
EERC
Critical Challenges. Practical Solutions.

BELL CREEK FIELD PROJECT – PLAINS CO_2 REDUCTION PARTNERSHIP

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Energy & Environmental Research Center

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

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Critical Challenges. Practical Solutions.

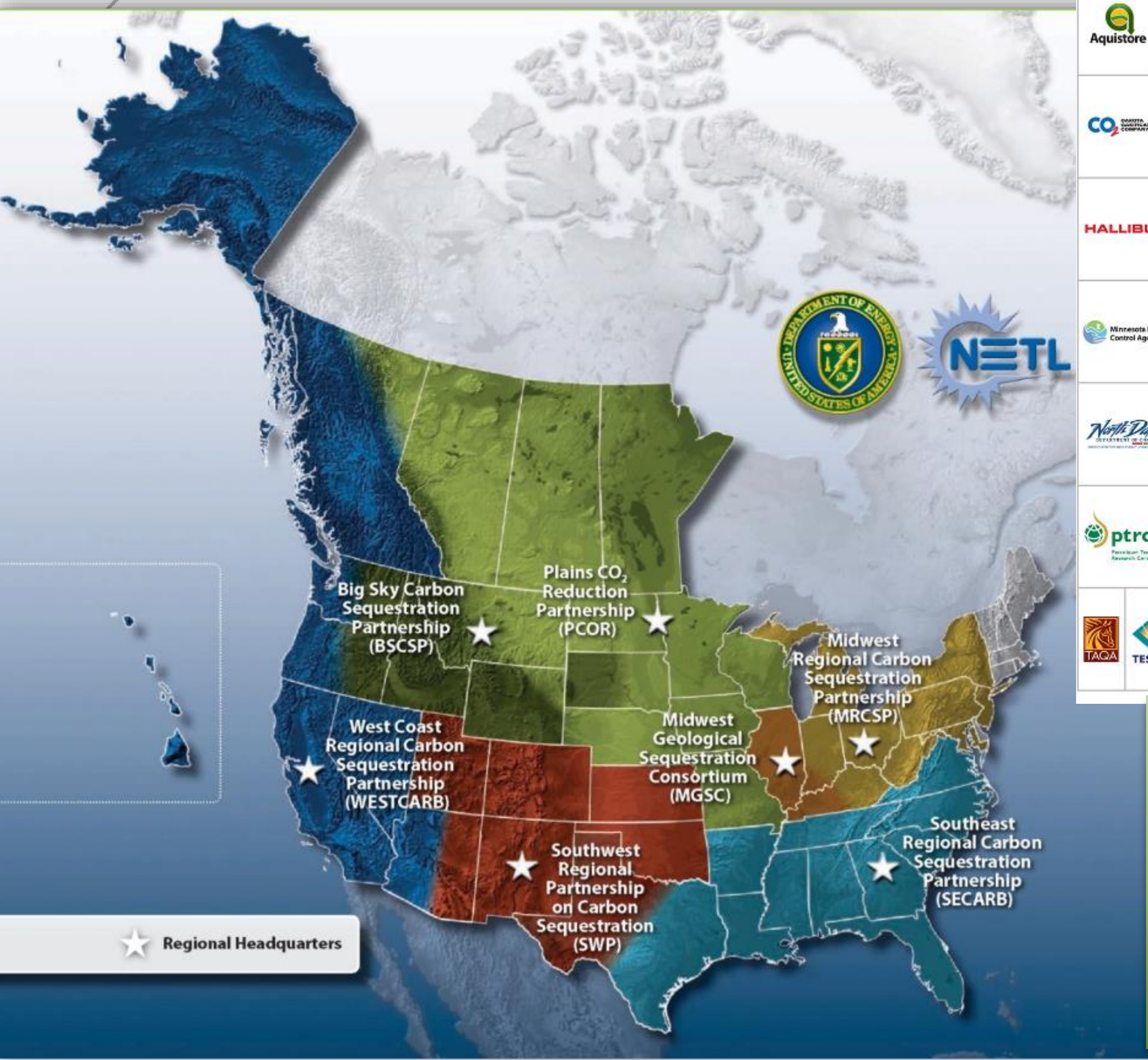
OUTLINE

- Plains CO_2 Reduction (PCOR) Partnership Program

- Technical Status
- Accomplishments
- Lessons Learned
- Synergy Opportunities
- Summary

PCOR PARTNERSHIP REGION

PCOR Partnership 2003 – Present



- Nine states
- Four Canadian provinces
- 1,382,089 mi^2
- 121 partners
- **Growing – 14 new members since 2013**
  - 2013 (one), 2014 (four), 2015 (four), 2016 (five)

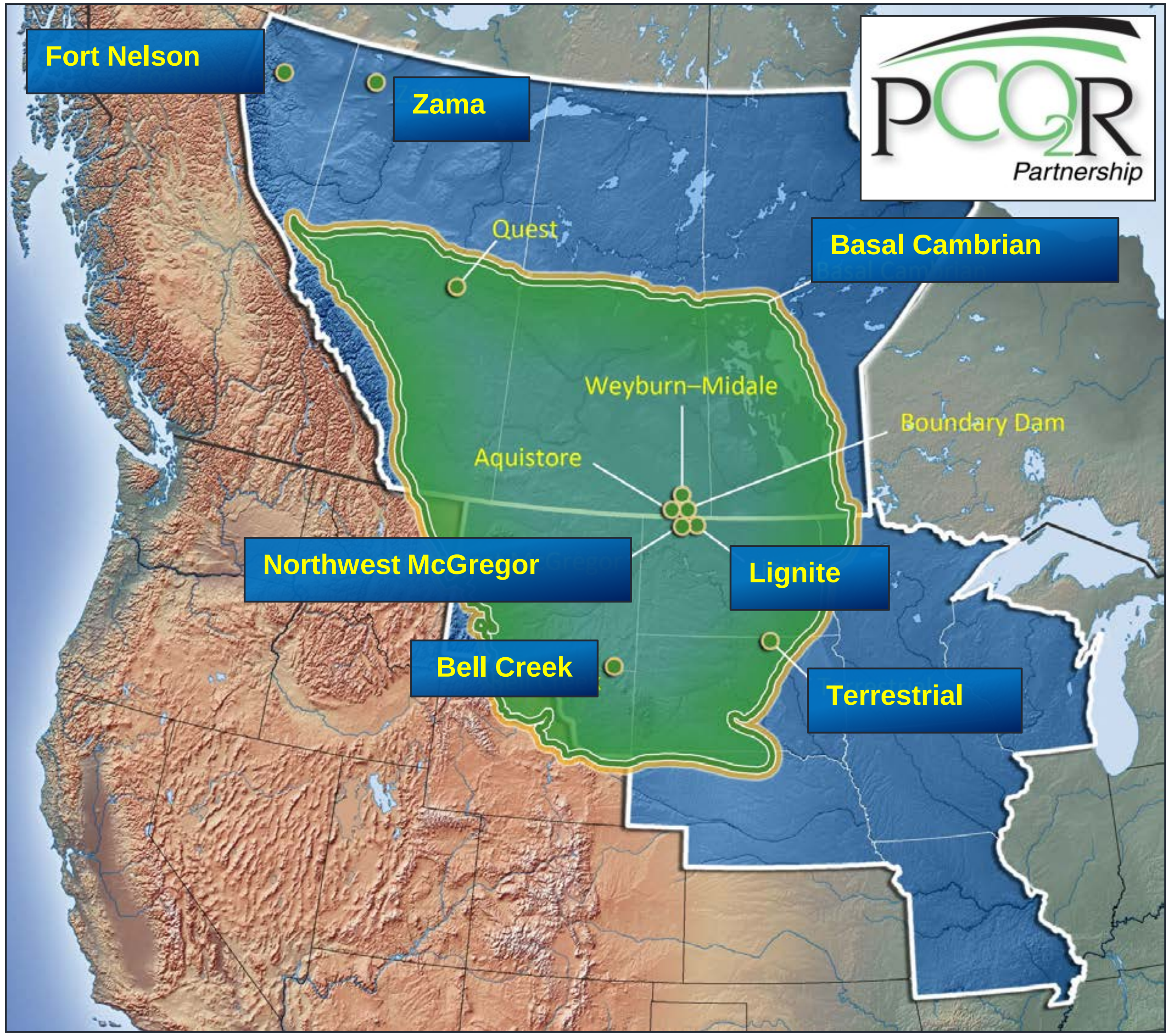
PCOR PARTNERSHIP COMPONENTS

Ongoing

- **Bell Creek project**
- Aquistore project
- Regional characterization
- Public outreach
- Regulatory awareness
- Water Working Group

Completed

- Fort Nelson project
- Zama project
- Basal Cambrian project
- Phase II pilot tests

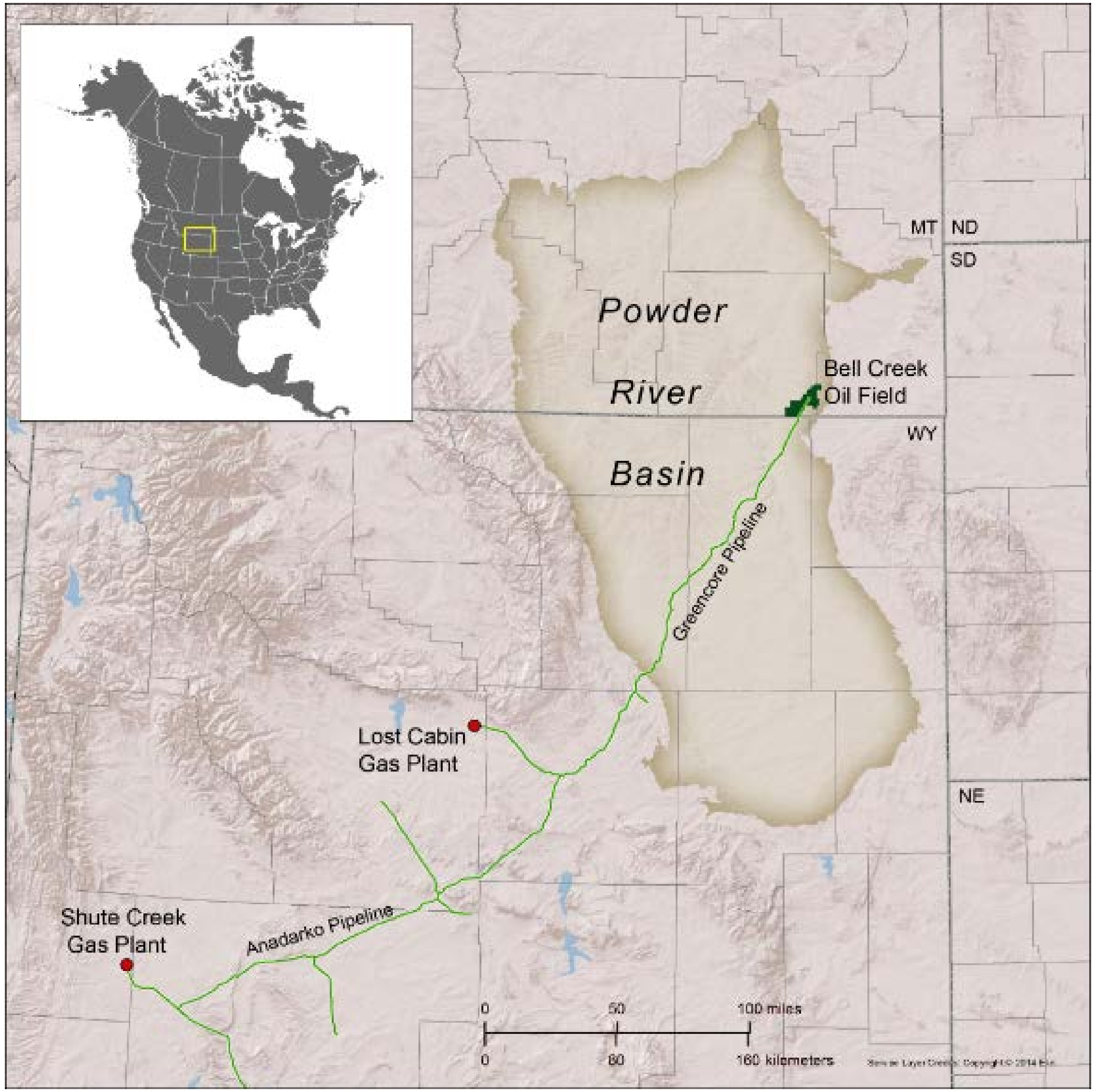


KEY ACCOMPLISHMENTS TO DATE

The PCOR Partnership has successfully:

- Integrated technical data using an adaptive management approach to demonstrate secure carbon dioxide (CO_2) storage.
- Applied multiple monitoring, verification, and accounting (MVA) strategies to track the presence and movement of injected CO_2, and found no evidence of out-of-zone migration of CO_2.
- Developed a regional vision for carbon capture and storage (CCS), and fostered active engagement from the partners, resulting in a pathway to commercial-scale CCS deployment.

