters to match the measured pressure response during the injection-falloff sequence

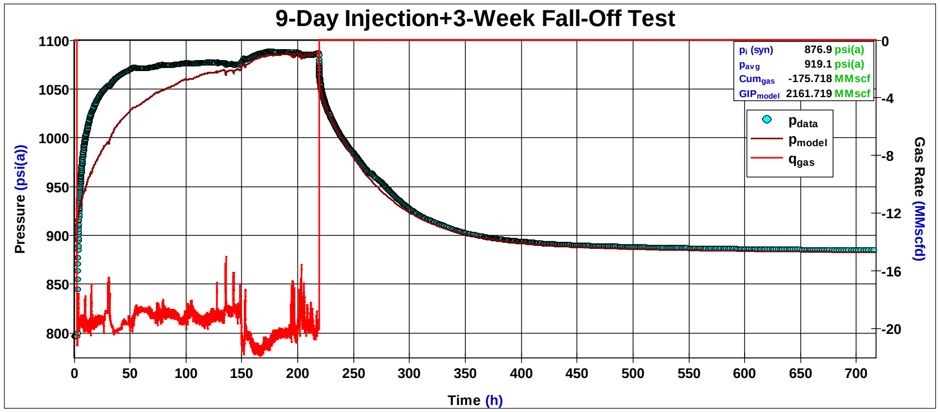
---------- Injection ------------ ----Fall-Off ---



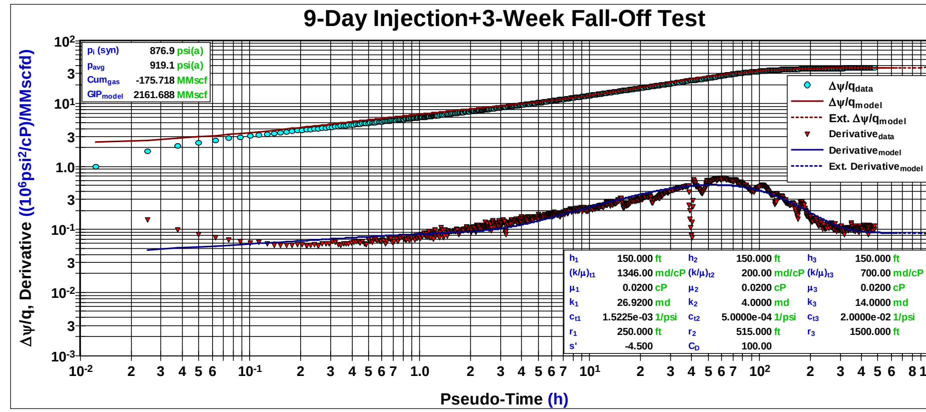
Example History Match Plot for a Single Injection Fall-Off Event

9-Day Test

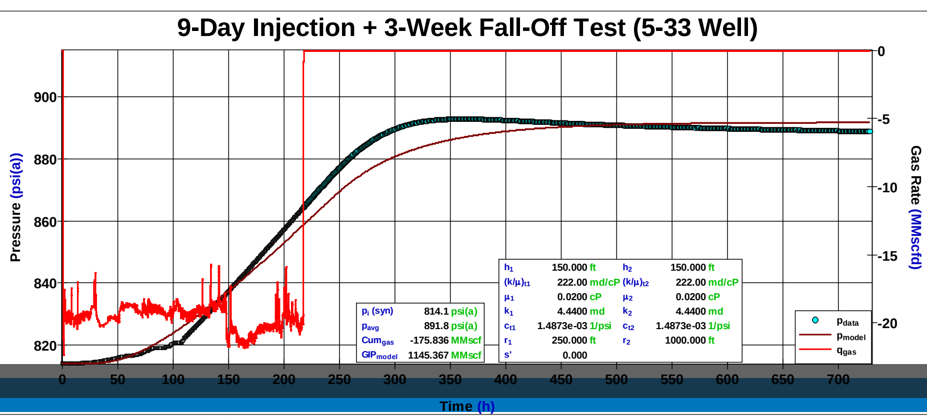
Injection Well Pressure Match



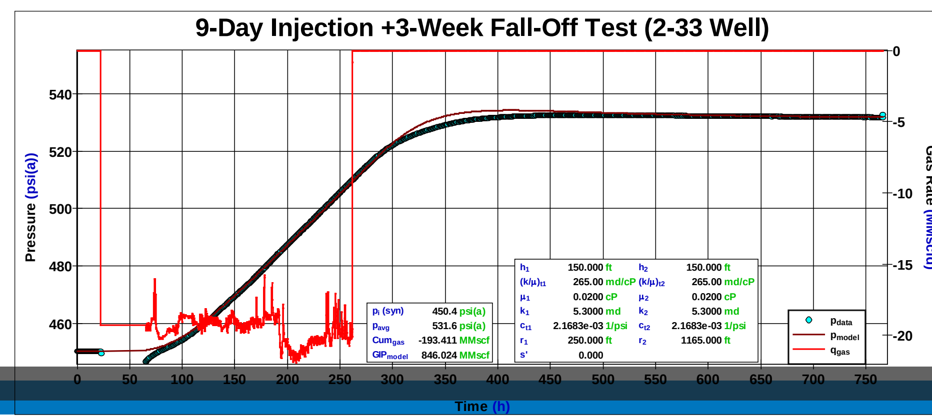
Injection Well Derivative Match



Monitoring Well 5-33



Monitoring Well 2-33



16-Week Test

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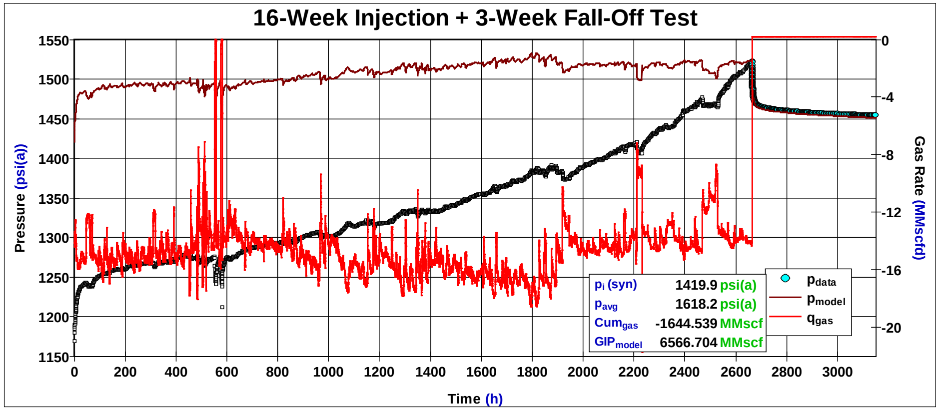
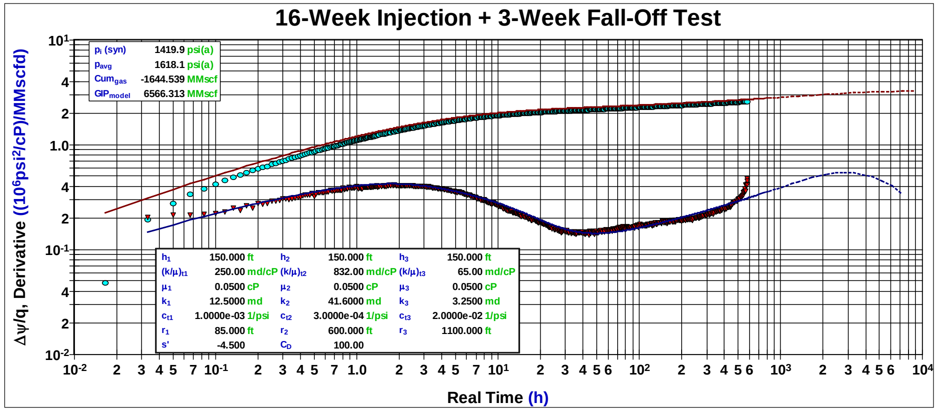
Injection Well
Pressure Match