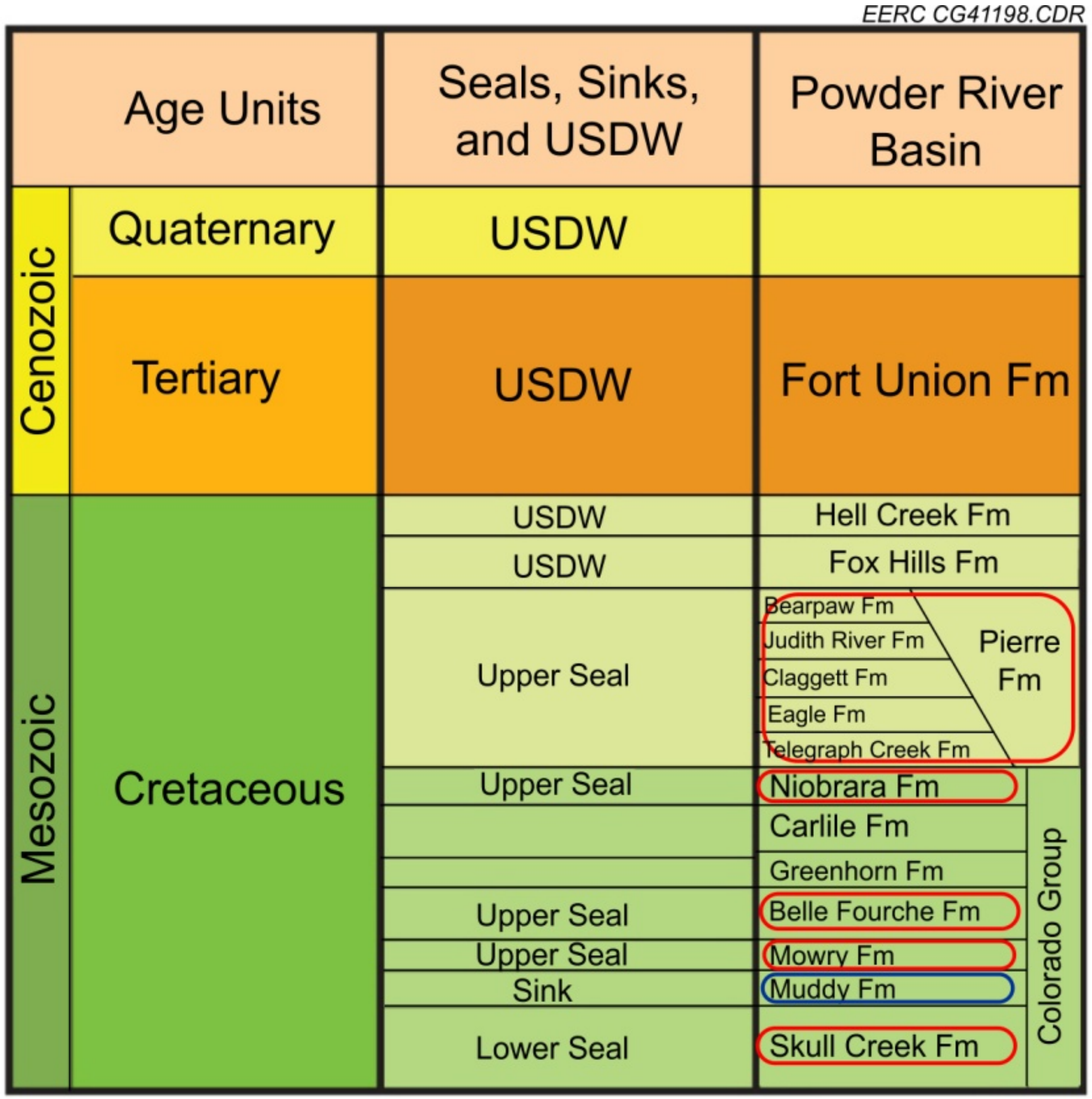
TECHNICAL STATUS: BELL CREEK



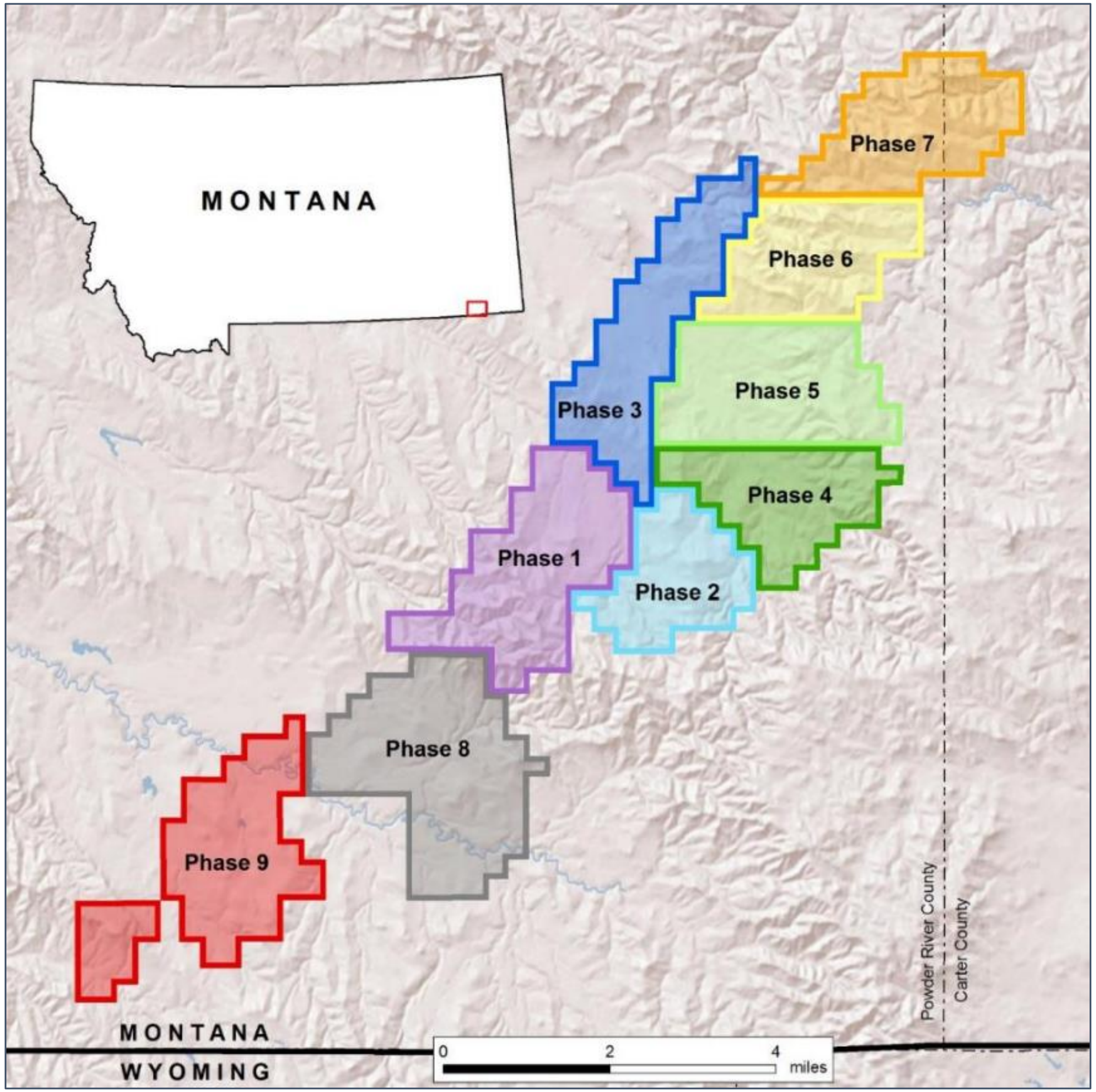
- Discovered in 1967, now undergoing CO_2-based tertiary recovery.
- CO_2 for enhanced oil recovery (EOR) is sourced from ExxonMobil's Shute Creek and Conoco Philips Lost Cabin natural gas-processing plants.
- CO_2 is transported via the Greencore and Anadarko pipelines to Bell Creek.

BELL CREEK PROPERTIES

- Cretaceous Muddy Sandstone Formation
- Approximately depth: 4400 ft
- Overlain by more than 2900 ft of siltstones and shales
- Average thickness: 40 ft
- Average porosity 25%–35%
- Average permeability: 150–1175 mD
- Reservoir water salinity: ~5000 ppm TDS (total dissolved solids)
- Oil gravity: 41º–32º API



BELL CREEK DEVELOPMENT

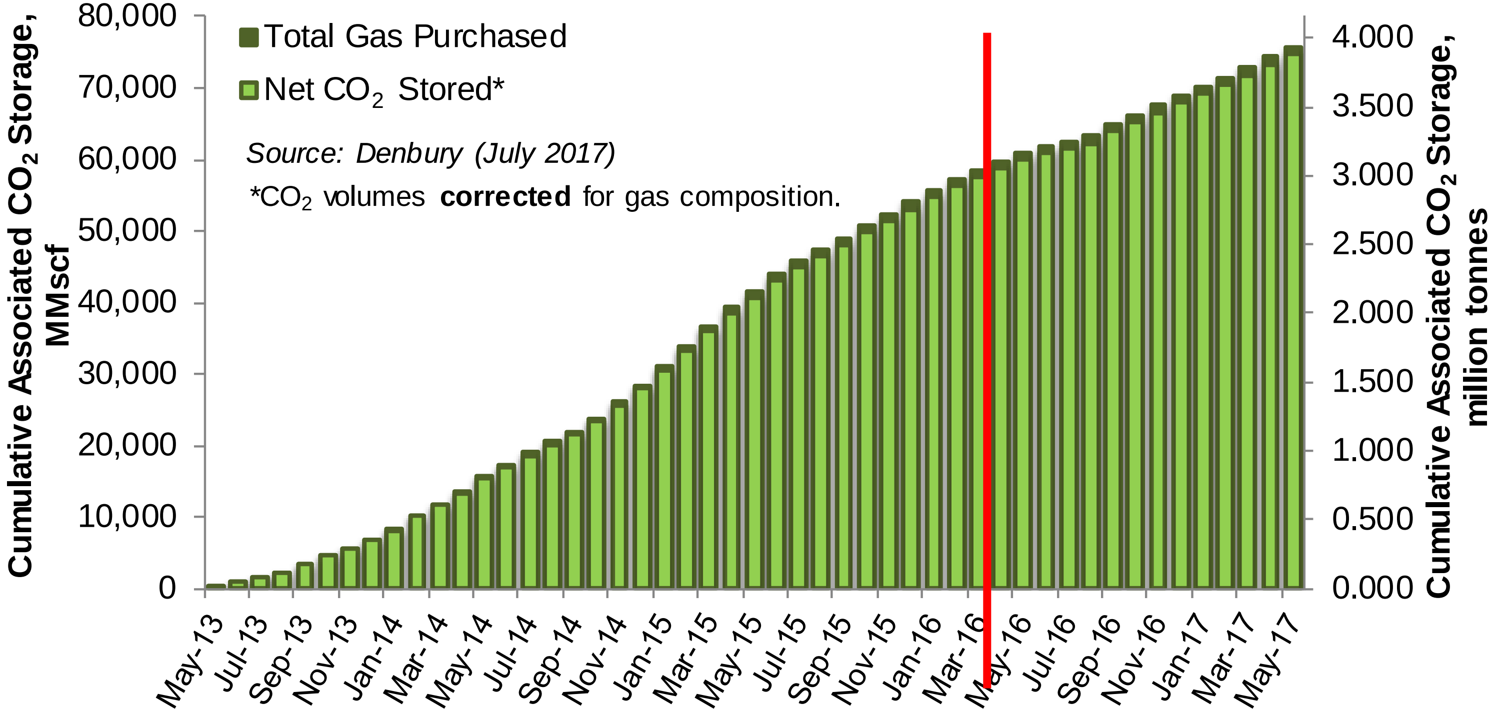


BELL CREEK ASSOCIATED CO_2 STORAGE

Associated CO_2 Storage:

As of March 2016 – ~3.0 million tonnes *(source: Denbury)*

As of May 2017 – ~3.9 million tonnes *(source: Denbury)*



Red line indicates end of Budget Period 4 of the PCOR Partnership Program

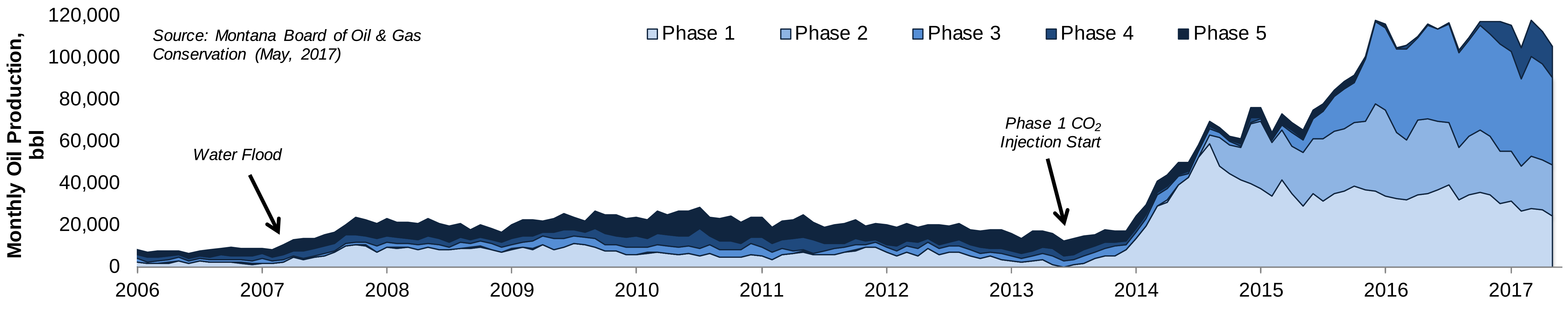
As much as 15 million tonnes of CO_2 may be stored through EOR.

BELL CREEK INCREASED PRODUCTION

As of May 2016

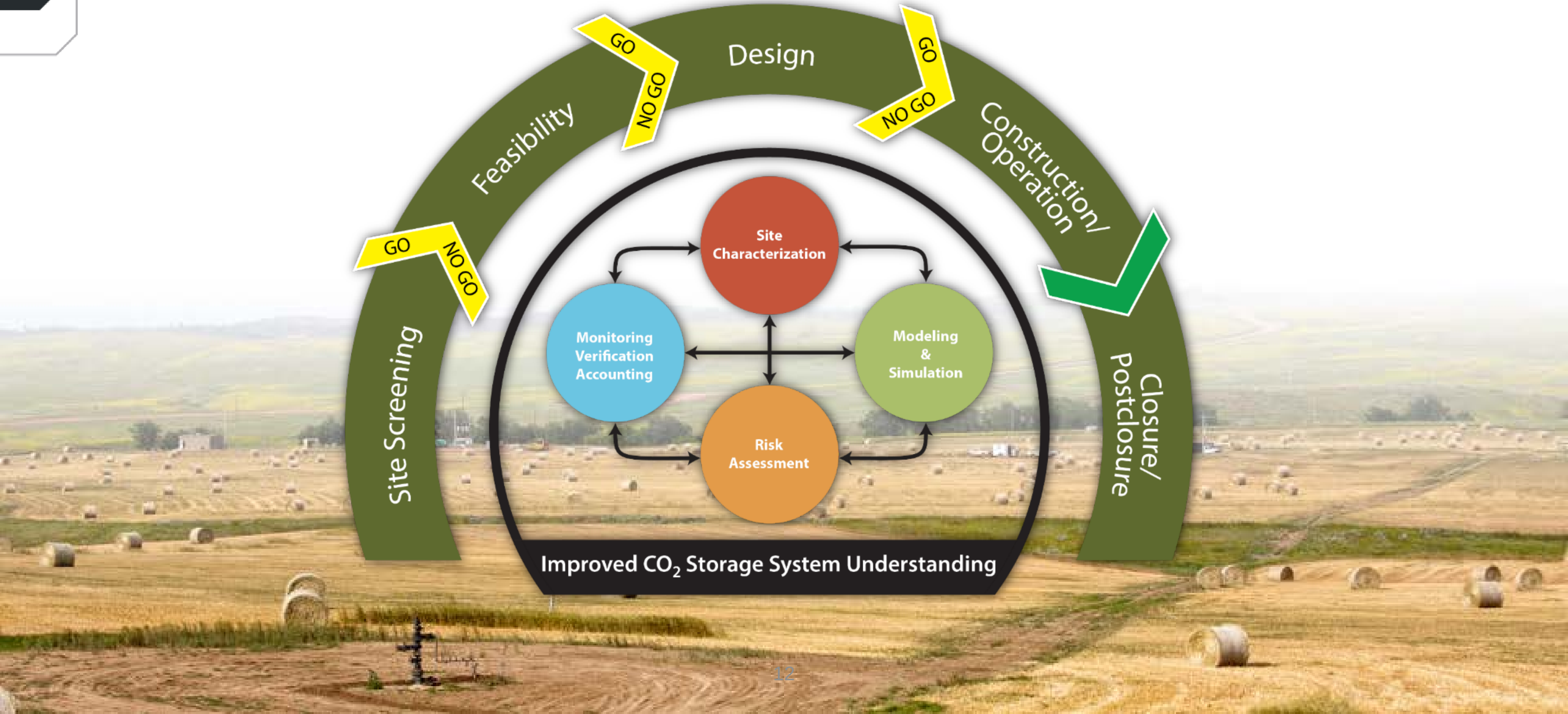
Incremental oil produced: ~3.9 million barrels

(source: Montana Board of Oil and Gas Database [MBOG])



Approximately 40–50 MMbbl of incremental oil will be produced through CO_2 EOR.