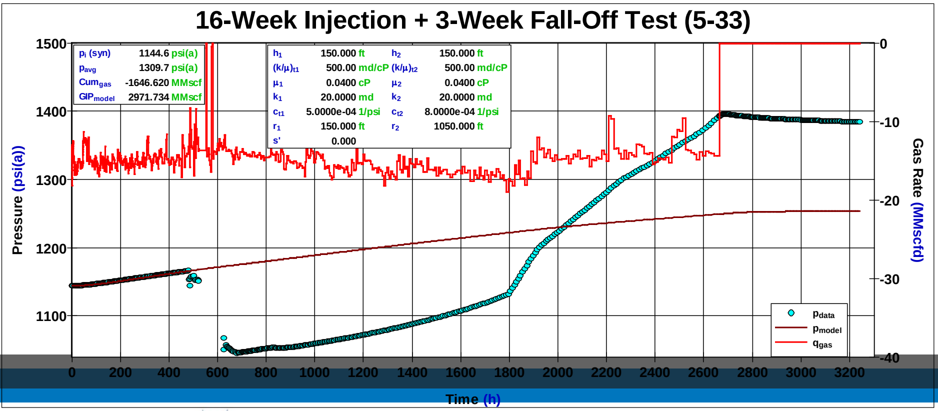
Injection Well
Derivative Match

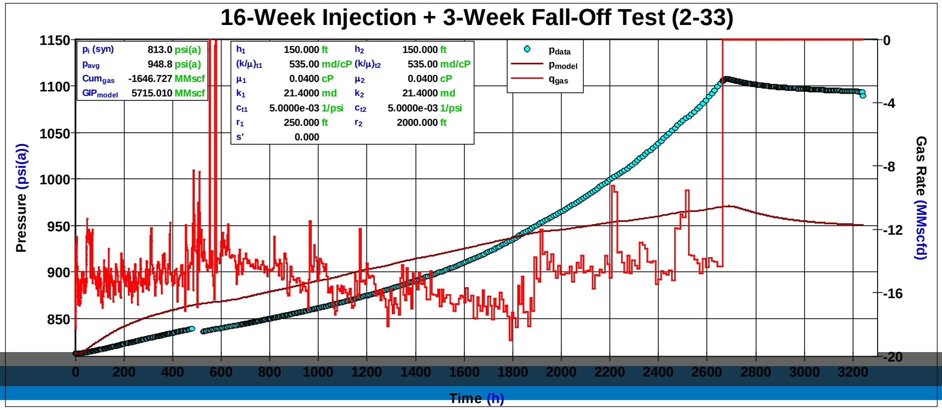




Monitoring Well 5-33

Monitoring Well 2-33



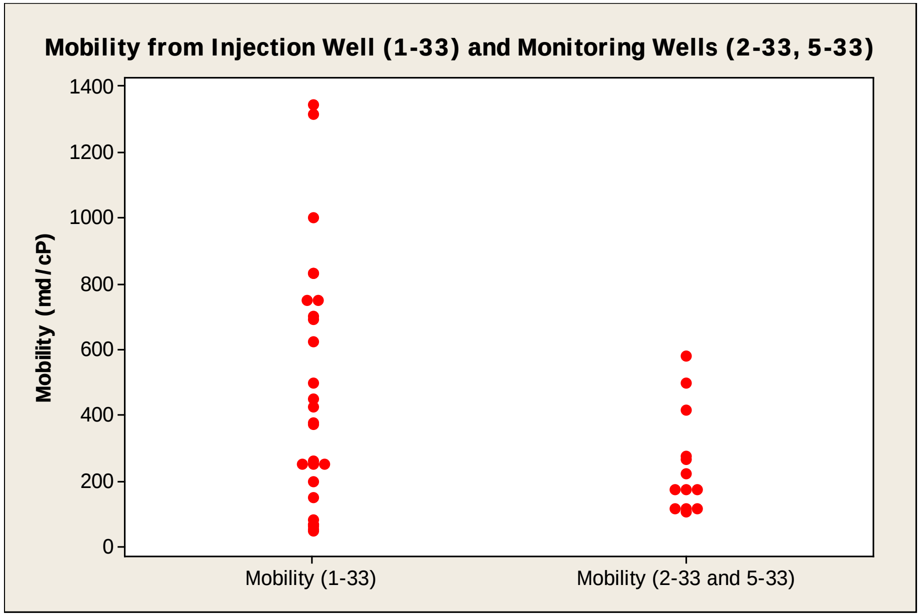


Could not match

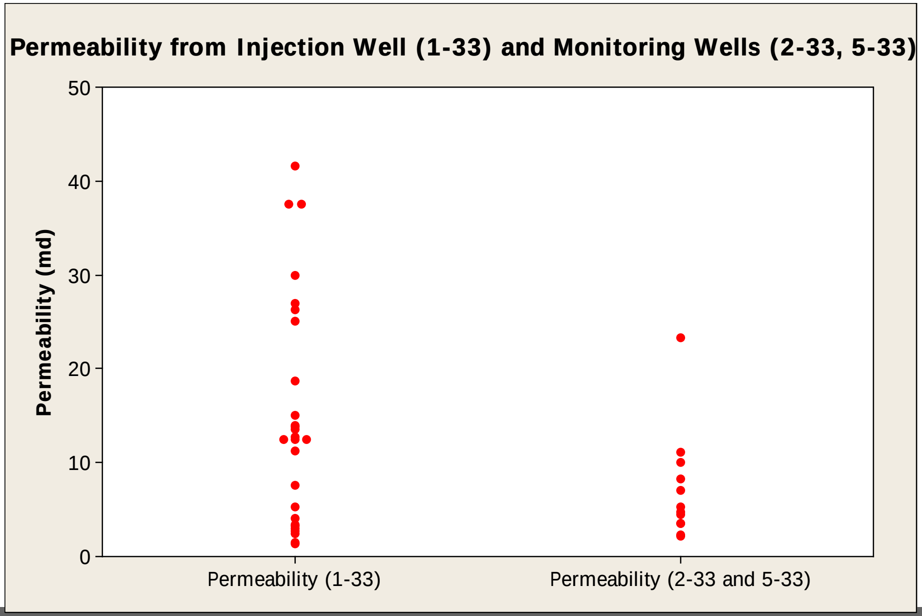
Could not match

Results

Comparison of Mobility Values from Injection Well Data (left) and Monitoring Well Data (right)



Comparison of Permeability Values from Injection Well Data (left) and Monitoring Well Data (right)