ADAPTIVE MANAGEMENT APPROACH



TECHNICAL CHALLENGES

- There are no technical barriers to accomplishing the PCOR Partnership objectives at Bell Creek.

- Technical challenges
  - Thin reservoir
  - Relatively low TDS formation water
  - Remote location
  - Lack of shallow (<300 m) geologic data
  - No direct control over CO_2 EOR operations
  - Weather

SITE CHARACTERIZATION APPROACH

- Maximize use of existing data.
- Conduct targeted field activities to cost-effectively address knowledge gaps.
- Establish baseline MVA data set.
- Add value to partners through site characterization activities, e.g., Denbury use of static geologic model.

SITE CHARACTERIZATION ACCOMPLISHMENTS

- Reviewed historic well files
- Collected and analyzed lidar (light detection and ranging) data
- Investigated multiple outcrops
- Drilled characterization wells
  - New core
  - Modern log suites
- Analyzed core
  - Existing and new
  - SCAL (special core analysis) and pressure–volume–temperature (PVT) testing
- Conducted ~41 mi^2 3-D seismic survey
- Collected baseline 3-D vertical seismic profiles (VSPs)
- Collected pulsed-neutron logs (PNLs)

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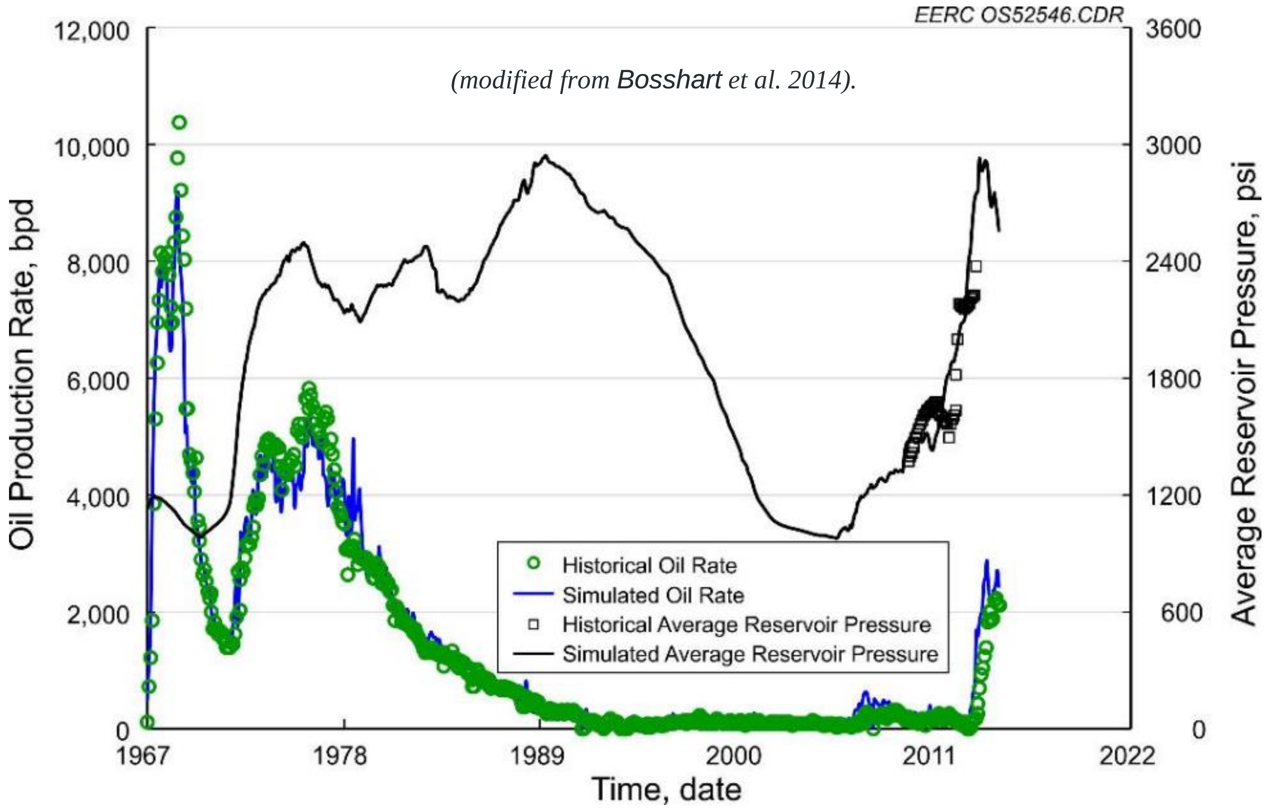
MODELING AND SIMULATION APPROACH

- Fit-for-purpose strategy where models are built to answer specific questions.
  - Identify data gaps
  - Identify potential risk scenarios
  - Guide the MVA program

MODELING AND SIMULATION ACCOMPLISHMENTS

- Matched and predicted CO_2 movement in reservoir
- Calibrated with historic data and MVA techniques
- Calibrated equation of state (EOS) with PVT data
- Investigated:
  - Scales from single well to regional
  - Potential near-surface impacts
  - Potential geomechanical and geochemical effects
  - Regional hydrodynamics
  - Impact of impurities in CO_2 on storage and sweep efficiency



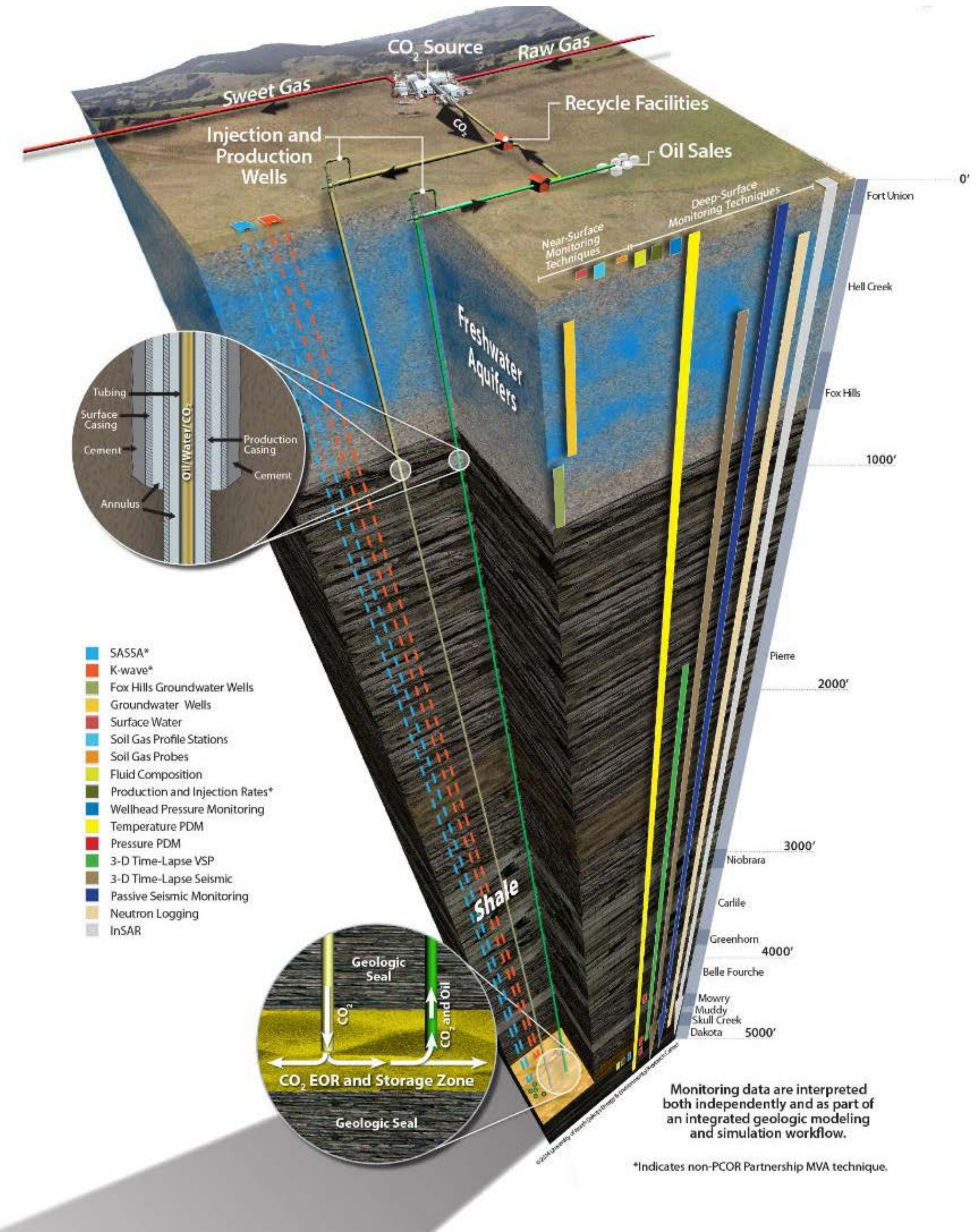
RISK MANAGEMENT: DECREASING RISK PROFILES OVER TIME

MVA: ADDRESSING PROJECT RISKS

MVA Technologies	Subsurface Technical Risks Addressed									
	Reservoir Capacity	Reservoir Injectivity	Reservoir Retention	Containment						Induced Seismicity
				Vertical Migration			Lateral Migration			
				CO_2	Oil	Brine	CO_2	Oil	Brine	
Soil Gas										
Soil gas probes				x						
Soil gas profile stations (SGPS)				x						
Water										
Surface water				x	x	x				
Groundwater wells				x	x	x				
Fox Hills/Hell Creek wells				x	x	x				
Production/Injection Rates	x	x	x							
Pressure/Temperature										
Wellhead P&T		x					x	x	x	
Down-hole P&T				x	x	x	x	x	x	
Distributed fiber optic temperature				x	x	x	x	x	x	
Bottom-hole pressure		x					x	x	x	
Geophysics										
3-D surface seismic	x	x	x	x			x			
3-D vertical seismic profile (VSP)							x			
Passive seismic										x
Pulsed Neutron Logs (PNLs)	x		x	x	x	x	x	x	x	
Other										
INSAR		x					x	x	x	
SASSA				x			x			
Krauklis seismic wave (K-wave)	x			x			x			

MVA APPROACH

- CO_2 MVA program overlaid on a commercial EOR project:
  - Guided by site characterization, modeling, simulation, and risk assessment.
  - Building off of the backbone of commercial operations data.
  - Minimize interference with commercial project.
- Two-pronged approach:
  - Surface/near-surface.
  - Deep subsurface.