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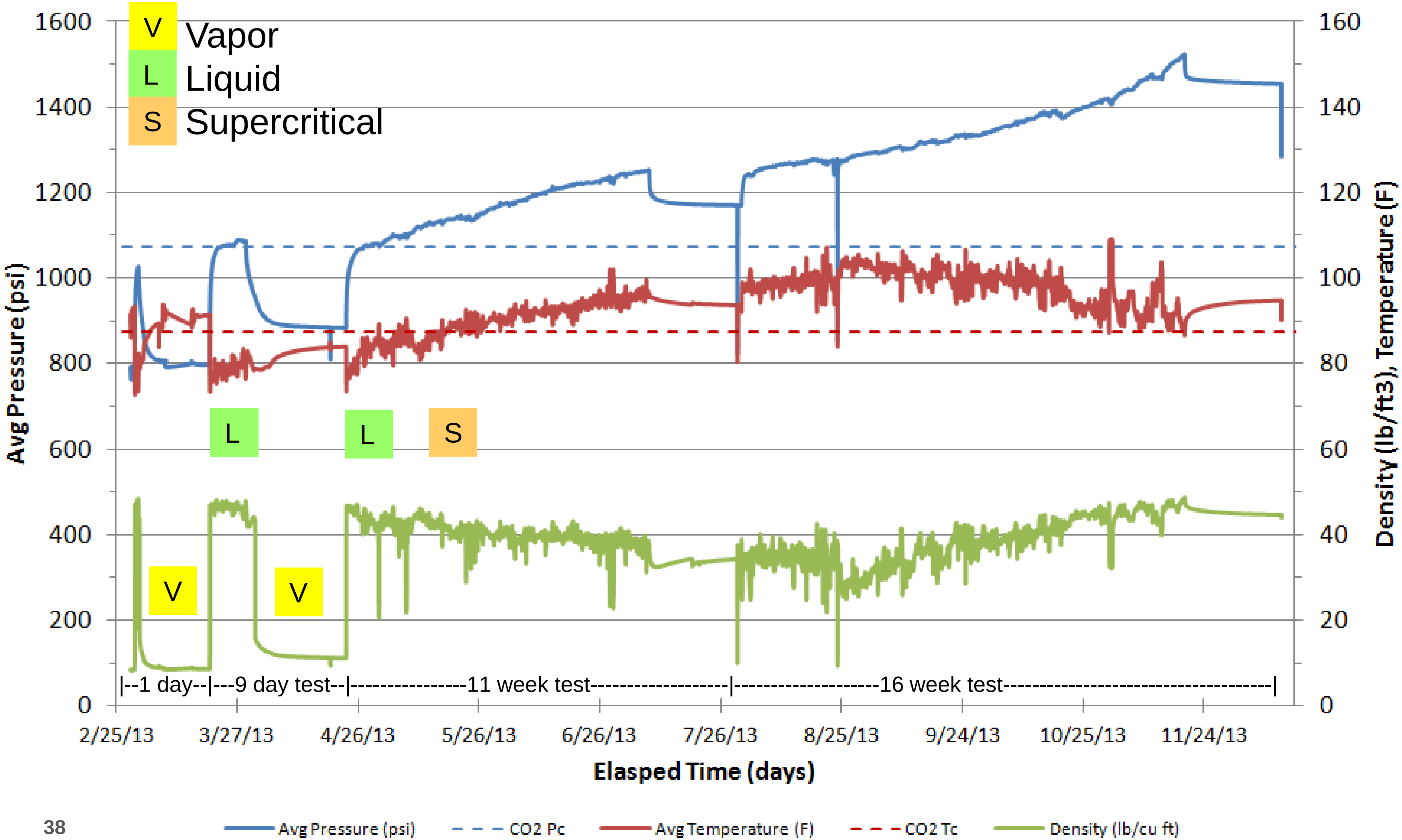
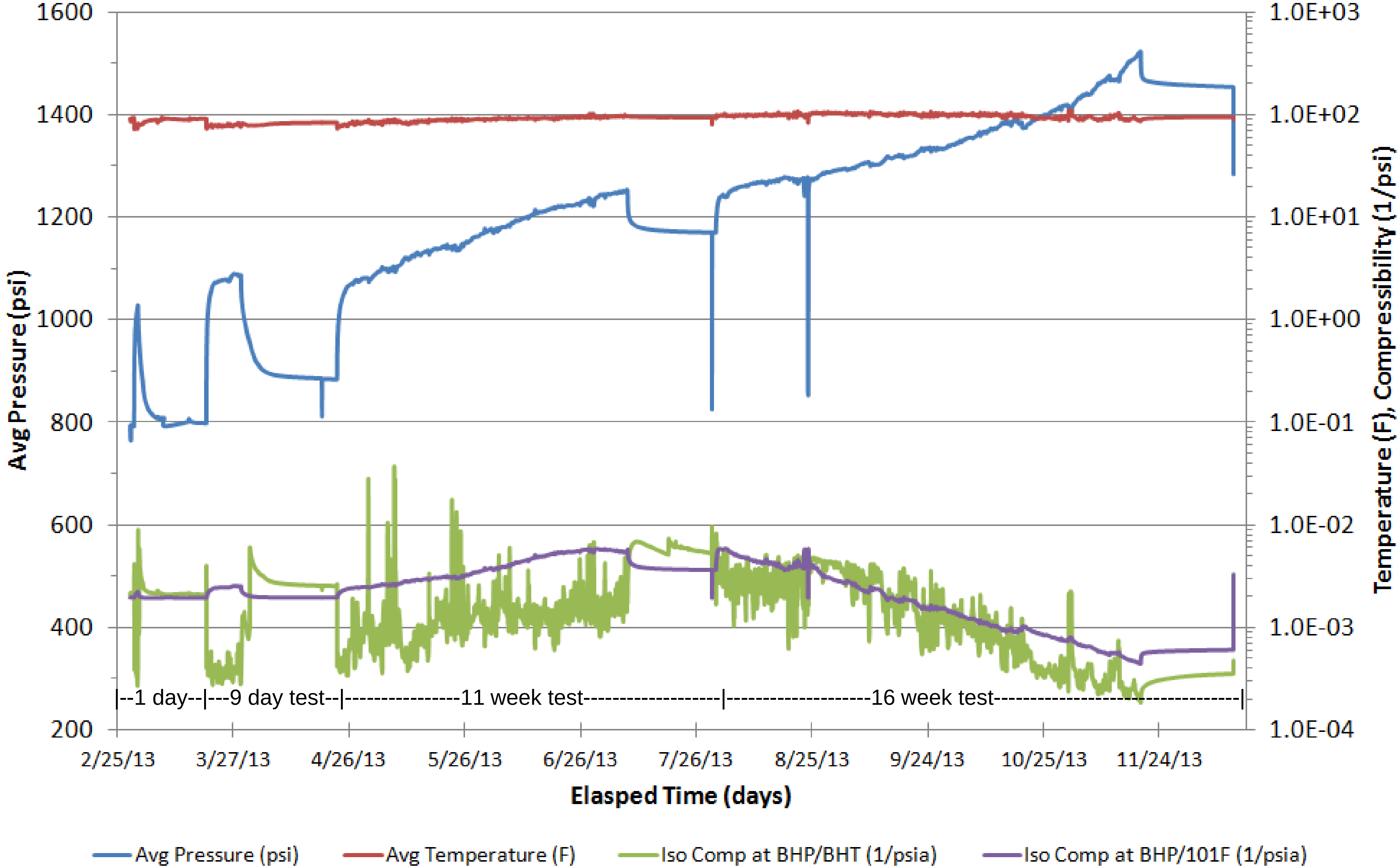
CO_2 Phase Behavior During Tests Based on P&T at Injection Well



CO_2 Compressibility During Tests Based on P&T at Injection Well

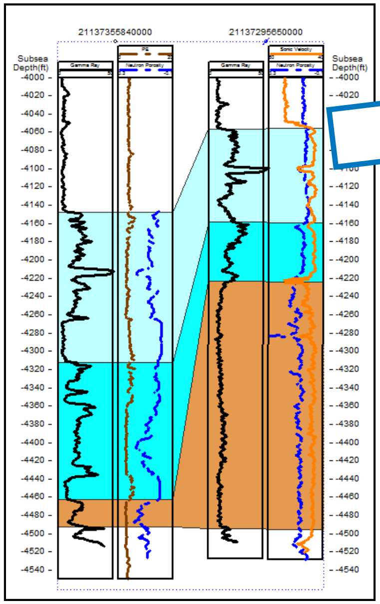


Summary of Fall-Off Testing (cont'd)

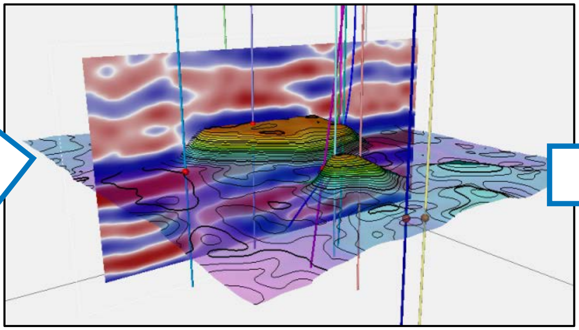
- It was not possible to match all injection/fall-off events
- Despite limitations of analytical modeling approach, the following conclusions can be made:
  - The Dover 33 reef behaves as a closed system, as evidenced by pressure build up over time
  - It can be modeled as a circular reservoir with radius of ~1,000 to 2,000 ft (most scenarios suggested radius <1,500 ft)
  - Permeability ranges from ~ 1 to 42 md based on injection well results and ~ 2 to 23 md based on monitoring well results
- EPA Class VI UIC Regulation requires periodic Fall-Off Testing; existing analytical methods may not be adequate for EOR reservoirs.

Field data has been integrated into geologic models of the reef

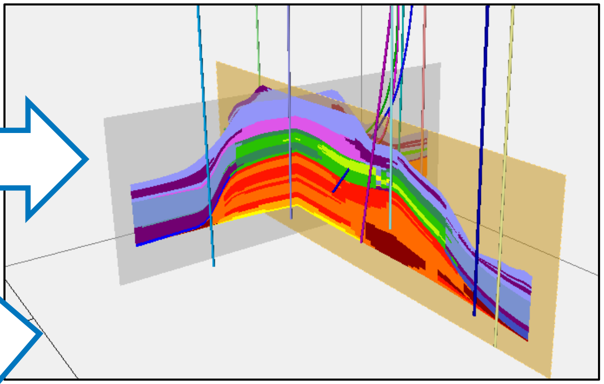
Log and core correlation

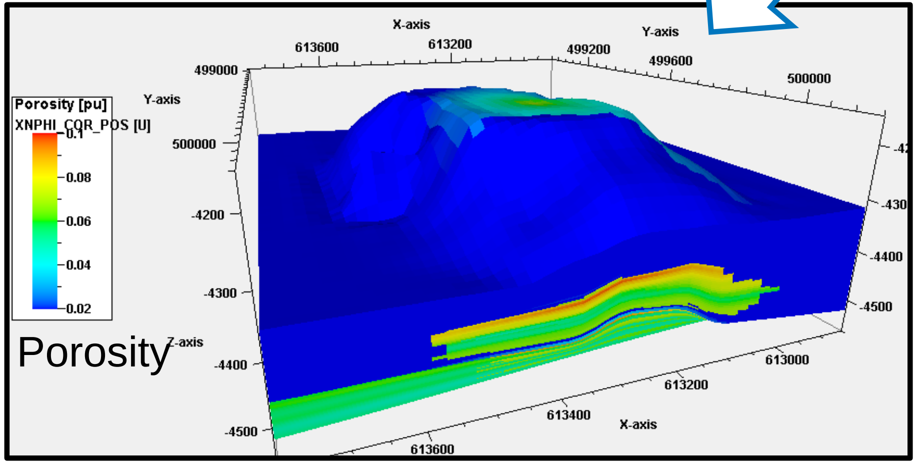


Seismic Interpretation



Geologic Framework Model



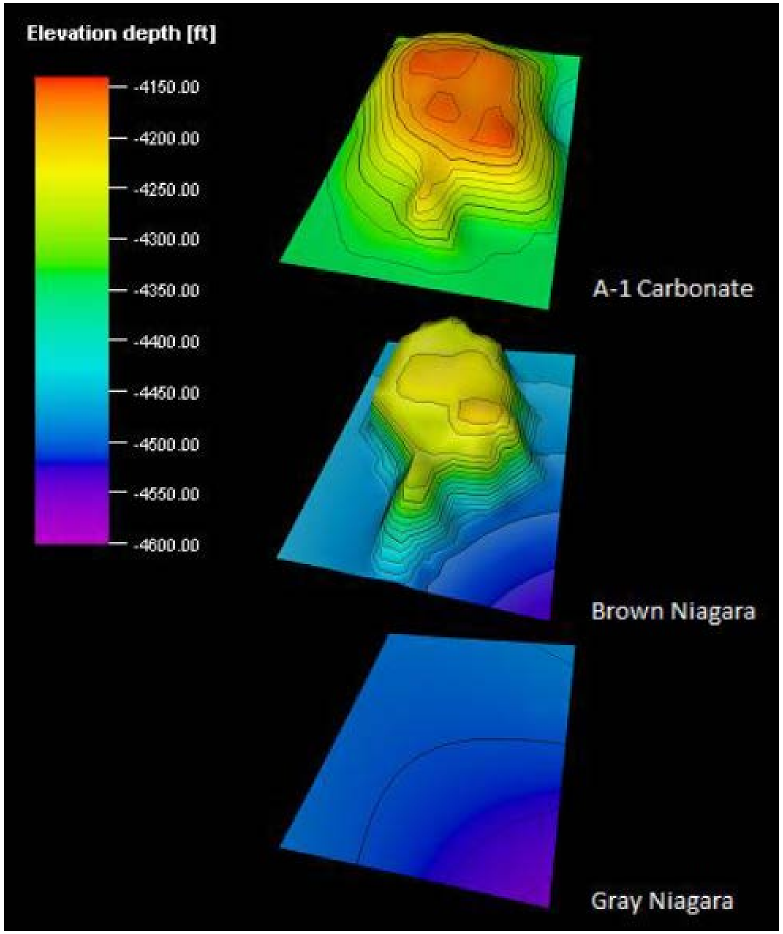


Final Geologic Model

Sensitivity of dynamic reservoir behavior to alternate geologic models

Static Earth Model (SEM) Level 1

Property distributions constrained by geologic formation surfaces.



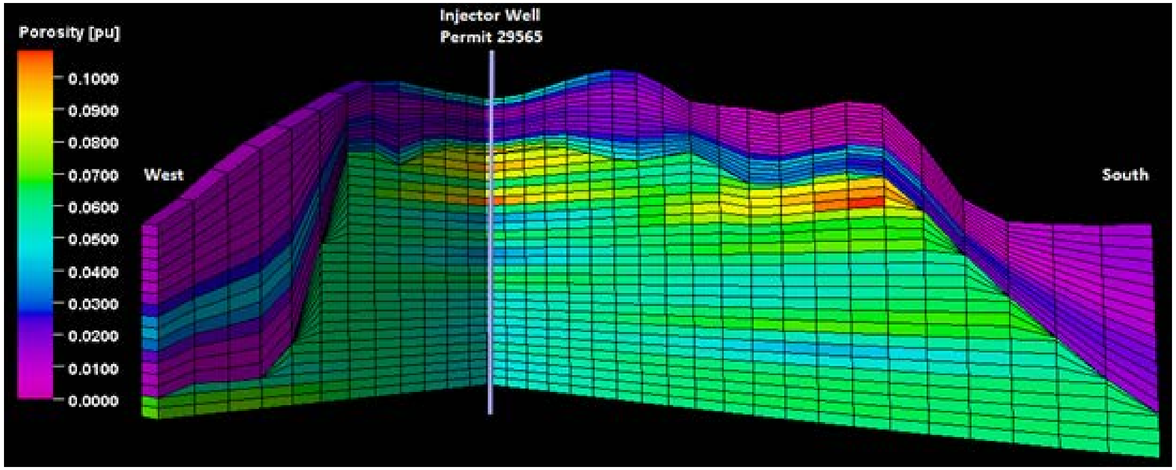
Static Earth Model (SEM) Level 2

Property distributions constrained by lithofacies.

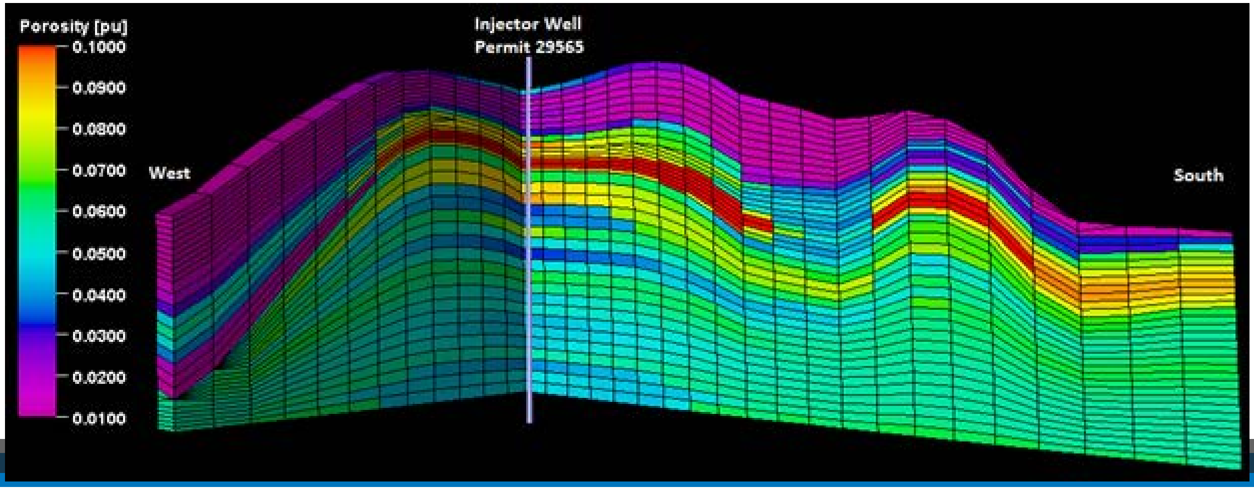
Geologic surfaces based on 3D seismic and well data.