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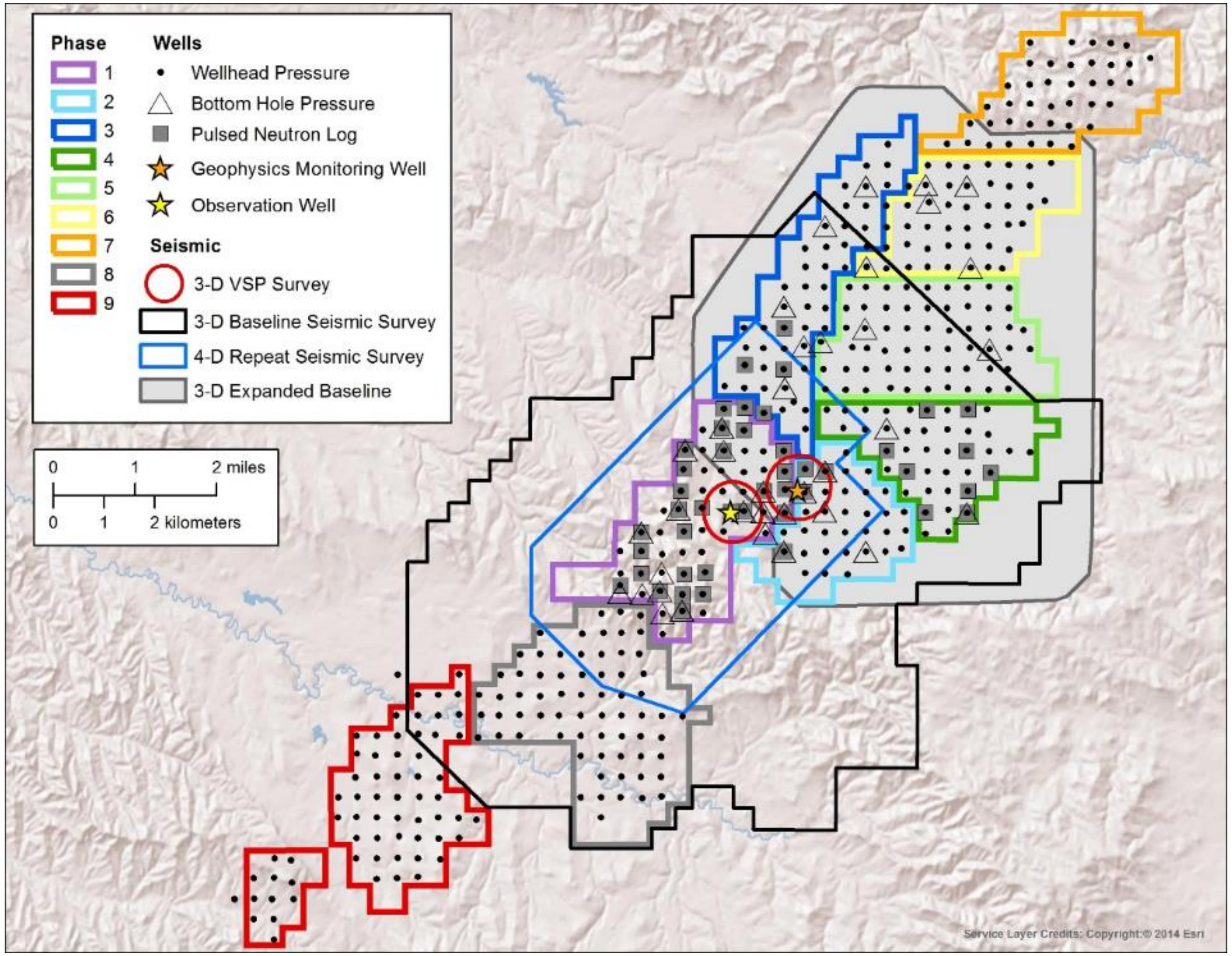
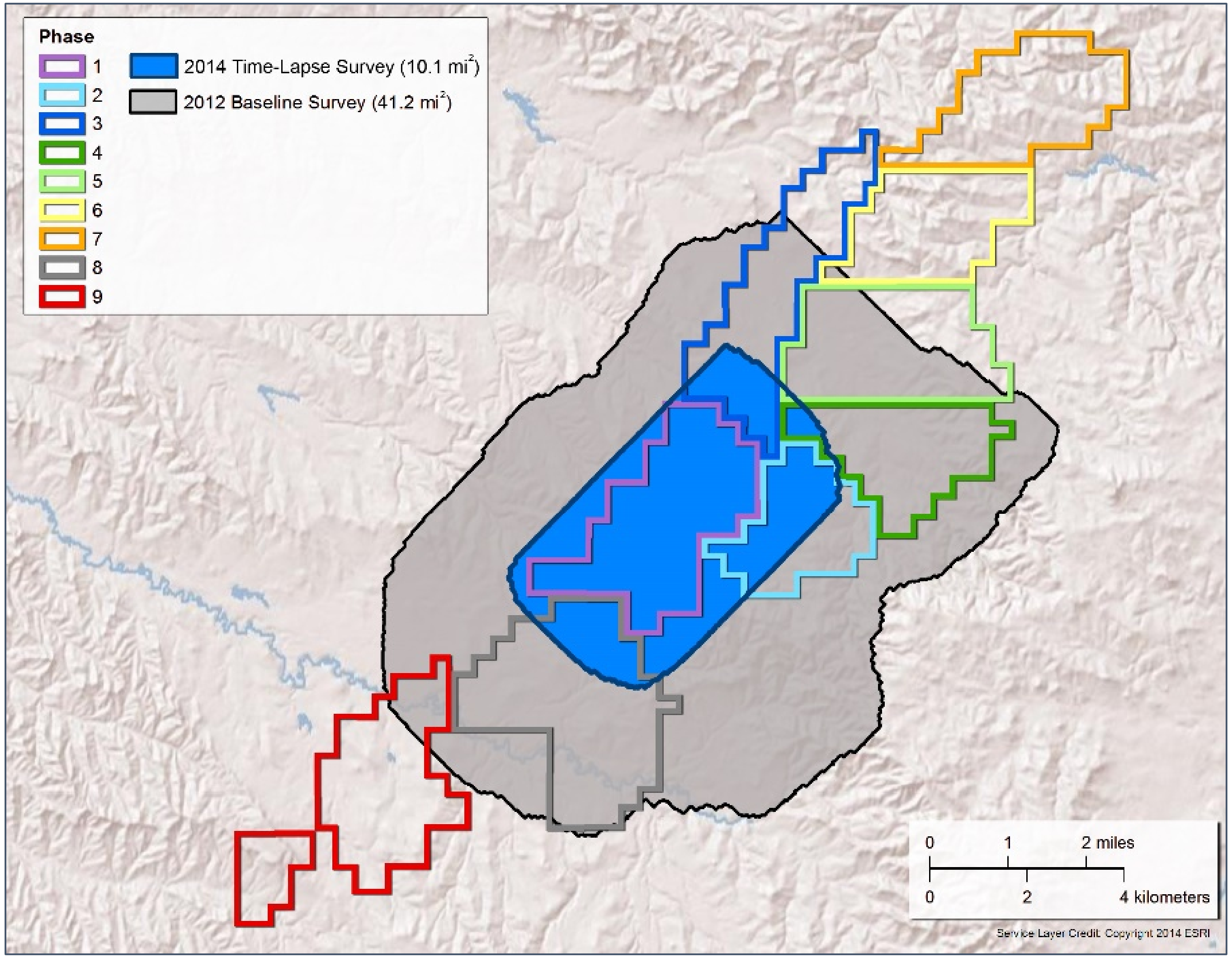
MVA ACCOMPLISHMENTS

- Completed baseline and two repeat 3-D seismic surveys
- Completed multiple PNL campaigns
- Performed soil gas and groundwater monitoring
- Installed permanent downhole geophone array
- Collected passive seismic data
- Drilled two dedicated groundwater-monitoring wells (lowest underground sources of drinking water [USDW])
- Collecting pressure and temperature data
- Acquiring injection and production data
- Conducted multiple VSP surveys
- Reviewed InSAR data



FIRST REPEAT 3-D SURVEY



Phase	Start of CO_2 Injection	Estimated Associated CO_2 Storage (Oct 2014), Mt
1	May 2013	1.04
2	Dec 2013	.166

Calculated using Montana Board of Oil and Gas data

- 41.2-mi^2 repeat (October 2014).
- ~1.2 Mt CO_2 stored in monitored area at the time of survey.

FIRST REPEAT 4-D DIFFERENCE INTERPRETATION (2012–2014)

CO_2 Banking Against Permeability Barrier

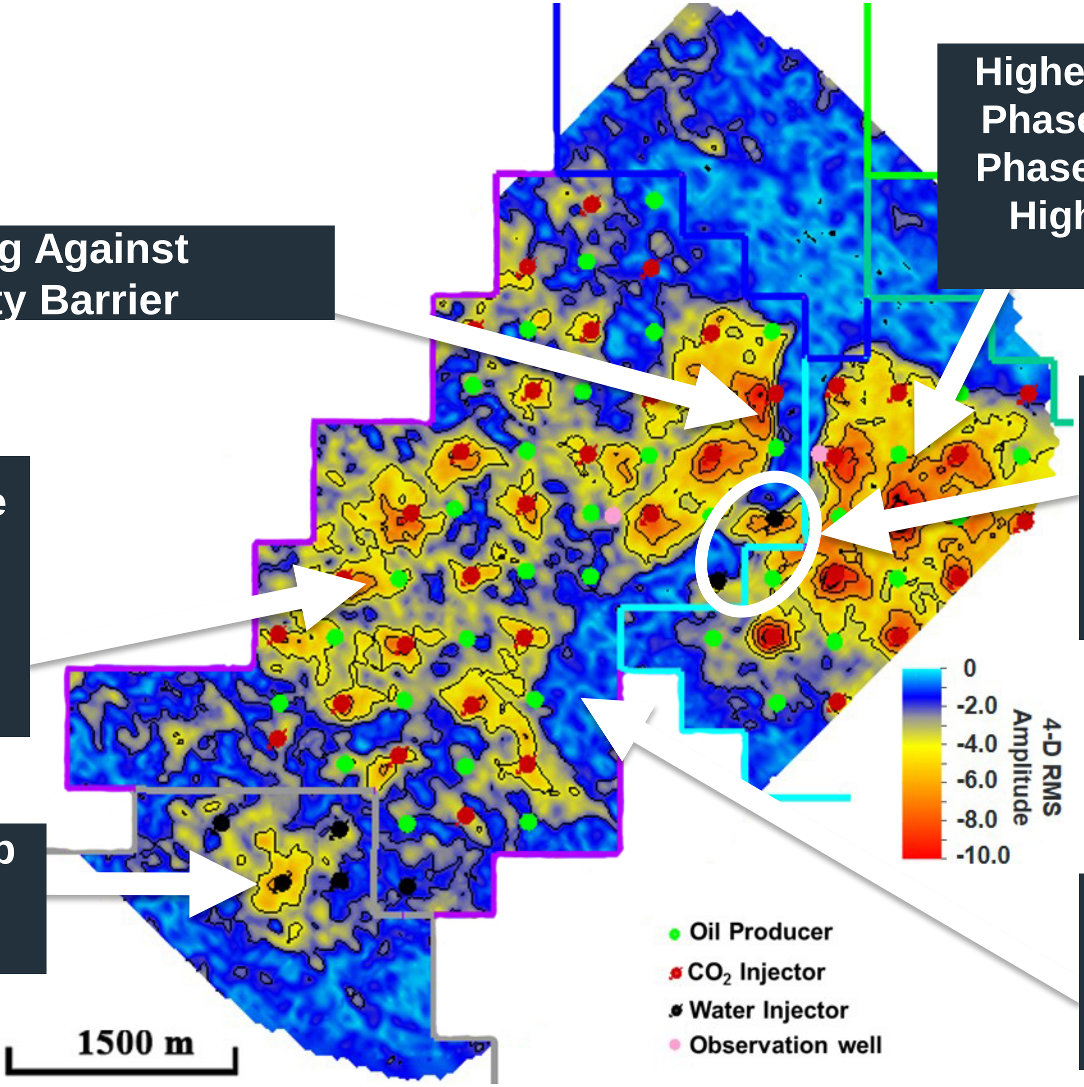
Higher Amplitude in Phase 2 Relative to Phase 1 Because of Higher Pressure Buildup

CO_2 and Pressure Moving Updip Away from the Injector Toward Producer

Fluid and Pressure Communication Between Phases 1 and 2

Pressure Buildup from Water Injection

Southeastern Extension of the Permeability Barrier

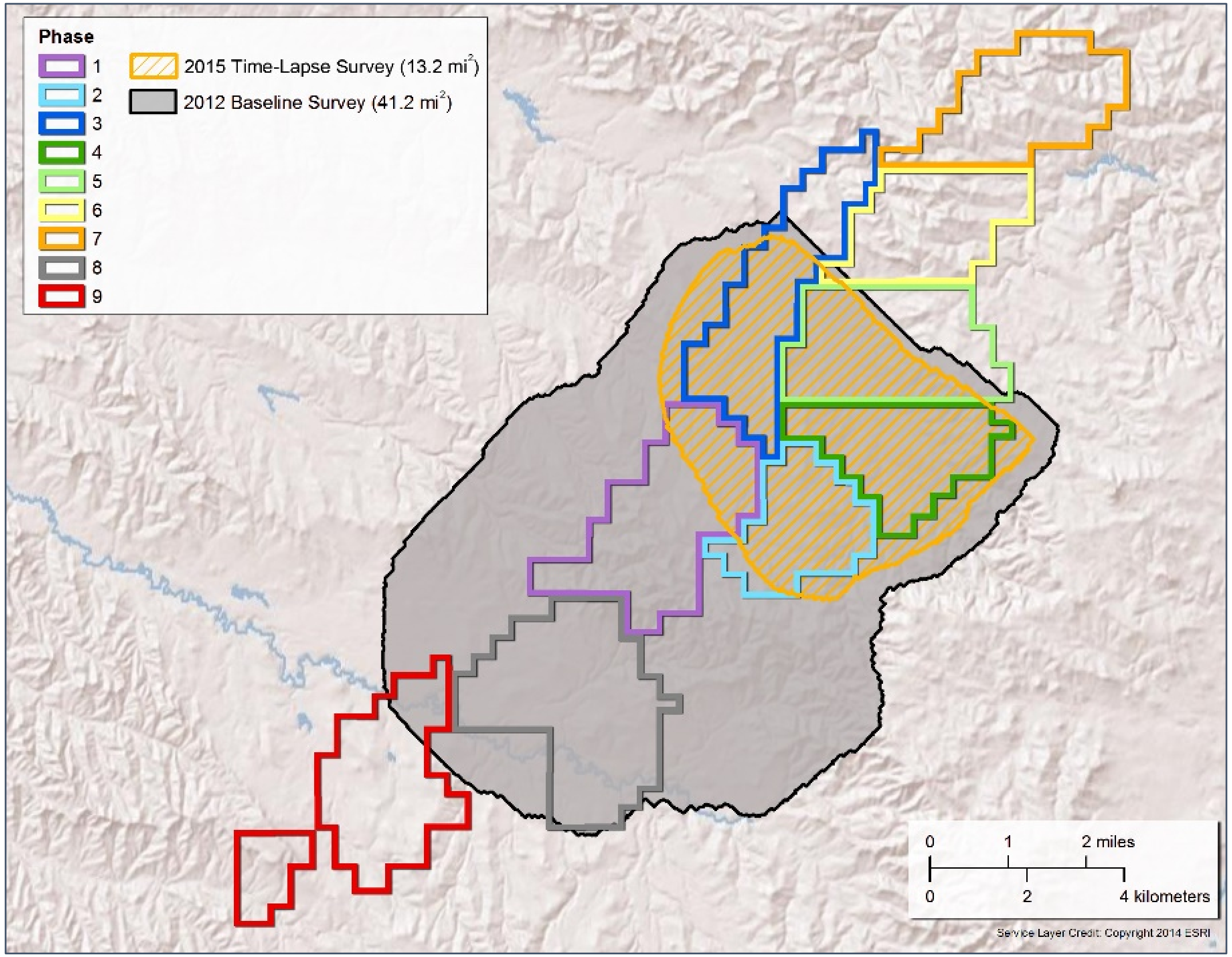


SECOND REPEAT 3-D SURVEY

Phase	Start of CO_2 Injection	Estimated Associated CO_2 Storage (Sept 2015), Mt
1	May, 2013	.415
2	Dec 2013	.519
3	Nov 2014	.481

Calculated using MBOG data

- Collected September 2015.
- 13.2 mi^2.
- ~1.42 Mt CO_2 stored in monitored area at the time of survey.