Dover-33 (carbonate reef) represented in various levels of geologic detail

SEM1 Porosity Model

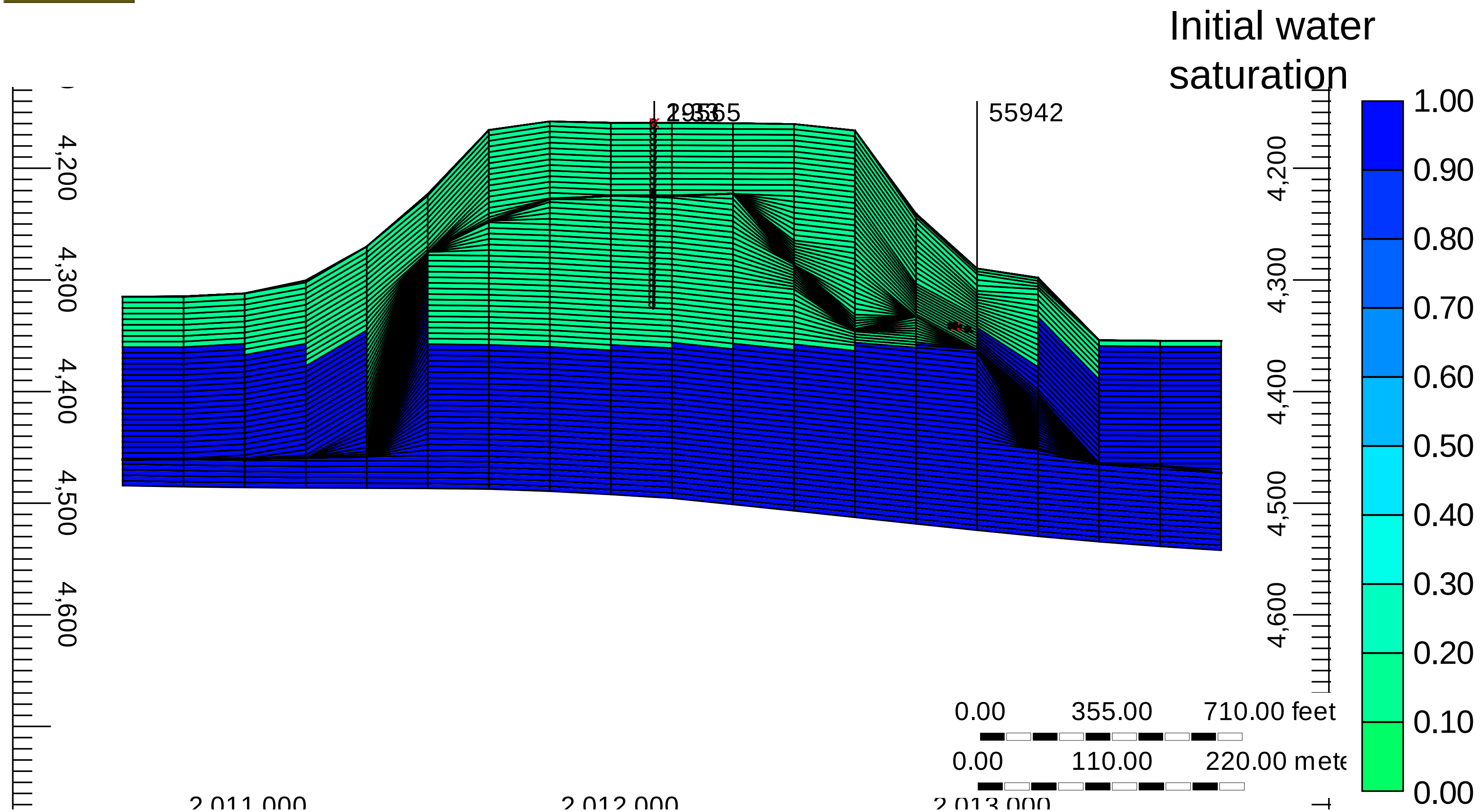


SEM2 Porosity Model



MRCSP MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP
NETL U.S. Department of Energy/NETL
Battelle The Business of Innovation

Initialization of SEM1 in black oil simulator



Goals of Reservoir Modeling

- Scientific – process understanding (e.g., how does CO_2 move through the formation and interact with oil/brine)
- Engineering – system design (e.g., well rates/location needed to maximize recovery and optimize storage)
- Calibration – history matching (e.g., update description of subsurface by comparing model predictions to observations)
- Regulatory – compliance demonstration (e.g., what is the risk of CO_2 leakage)
- Outreach – visualization (e.g., animation of system evolution)

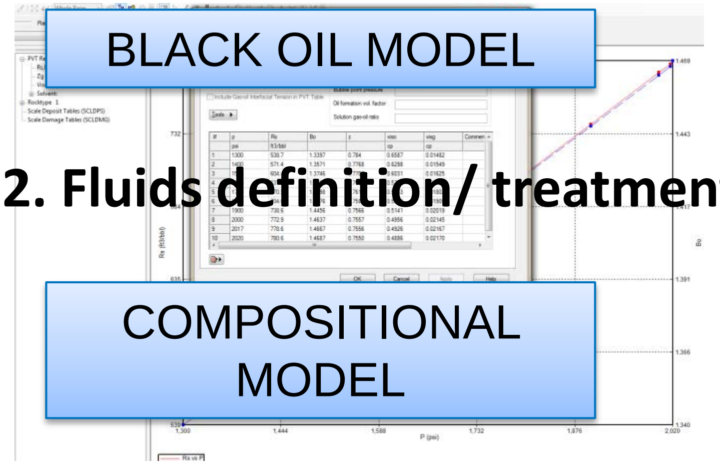
Phase-III Modeling Tasks

- Task 1.11 – Assessment and Modeling of Niagaran Reefs
  - CO_2 storage potential in Niagaran reef trend
- Task 3.4 – Reservoir Modeling & Analysis (Late Stage Reefs)
  - Prediction/history matching of CO_2 injection response
- Task 4.3 – Reservoir Modeling & Analysis (Active Reefs)
  - Prediction/history matching of CO_2 injection response
- Task 5.4 – Reservoir Modeling & Analysis (New Reefs)
  - Design of optimal CO_2 injection scenarios
  - Prediction/history matching of CO_2 injection response