SECOND REPEAT: 4-D DIFFERENCE INTERPRETATION (2012–2015)

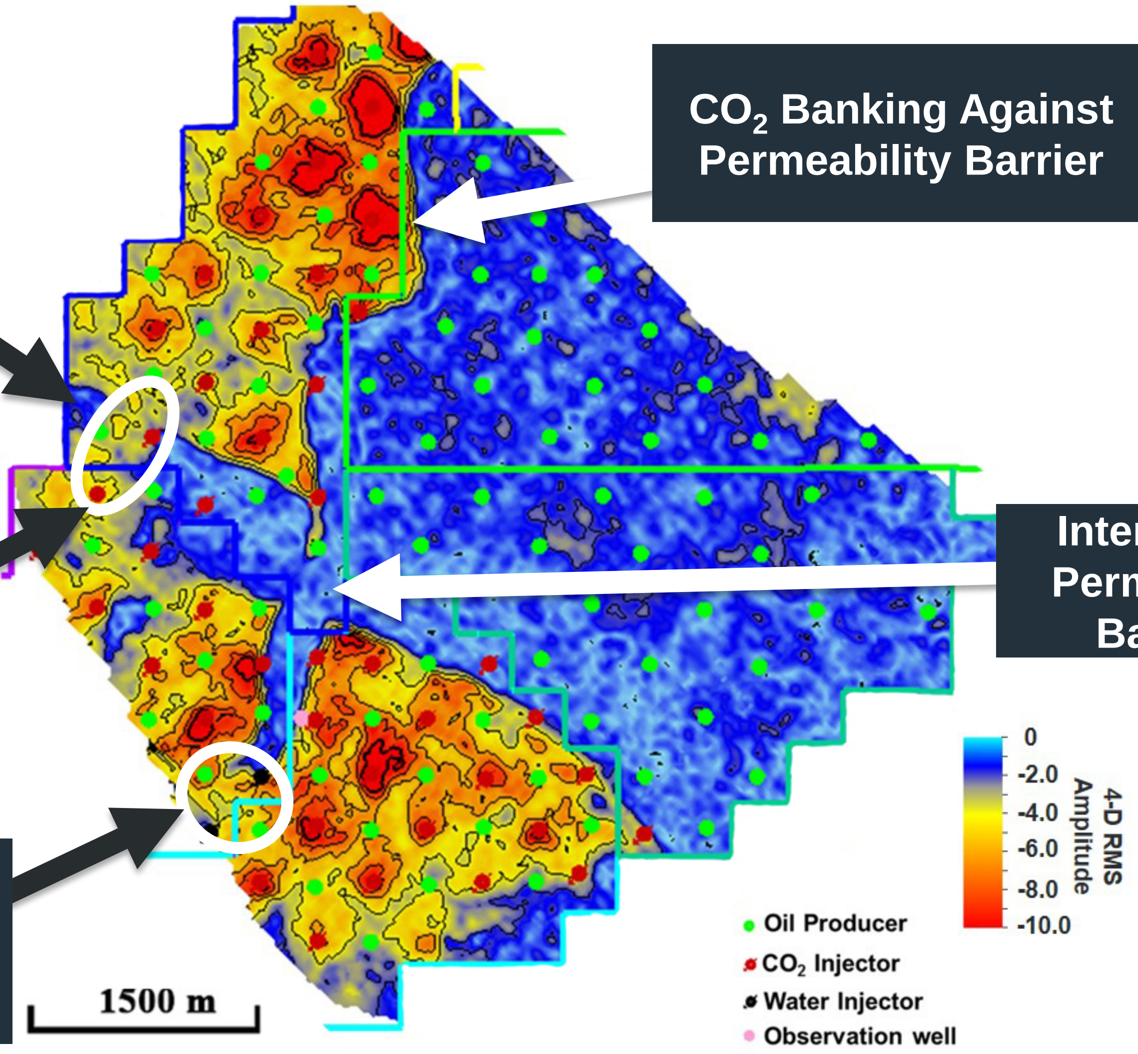
Extension of Permeability Barrier

CO_2 Banking Against Permeability Barrier

Fluid and Pressure Communication Between Phases 1 and 3

Intersecting Permeability Barriers

Fluid and Pressure Communication Between Phases 1 and 2

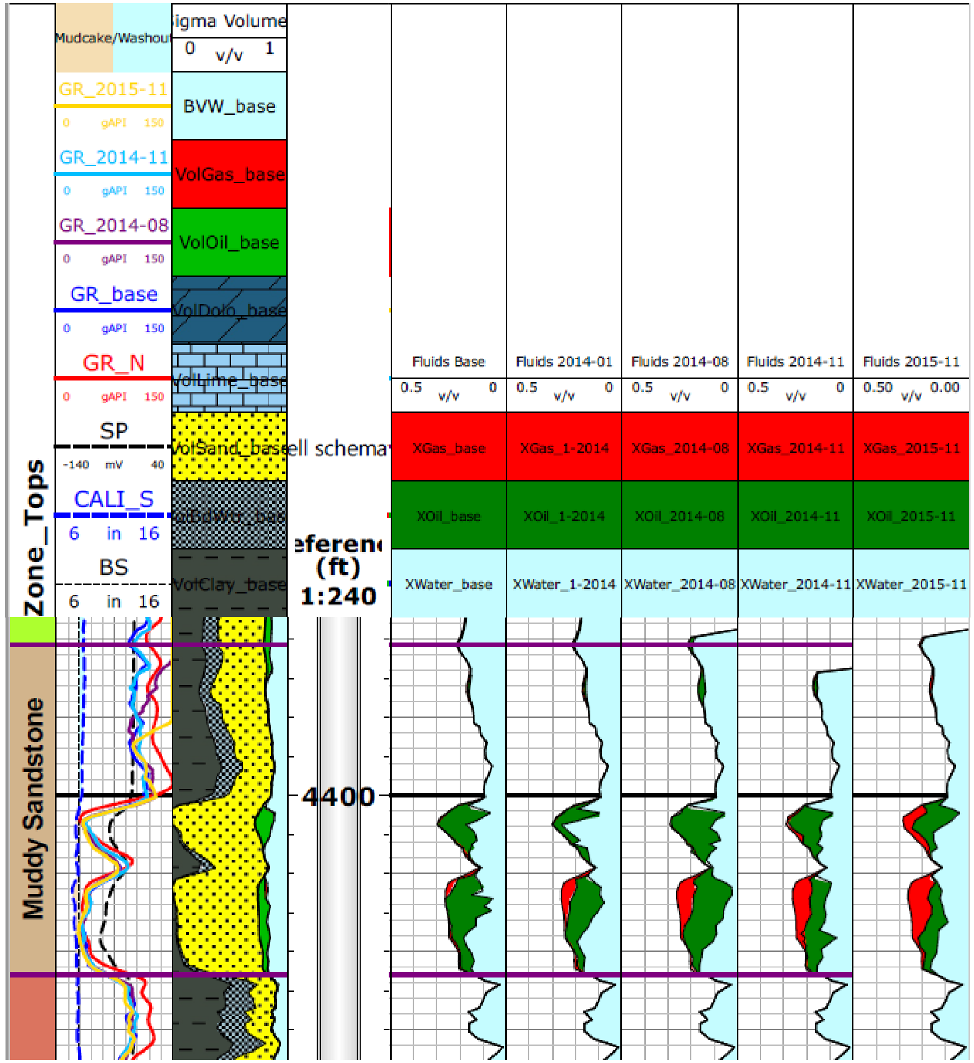


PULSED-NEUTRON LOGS

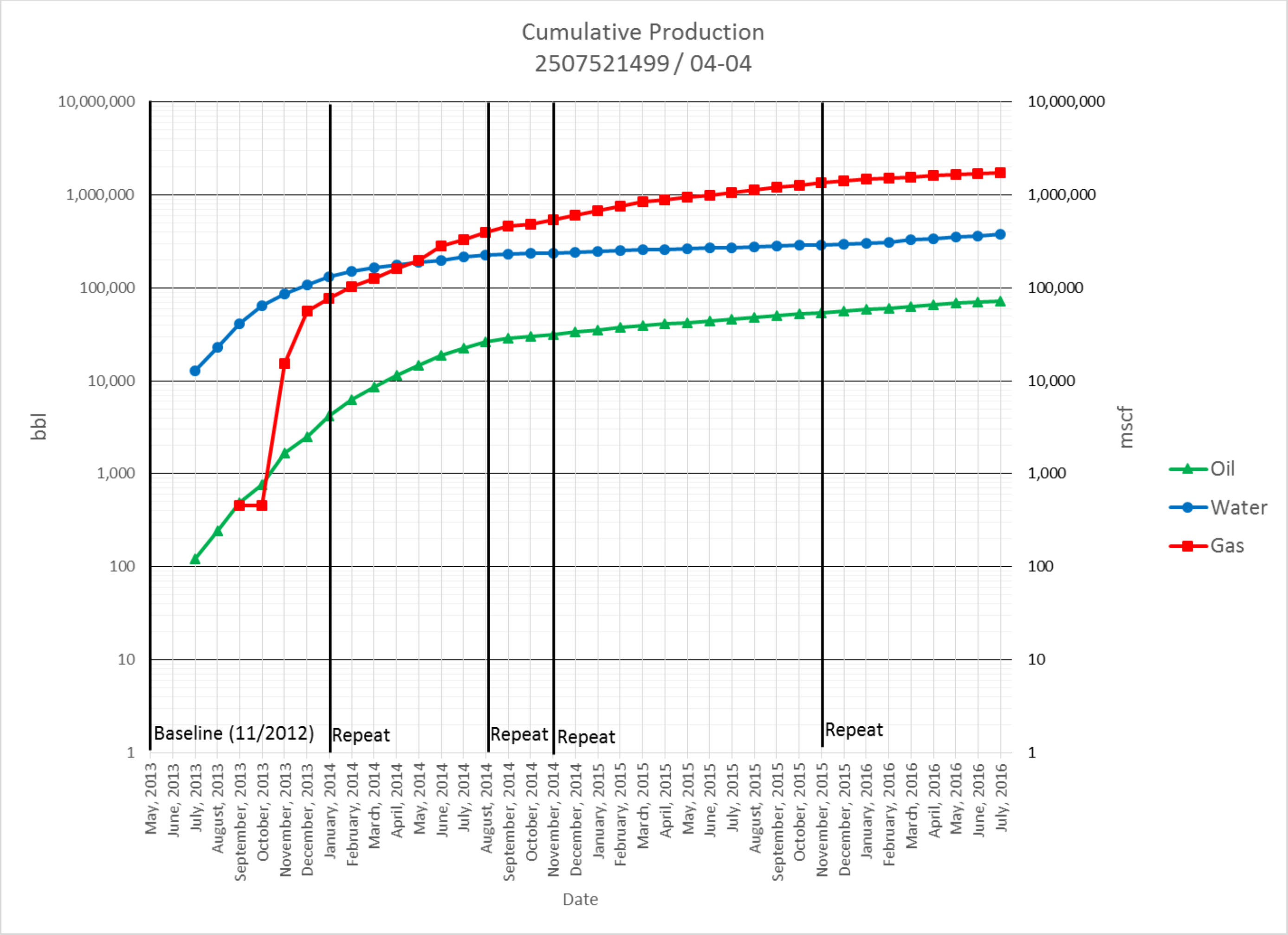
- Seven PNL campaigns:
  - 45 wells (92 total logs) logged to date:
    - 45 baseline
    - 47 repeat

PNL RESULTS

Time-Lapse PNL Results



Production Data



SUMMARY AND RESULTS: 4-D SEISMIC AND PNLS

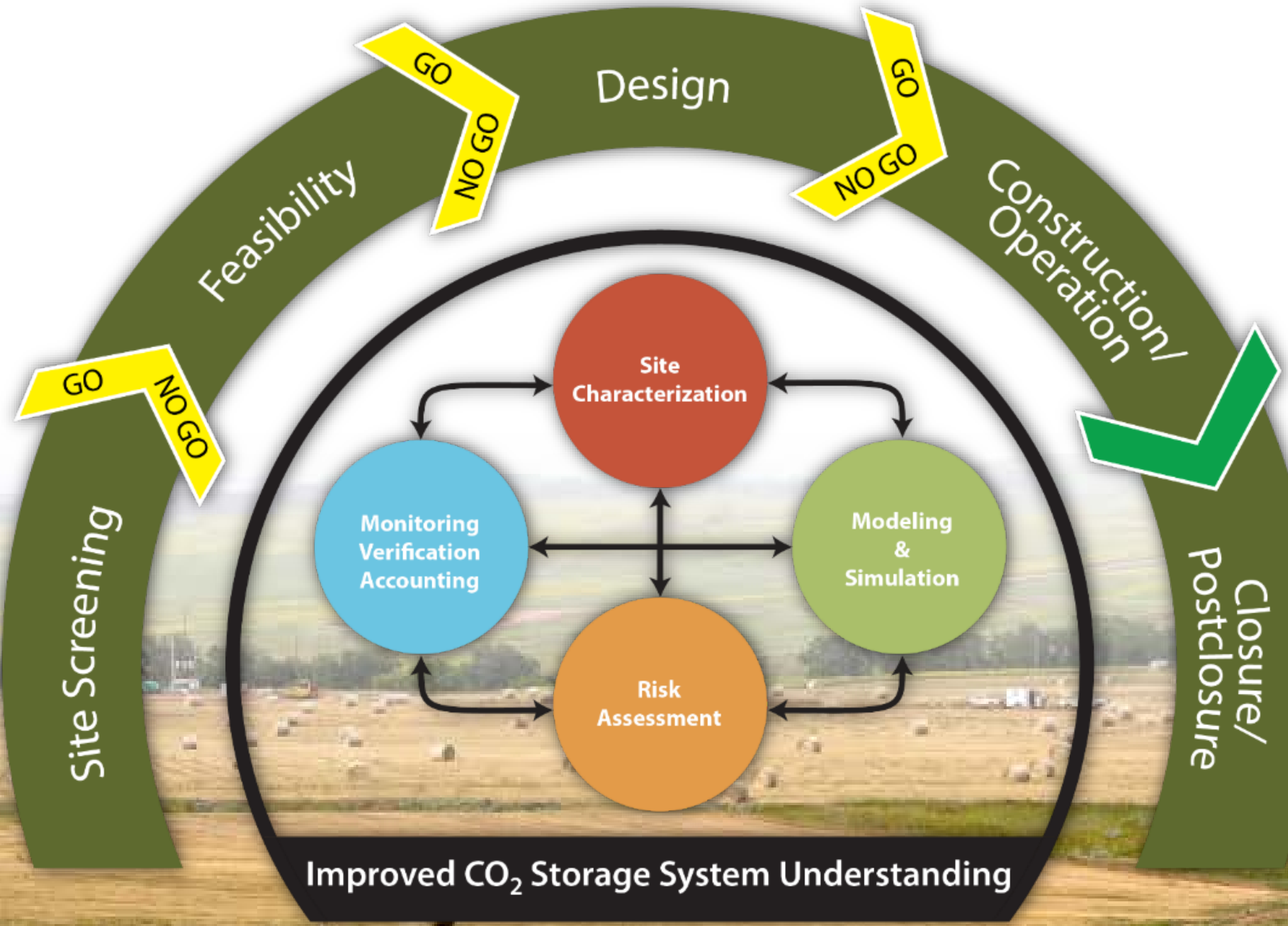
- 4-D seismic shown to be very effective at monitoring CO_2 saturation changes and pressure changes, even in thin reservoir.

- CO_2 can act as a tracer, illuminating extent and location of suspected pressure and fluid communication pathways and barriers.

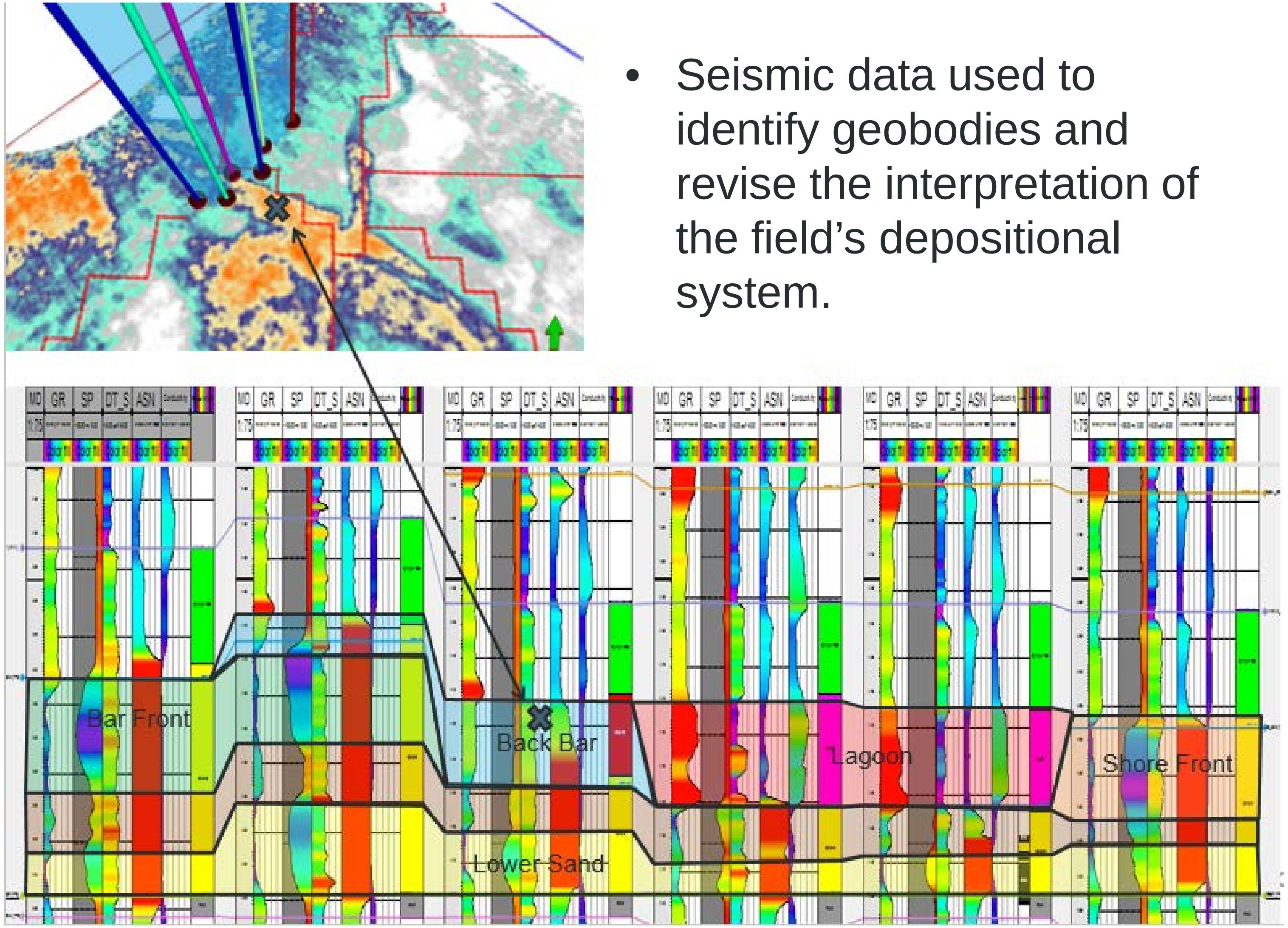
- Can provide insight into “anomalous” field measurements (e.g., unexpected changes in pressure, water cut, oil production).

- PNLs support interpretation of 4-D seismic amplitude response (separating pressure effects from CO_2 saturation change).

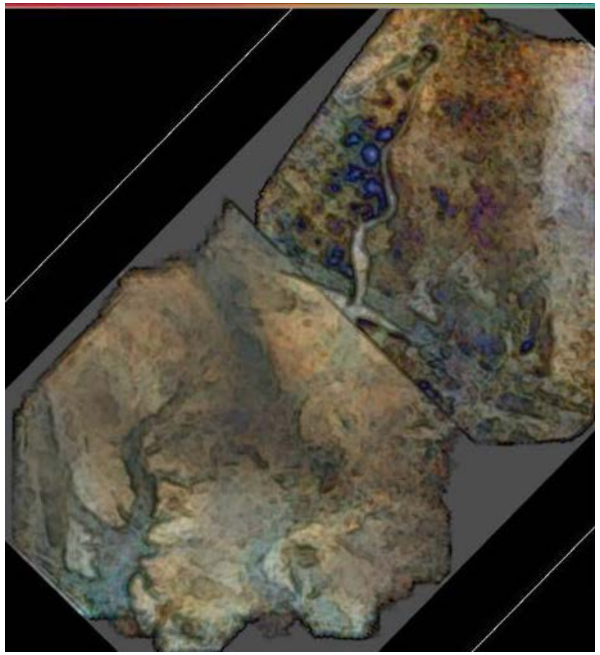
INTEGRATION ACCOMPLISHMENTS



IMPROVED GEOLOGIC MODEL



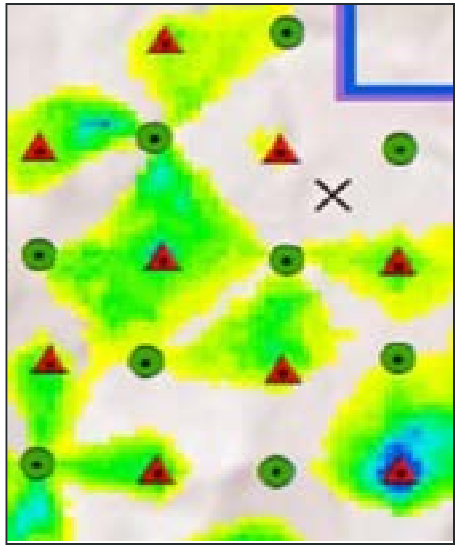
- Seismic data used to identify geobodies and revise the interpretation of the field's depositional system.



Seismic Frequency Decomposition: Image Credit: Thang Pham, Senior Geophysicist, Denbury Onshore LLC

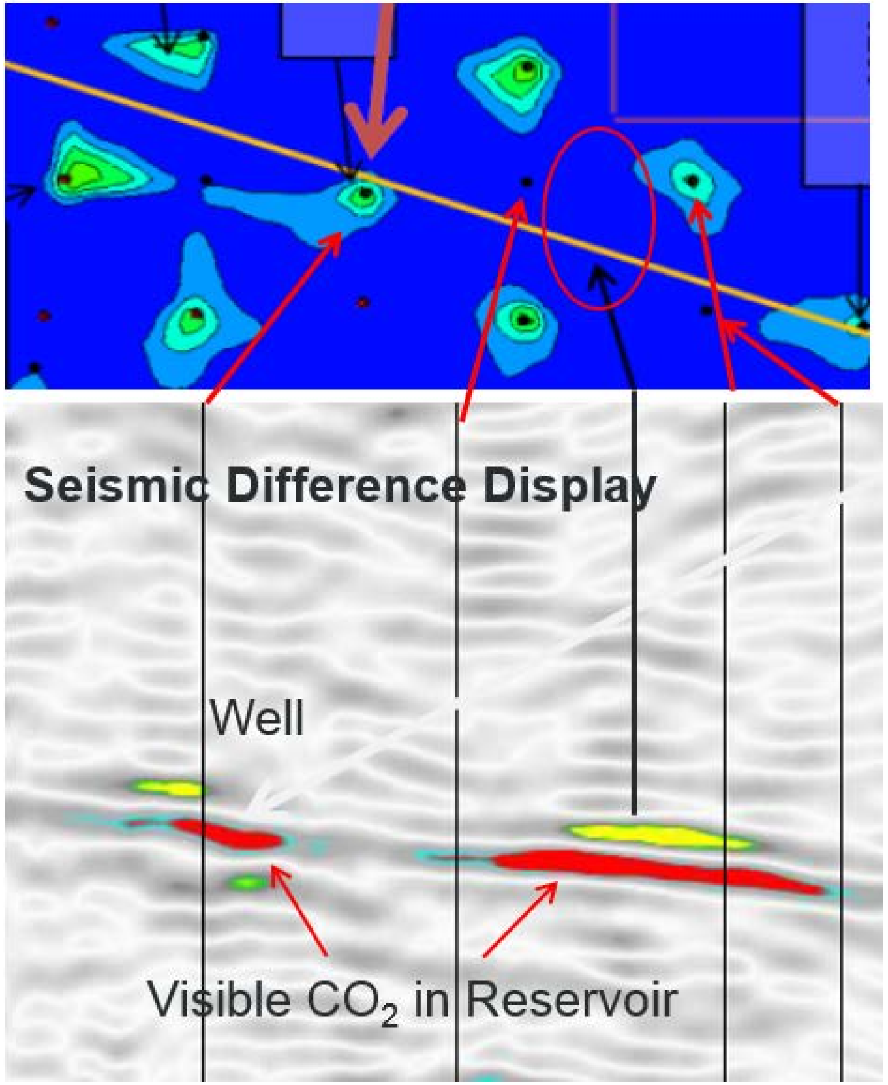
SIMULATION-GUIDED MONITORING

- Simulation was used to predict location and saturation of CO_2.
- 2-D seismic line used to confirm ability of seismic to detect CO_2 in the reservoir.
- Results supported decision to conduct large 3-D survey.



Predictive Simulation Results (CO_2 saturation)

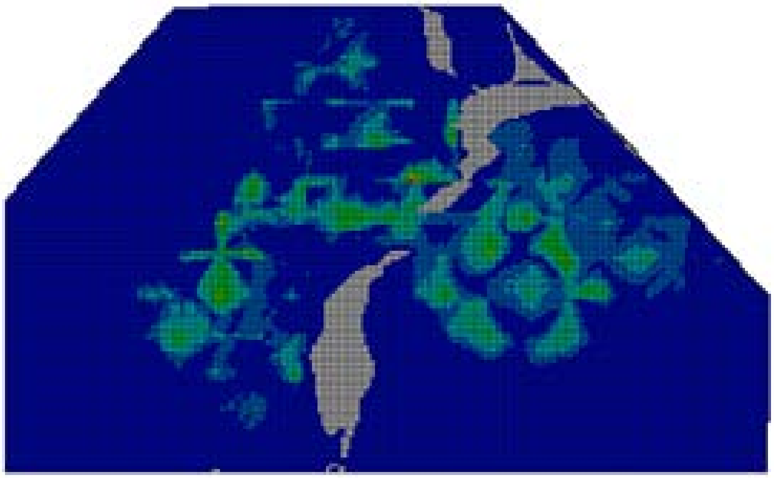
Seismic Line Overlaying Simulation



MVA-GUIDED SIMULATION

- Pressure and fluid communication revealed by 4-D seismic helped explain Phase 1 model history-matching issues.

- A combined Phase 1 and 2 was developed in response.