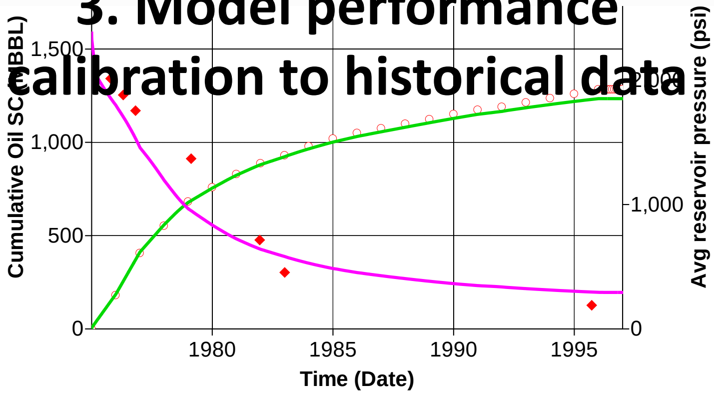
Task 3 (Dover 33) Dynamic Modeling

1. System / reservoir specification

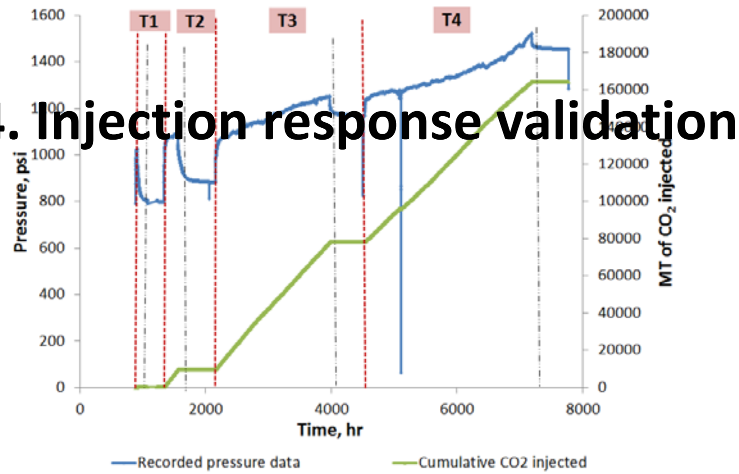
2. Fluids definition/ treatment



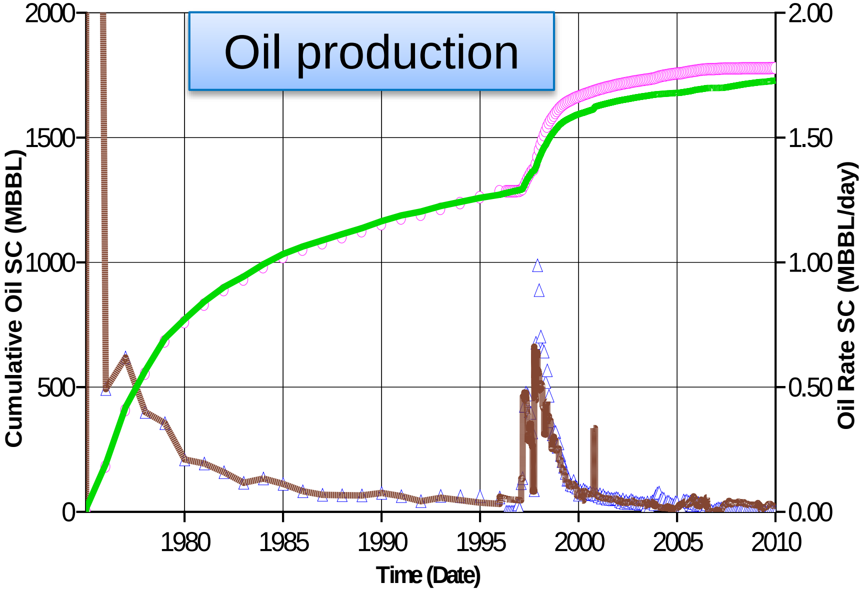
3. Model performance calibration to historical data

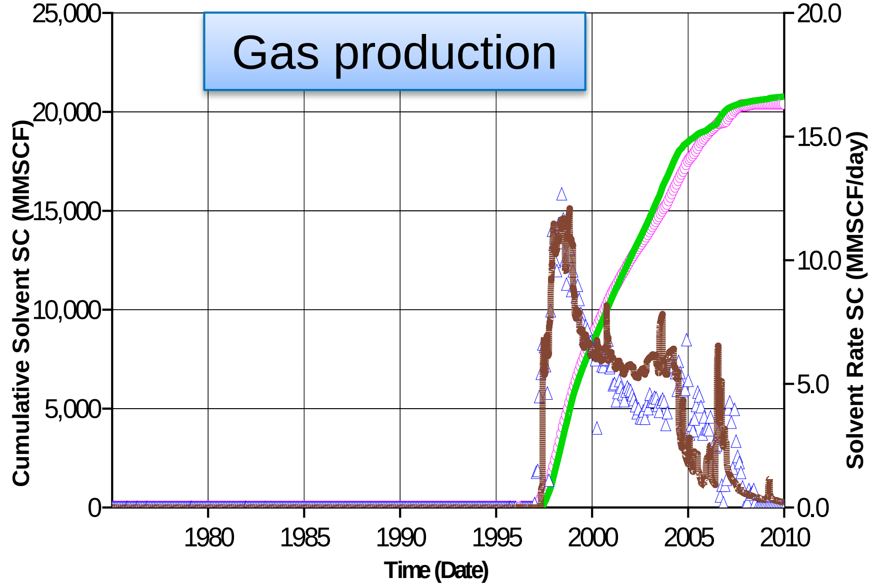


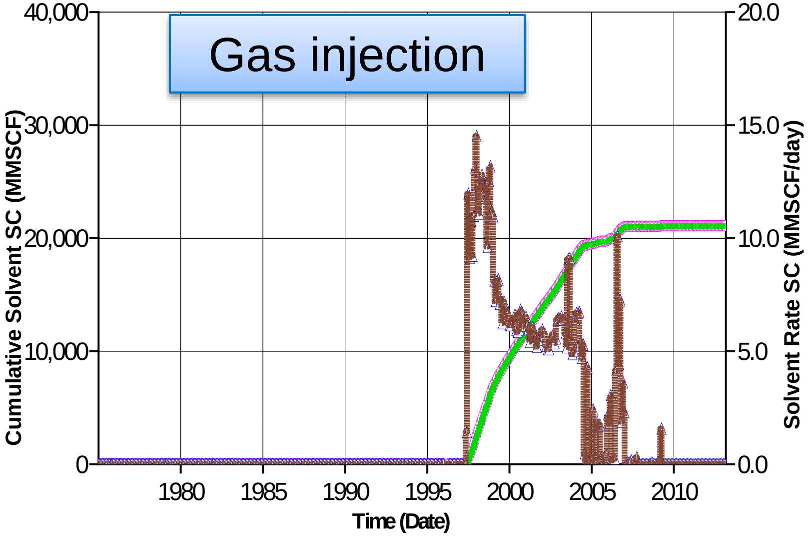
4. Injection response validation

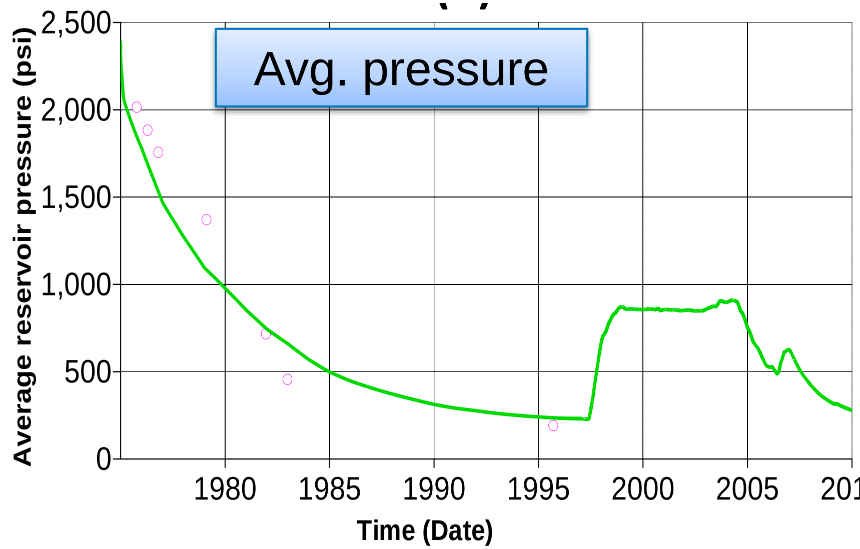


Black-oil Model History Match









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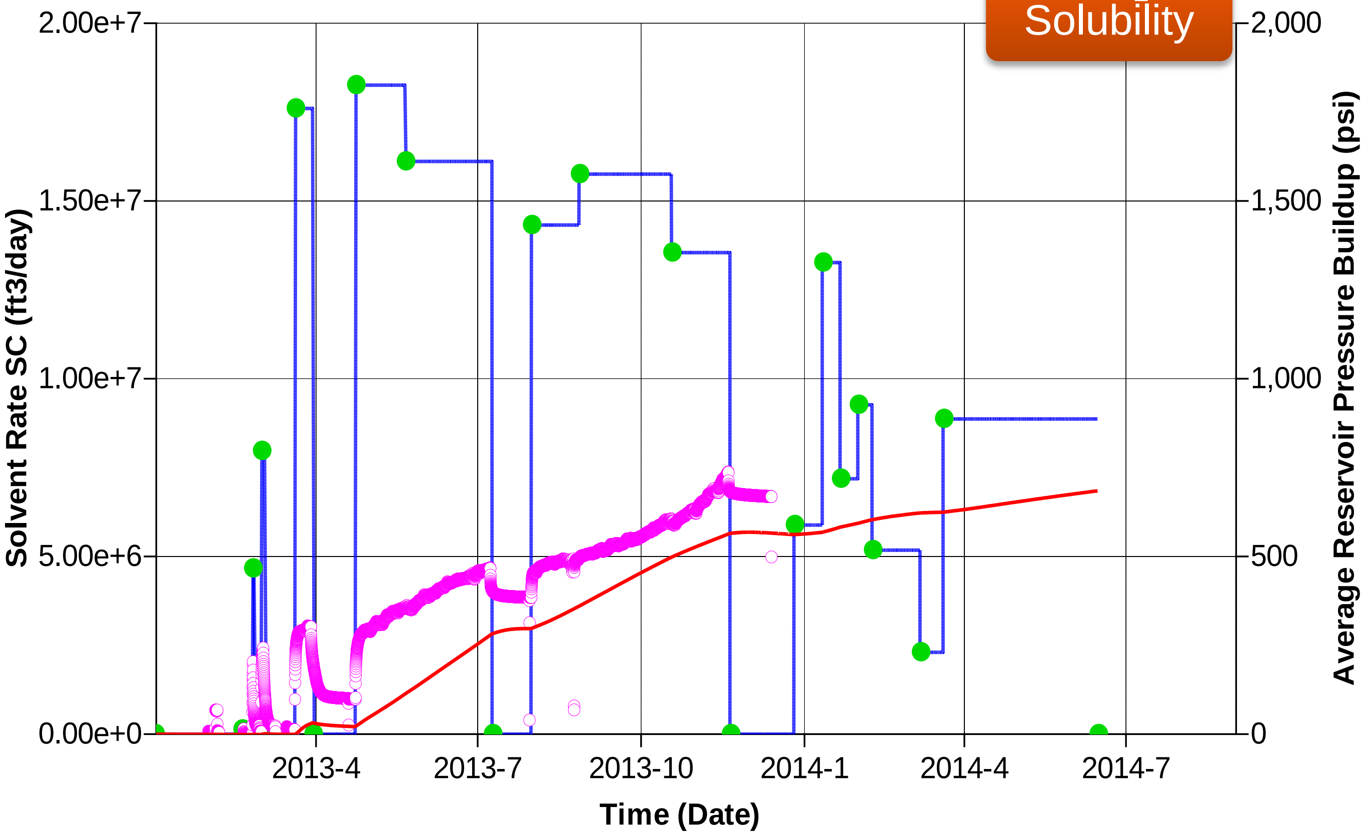
“Validation” with Phase III Injection Data

Pressure under-predicted possibly due to

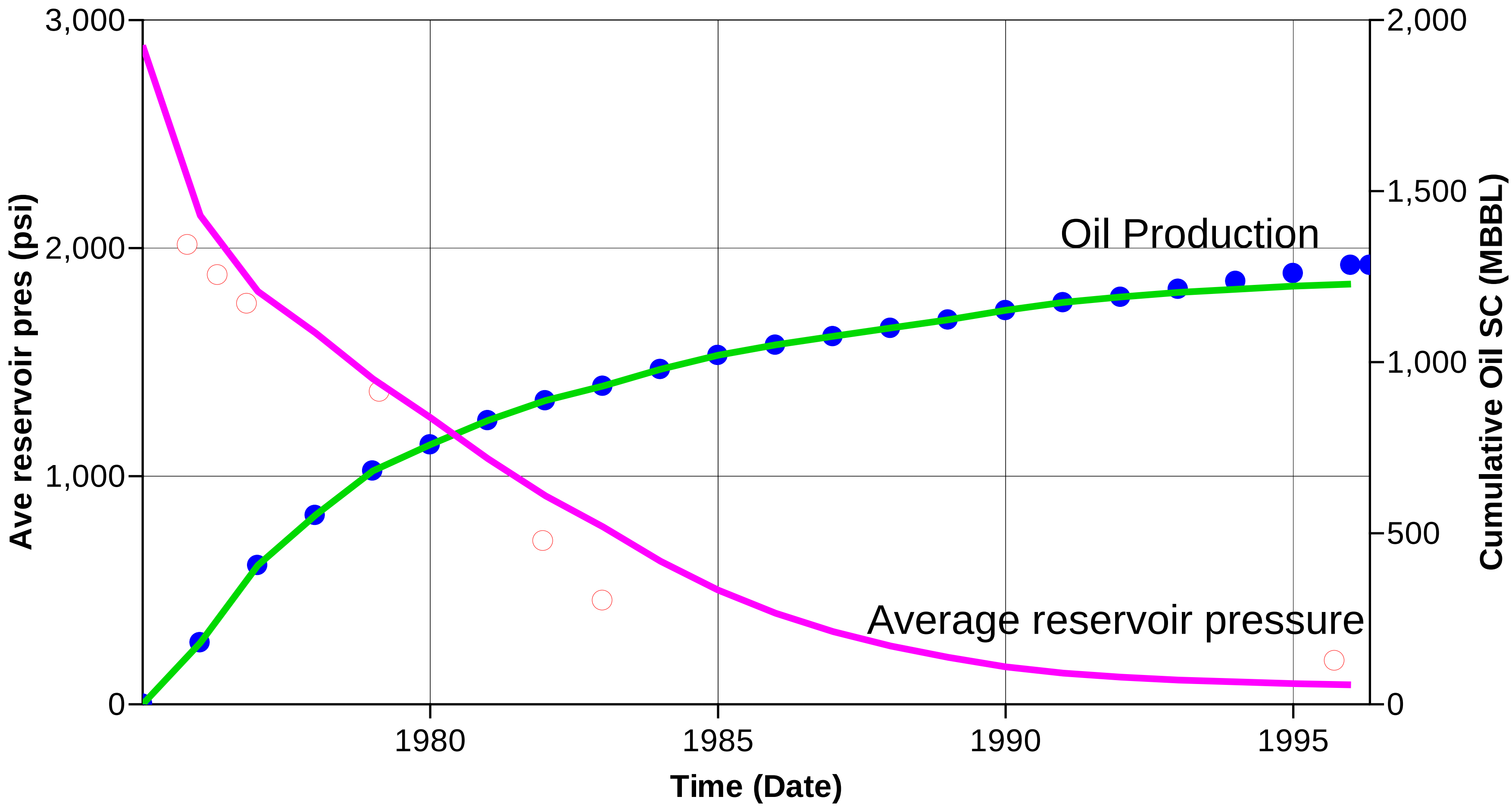
- Reservoir dimensions
- CO_2 Solubility

Compositional model



Compositional Model History Match

Primary Production



Ongoing/Future Modeling Activities

- Complete compositional model history match for secondary recovery period
- Predict injection pressure response for Phase III injection, and adjust model parameters as needed to match field data
- Repeat exercise for Level 2 SEM (lithofacies model)
- Extract single-well simulation model for detailed analysis of transient pressure response from injection-falloff periods.
- Incorporate geochemical and geo/mechanical aspects
- Investigate applicability of material balance type models

Material Balance with CO_2 Injection

Fluids produced – CO_2 injected

$$N_P(B_o - R_s B_g) + G_P B_g + G_{P,CO_2} B_{CO_2} \qquad G_{i,CO_2} B_{CO_2}$$