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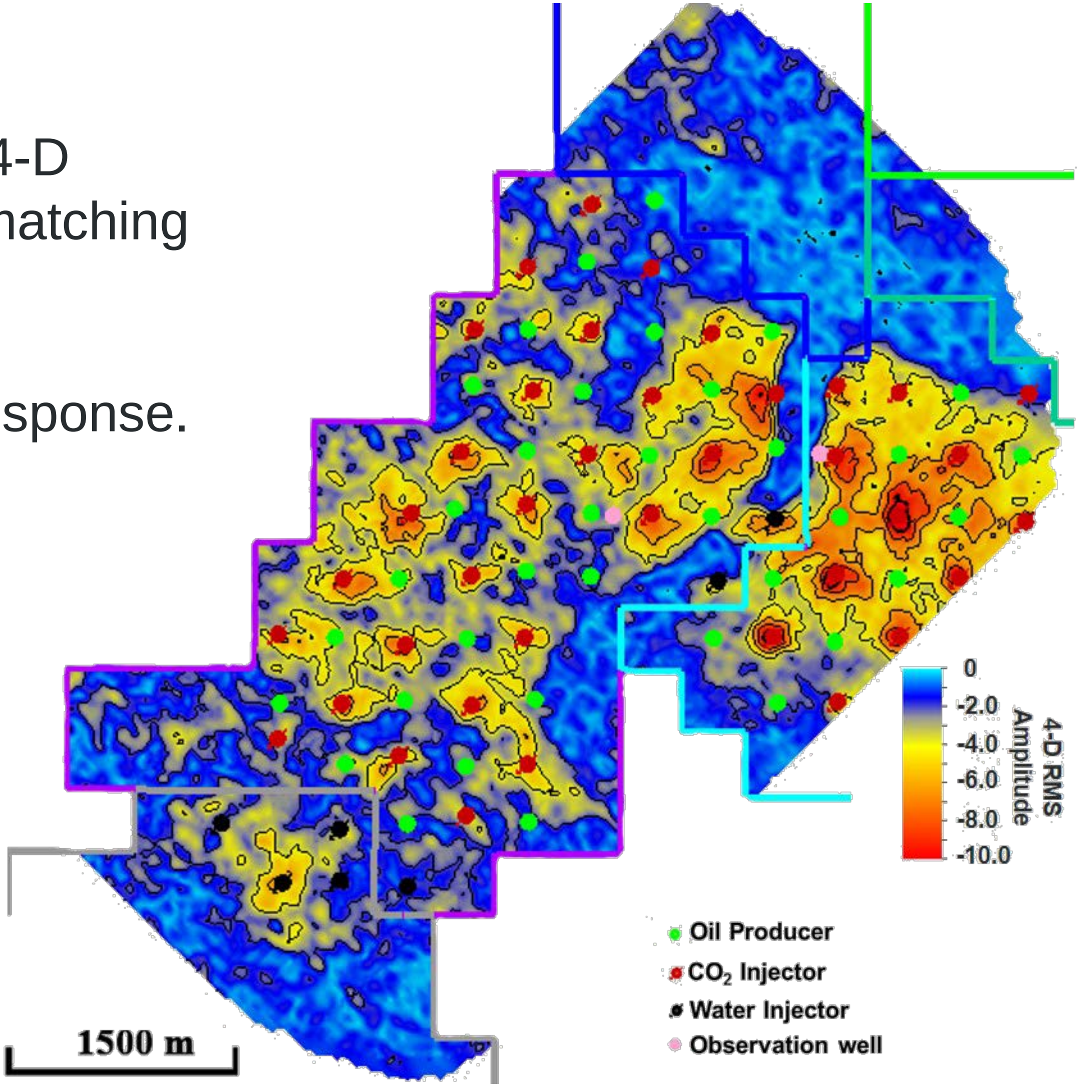
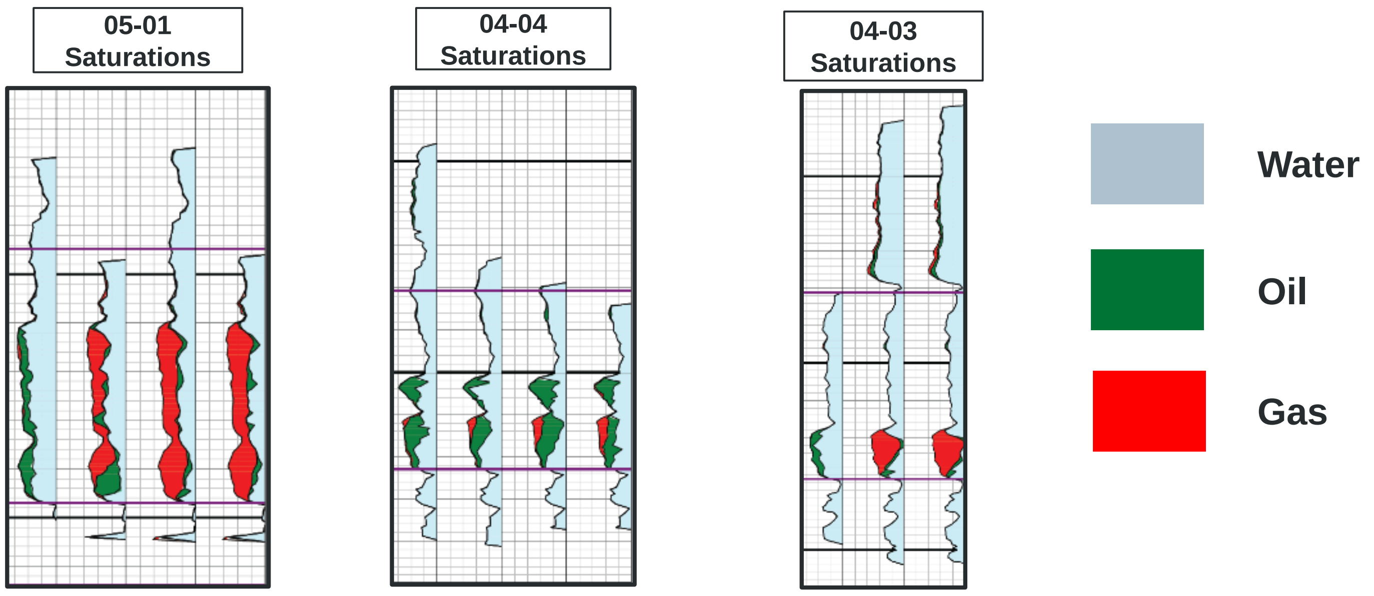
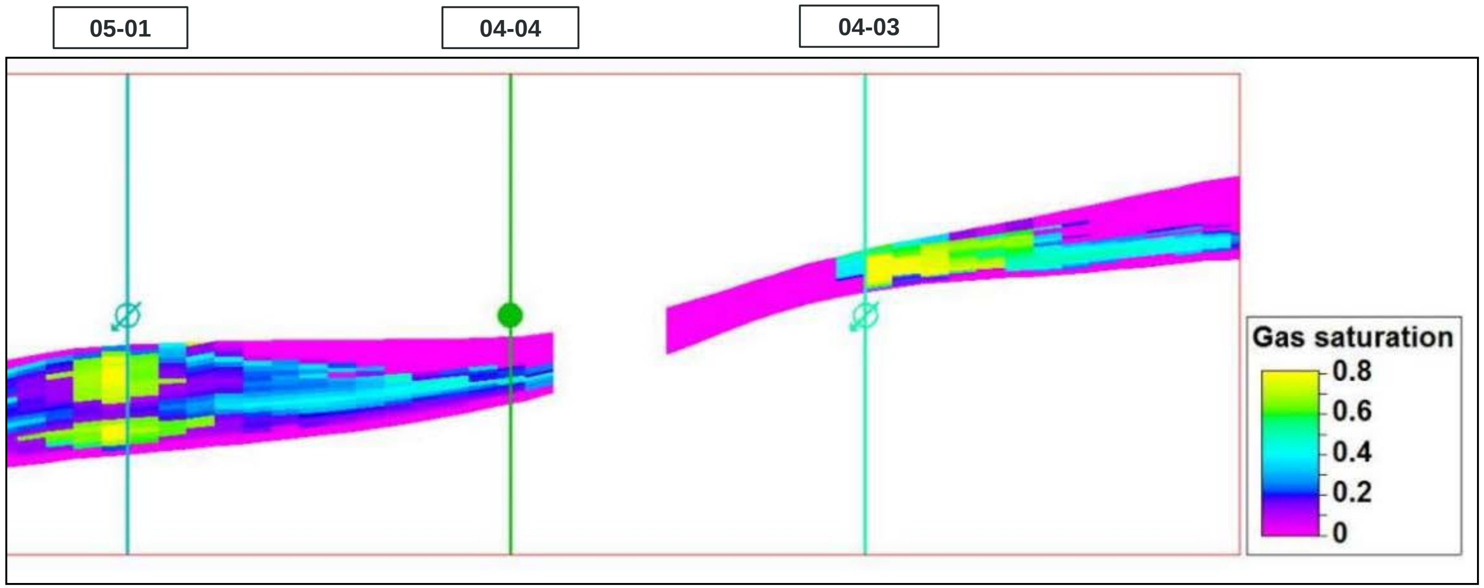
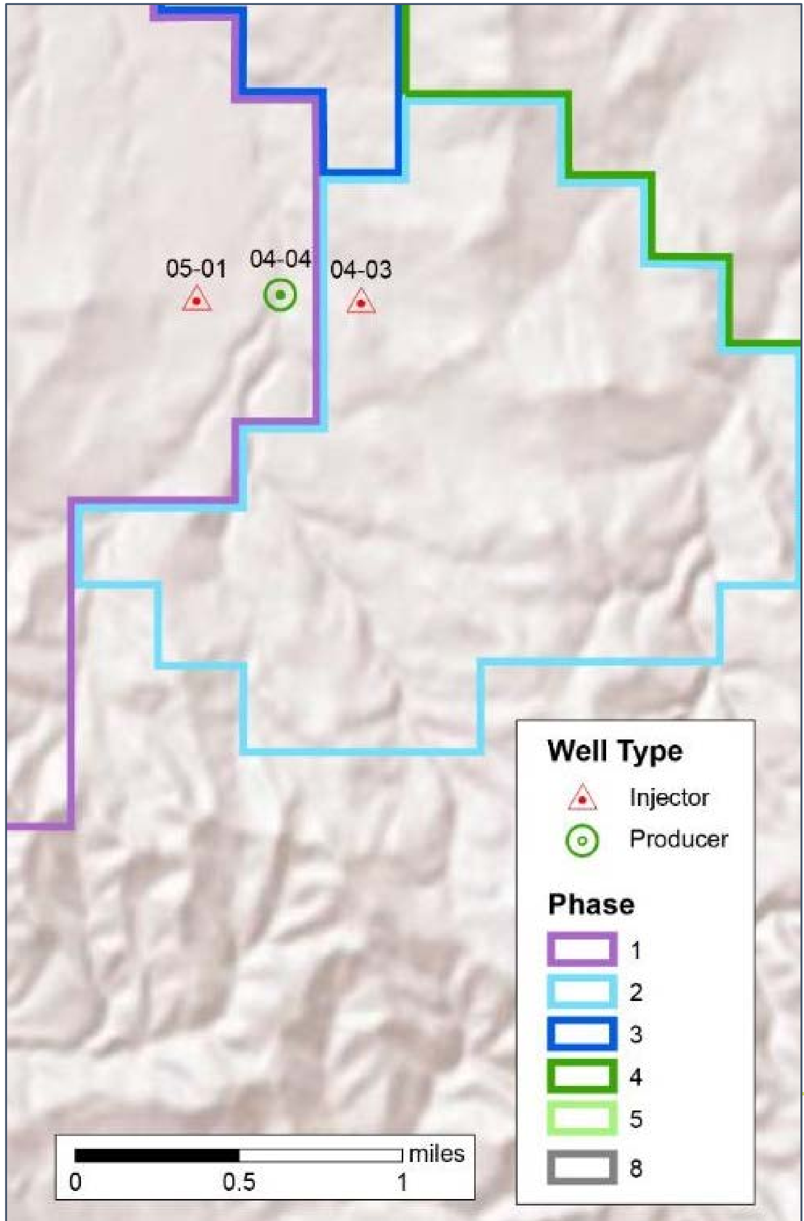


MVA FOR SIMULATION VALIDATION – PNLS







OUTREACH IS KEY

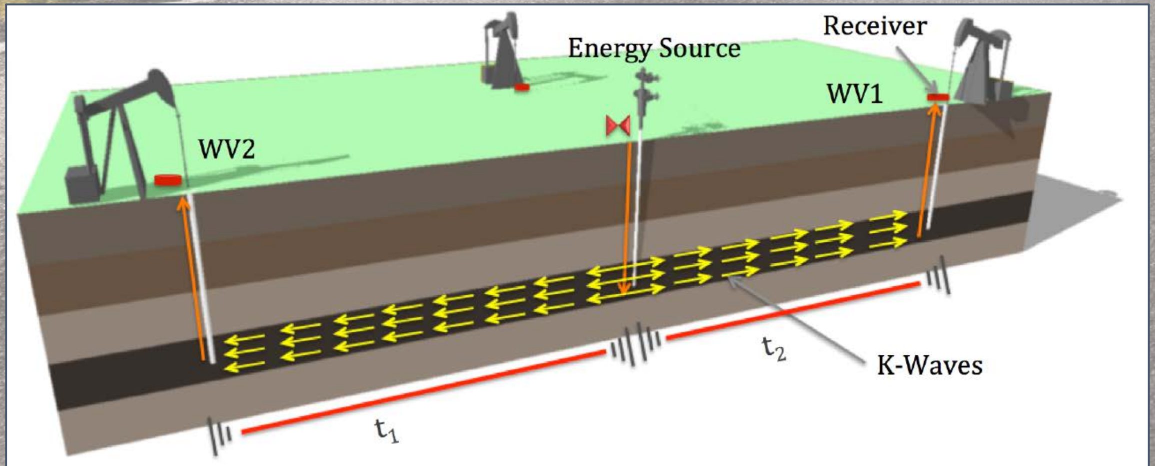
- Documentary:
  - Coal Powered! (*working title*)

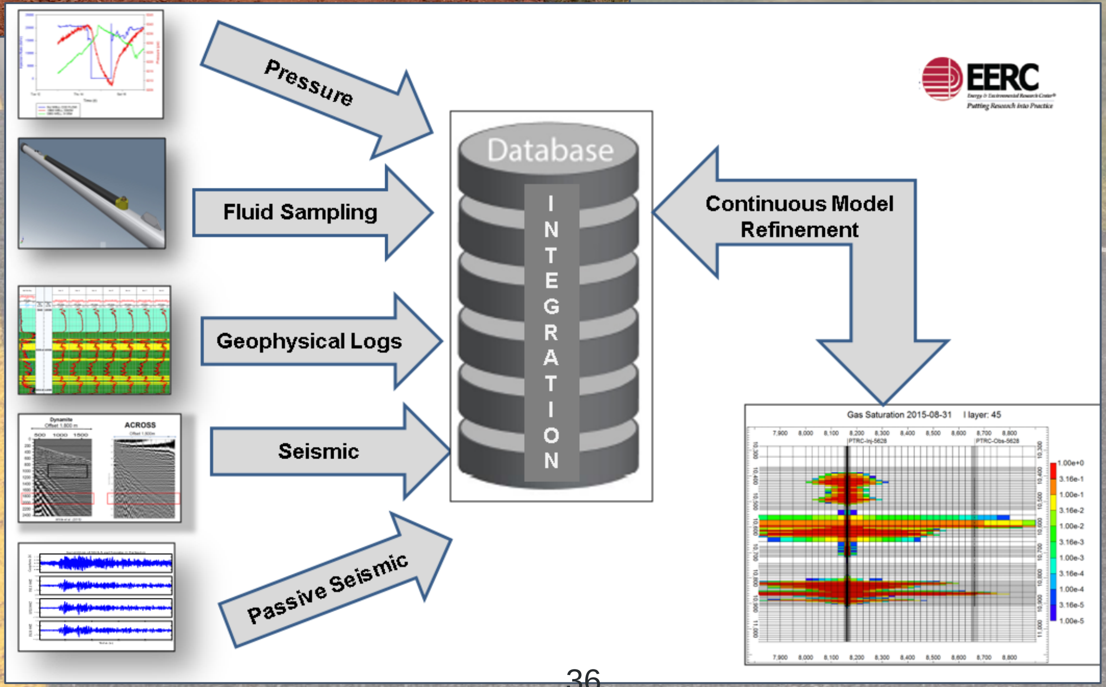
LESSONS LEARNED/KEY FINDINGS

- The PCOR Partnership region has outstanding potential storage opportunities.
- MVA techniques are applicable to associated CO_2 storage during CO_2-EOR.
- Adaptive management approach is readily applicable to future geologic CO_2 storage projects in this region and others.
- PCOR Partnership provides platform to test various techniques and technologies. A significant time gap can exist between data collection and analysis and integration.

SYNERGY OPPORTUNITIES: MVA EVOLUTION

- Faster processing for quicker integration
  - Improve performance predictions
  - Inform operational decisions with actionable results
- Intelligent monitoring
- Low environmental impact
- No impact on operations
- Semiautonomous and scalable
- Viable and cost-effective long term





THE PCOR PARTNERSHIP IS SUCCESSFULLY:

- Achieving CO_2 storage on a commercial scale.
- Investigating relationship between the CO_2 EOR process and long-term storage of CO_2.
- Validating MVA methods to effectively monitor CO_2 storage.
- Using commercial oil/gas practices as the backbone of MVA strategies, and augment with additional cost-effective techniques.
- Sharing lessons learned for the benefit of similar projects across the region.

CONTACT INFORMATION

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THANK YOU!

Critical Challenges. **Practical Solutions.**

APPENDIX

ADDRESSING RCSP PROGRAM GOALS

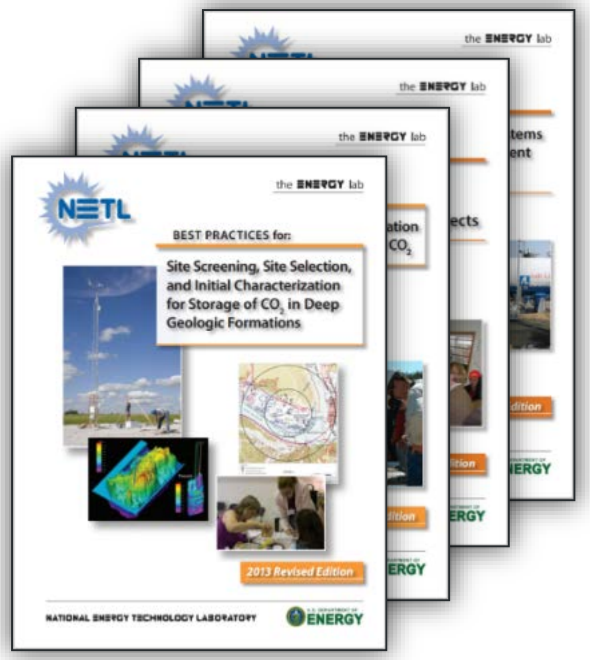
- Develop technologies that will support the industry's ability to predict CO_2 storage capacity in geologic formations to within ±30%:
  – *Conducting pilot tests and demonstration projects in hydrocarbon reservoirs, saline formations, and coal seams to improve understanding of sweep and storage efficiency.*
  – *Evaluating oil fields, saline formations, and coal seams to estimate volumetric and dynamic storage resource through characterization and simulation.*
  – *Conducting complementary projects that incorporate lessons learned from the PCOR Partnership to improve methods to estimate CO_2 storage resource.*
    - *DOE project – Optimizing and Quantifying CO_2 Storage Capacity/Resource in Saline Formations and Hydrocarbon Reservoirs (2012–2016)*
    - *Joint IEAGHG and DOE projects – CO_2 Storage Efficiency in Deep Saline Formations – Stages 1 and 2*
    - *Identification of Residual Oil Zones in the Williston and Powder River Basins*
    - *North Dakota Integrated Carbon Storage Complex Feasibility Study (CarbonSAFE)*

ADDRESSING RCSP PROGRAM GOALS

- Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness:
  - *Testing new techniques or combining techniques to better account for injected CO_2 in the demonstration tests.*
  - *Evaluating different injection strategies for improving both storage efficiency and hydrocarbon recovery in collaboration with commercial partner Denbury Onshore LLC (Denbury).*
- Develop and validate technologies to ensure 99% storage permanence:
  - *Evaluating the existing technologies used to monitor, verify, and account for the injected CO_2 to determine detection limits.*
  - *Multiple MVA techniques, including 4-D seismic and pulsed-neutron logs (PNLs), have been used at Bell Creek to successfully track the presence and movement of CO_2 in the reservoir and have shown no evidence of out-of-zone migration or negative environmental impact.*

ADDRESSING RCSP PROGRAM GOALS

- Develop best practices manuals (BPMs) for MVA and assessment; site screening, selection, and initial characterization; public outreach; well management activities; and risk analysis and simulation:
  - Participated in updating several DOE BPMs
    - Site characterization
    - Risk assessment/simulation
    - MVA
    - Operations
    - Outreach
  - PCOR Partnership BPMs (in development)
    - Fort Nelson Test Site – Feasibility Study
    - Adaptive management approach
    - Site characterization
    - Modeling and simulation
    - Risk assessment
    - MVA
  - Produced videographic BPM: “Installing a Casing-Conveyed Permanent Downhole Monitoring (PDM) System.”



PCOR PARTNERSHIP BELL CREEK OBJECTIVES

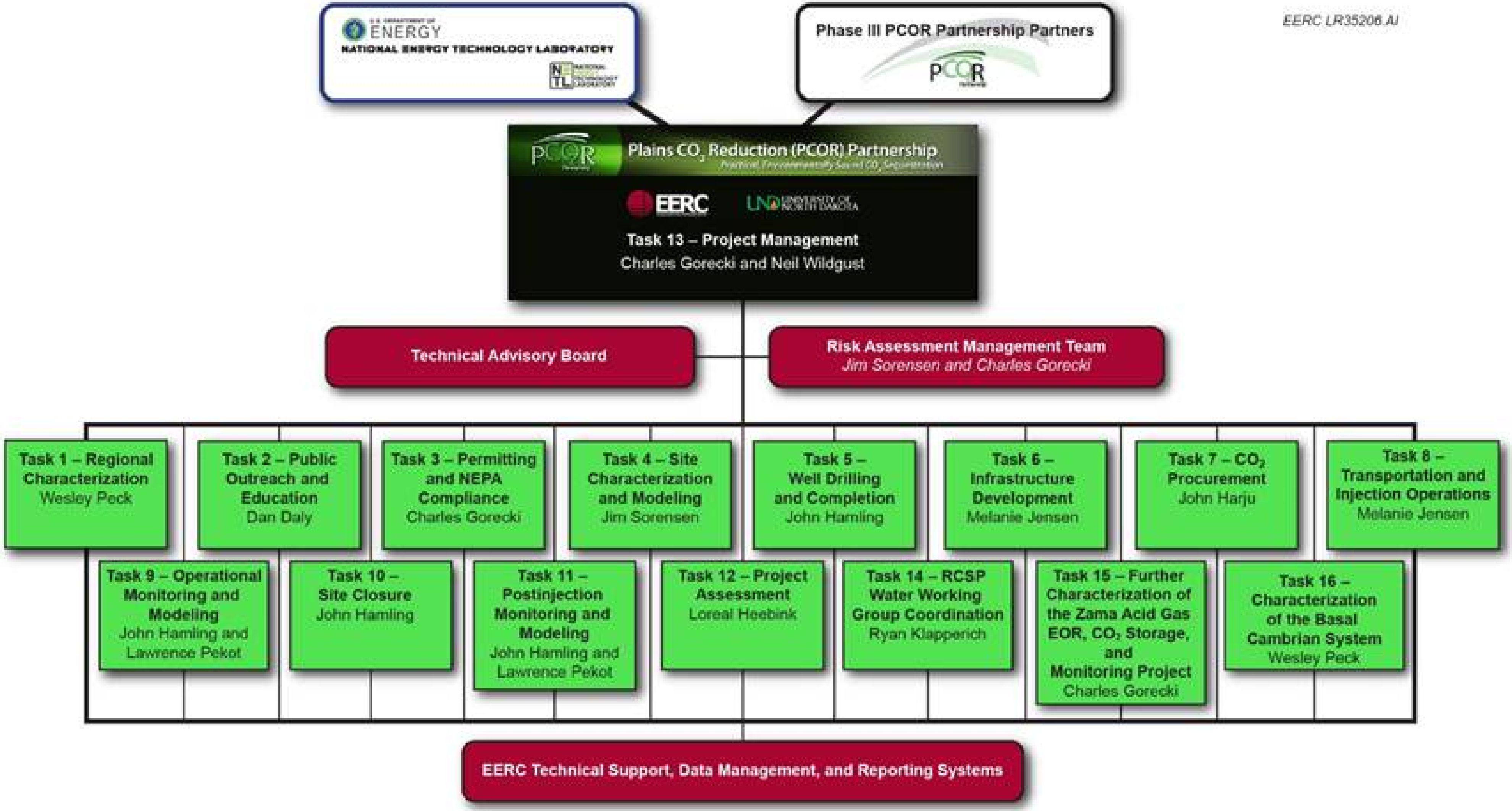
- Safely and permanently achieve CO_2 storage associated with commercial-scale EOR.
- Demonstrate that oil-bearing formations are viable sinks with significant storage capacity to help meet near-term CO_2 storage objectives.
- Establish MVA methods to safely and effectively monitor CO_2 storage.
- Use commercial oil/gas practices as the backbone of the MVA strategy, and augment with additional cost-effective techniques.
- Share lessons learned for the benefit of similar projects across the region.
- Establish a relationship between the CO_2 EOR process and long-term associated CO_2 storage.

PROJECT OVERVIEW: SCOPE OF WORK

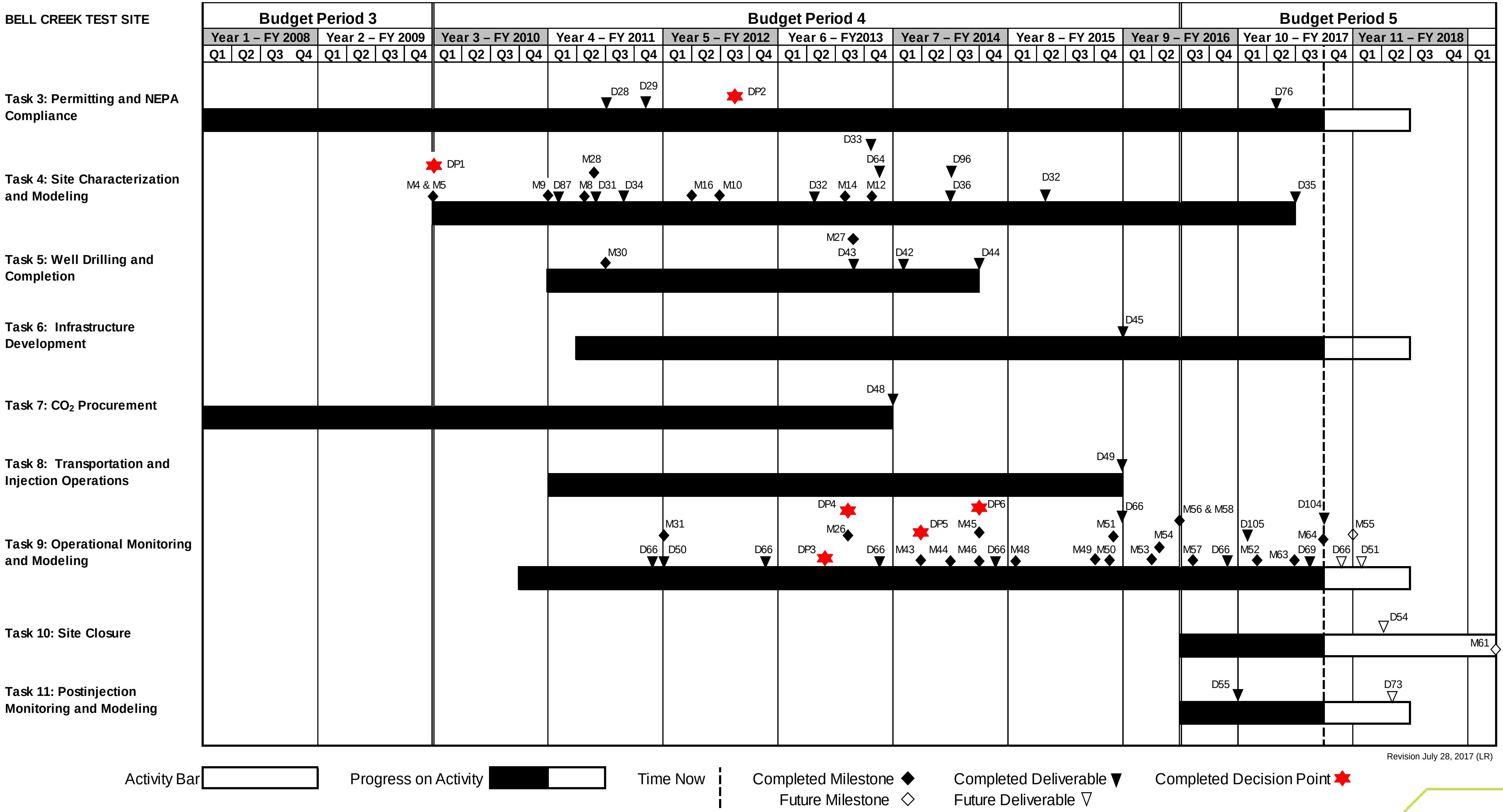
- Project advantages
  - Full-scale CO_2 EOR project provides opportunity to deploy an MVA program on a commercial project with hundreds of wells.
  - Integrate with established CO_2 operators and learn from their operational experiences.
  - CO_2 EOR has the potential to increase domestic production, produce oil with reduced carbon intensity, store millions of tonnes of CO_2, develop the infrastructure for wide-scale CCS deployment, and help develop the techniques for monitoring and accounting for CO_2 in all storage project types.

- Project limitations
  - Regional Carbon Sequestration Partnership (RCSP) Program is scheduled to end in 2018, but the commercial CO_2 EOR project will continue. If the program were extended, this would offer the opportunity to further refine operational monitoring at a commercial project.
  - No postinjection-monitoring period because of injection continuing beyond the time line of the PCOR Partnership Program; however, a conceptual postinjection-monitoring plan will be developed.
  - Some data are confidential because of commercial aspect of CO_2 EOR project.

ORGANIZATION CHART



PROJECT SCHEDULE



DELIVERABLES, MILESTONES, AND KEY DECISION POINTS

Key for Deliverables	
D28	Environmental Questionnaire
D29	Permitting Action Plan
D31	Geological Characterization Experimental Design Package
D32	Geomechanical Report
D33	Preinjection Geochemical Report
D34	Baseline Hydrogeological Experimental Design Package
D35	Best Practices Manual – Site Characterization
D36	Wellbore Leakage Final Report
D42	Injection Experimental Design Package
D43	Monitoring Experimental Design Package
D44	Drilling and Completion Activities Report
D45	Infrastructure Development Report
D48	Procurement Plan and Agreement Report
D49	Transportation and Injection Operations Report
D50	Site Characterization, Modeling, and Monitoring Plan
D51	Best Practices Manual – Monitoring for CO_2 Storage and CO_2 EOR
D54	Site Closure Procedures Report
D55	Cost-Effective Long-Term Monitoring Strategies Report
D64	Site Characterization Report
D66	Simulation Report
D69	Simulation Best Practices Manual
D73	Monitoring and Modeling Fate of CO_2 Progress Report
D76	Regional Regulatory Perspective
D87	Geomechanical Experimental Design Package
D96	3-D Seismic Acquisition and Characterization Report
D104	Analysis of Expanded Seismic Campaign
D105	Comparison of Non-EOR and EOR Life Cycle Assessment

Key for Milestones	
M4	Test Site Selected
M5	Data Collection Initiated
M8	Wellbore Leakage Data Collection Initiated
M9	Geological Model Development Initiated
M10	Wellbore Leakage Data Collection Completed
M12	Preinjection Geochemical Work Completed
M14	Geological Characterization Data Collection Completed
M16	Initiation of Production and Injection Simulations
M26	CO_2 Injection Initiated
M27	MVA Equipment Installation and Baseline MVA Activities Completed
M28	Geological Characterization Experimental Design Package Completed
M30	Baseline MVA Activities Initiated
M31	Site Characterization, Modeling, and Monitoring Plan Completed
M43	First Full-Repeat Sampling of the Groundwater- and Soil Gas- Monitoring Program Completed
M44	First 3-D VSP Repeat Surveys Completed
M45	First Full-Repeat of Pulsed-Neutron Logging Campaign Completed
M46	First Year of Injection Completed
M48	1 Million Metric Tons of CO_2 Injected
M49	1.5 Million Metric Tons of CO_2 Injected
M50	Two Years of Near-Surface Assurance Monitoring Completed
M51	Initial Analysis for First Large-Scale Repeat Pulsed-Neutron Logging Campaign Post-Significant CO_2 Injection Completed
M52	Initial Analysis of Extended Pulsed-Neutron Logging Campaign Data Completed
M53	Expanded Baseline and Time-Lapse 3-D Surface Seismic Survey Completed
M54	Initial Processing and Analysis of Historic InSAR Data Completed
M55	Initial Investigation of Crude Oil Compositional Changes During CO_2 EOR Completed
M56	Life Cycle Analysis for Primary and Secondary Recovery Oil Completed
M57	Life Cycle Analysis for EOR Completed
M58	Completion of 2.75 Million Metric Tons of CO_2 Stored
M61	Site Closure for Bell Creek Test Completed
M63	Initial Analysis of Processed InSAR Data Completed
M64	Initial Analysis of Expanded Seismic Campaign Data Completed

Key for Decision Points	
DP1	Site Selected
DP2	NEPA Requirements Met and Permitting Completed - Cleared for Injection
DP3	Injection Date Scheduled
DP4	Initiate Performance Monitoring
DP5	Determination to Extend Program into Next Commercial Development Area of the Field
DP6	Determination to Continue with Monitoring Program

PUBLICATIONS

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