= Fluid expansion + Formation expansion

$$N\{B_o - B_{oi} + (R_{si} - R_s)B_g\} \qquad N\{B_{oi}(c_f + c_w S_{wi})\Delta P/(1 - S_{wi})\}$$

+ Expansion of CO_2 contacted oil + Expansion of CO_2 contacted water

$$V_{m,o}(B_{m,o} - B_o)/B_o \qquad V_{m,w}(B_{m,w} - B_w)/B_w$$

– CO_2 dissolved in oil – CO_2 dissolved in water

$$\frac{(N - N_p)B_o R_{s,CO_2}}{B_{o,CO_2}} \qquad \frac{NB_{oi}S_w R_{sw}}{S_{oi}B_w}$$

after Tian & Zhao, JCPT, 2008

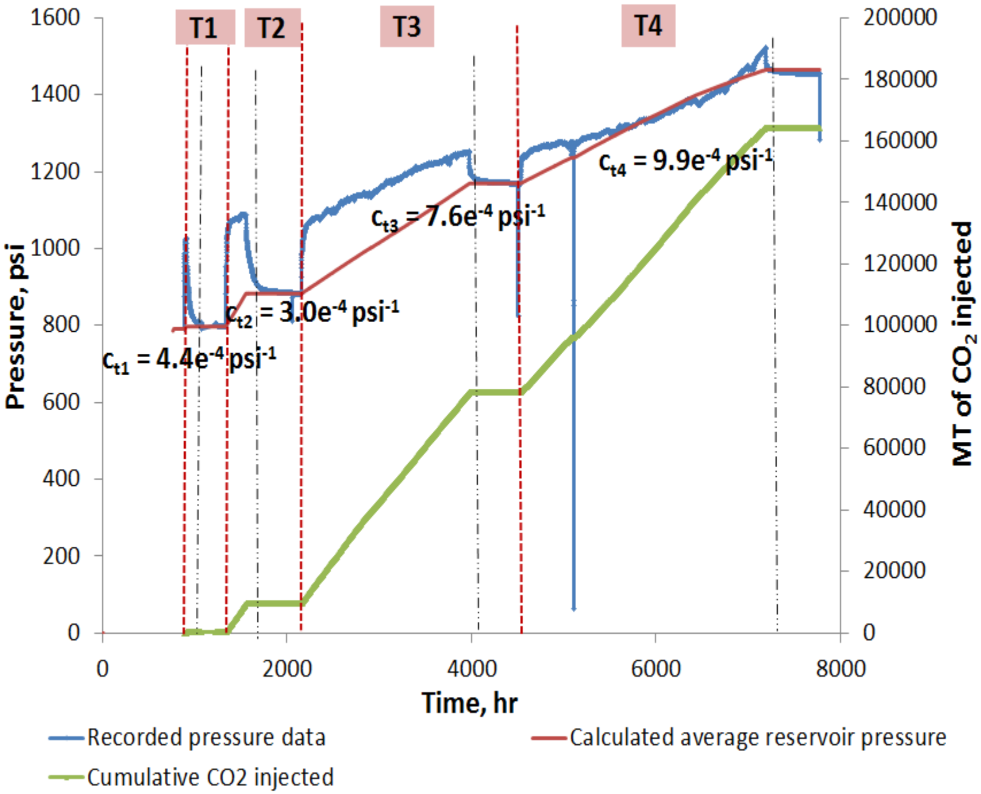
Injection Response in a Closed Volume

$$(P_i - \overline{P}) = \frac{Q}{Ah\phi c_t}$$

$$c_t = c_o S_o + c_g S_g + c_w S_w + c_f$$

- If c_t is known, we can predict pressure buildup from injection of known volume (or storage capacity upto discovery pressure)
- $c_o \sim 10^{-5}$ psi^{-1}; c_w, $c_f \sim 10^{-6}$ psi^{-1}
- $c_g \sim 10^{-4}$ psi^{-1} (pressure. dependent)
- [Q] Can we obtain insights on c_t versus p relation from field data?

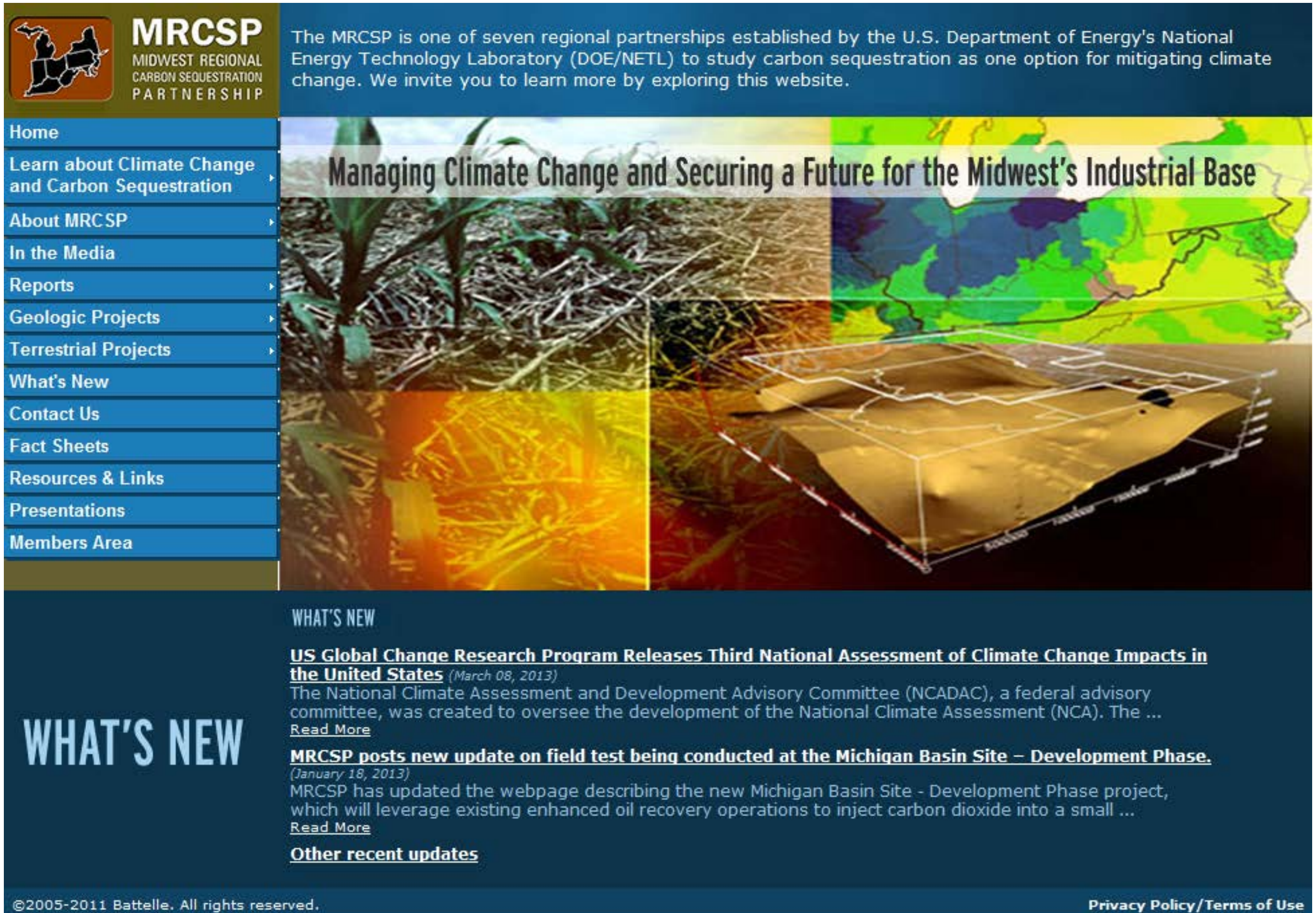
Dover 33 Data



What Can We Learn From Modeling?

- Workflow for building SEMs with limited data, and calibrating dynamic models to production history
- Impact of geologic uncertainty on reservoir behavior
- Factors affecting CO_2 retention in closed systems
- Simplified models for predicting CO_2 storage capacity in depleted reef reservoirs
- Significance of coupled processes in depleted reefs

Questions?



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