Southwest Regional Partnership Phase 3:

Transition to Post-Injection Monitoring of CCUS in an Active Oil Field

DE-FC26-05NT42591

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U.S. Department of Energy
National Energy Technology Laboratory
2021 Carbon Management and Oil and Gas Research Project Review Meeting
August 4, 2021

ACKNOWLEDGEMENTS

AND MANY STELLAR SCIENTISTS AND ENGINEERS

WHO MAKE THIS PROJECT TRULY TERRIFIC

(EXTRA THANKS TO WORKING GROUP LEADERS)

U.S. Department of Energy

National Energy Technology Laboratory

2021 Carbon Management and Oil and Gas Research Project Review Meeting

August 4, 2021

Presentation Outline

- Technical Status
- Accomplishments to Date:
  - Characterization
  - Monitoring, Verification and Accounting
  - Modeling and Simulation
  - Risk Assessment
- Lessons Learned
- Synergy Opportunities
- Project Summary

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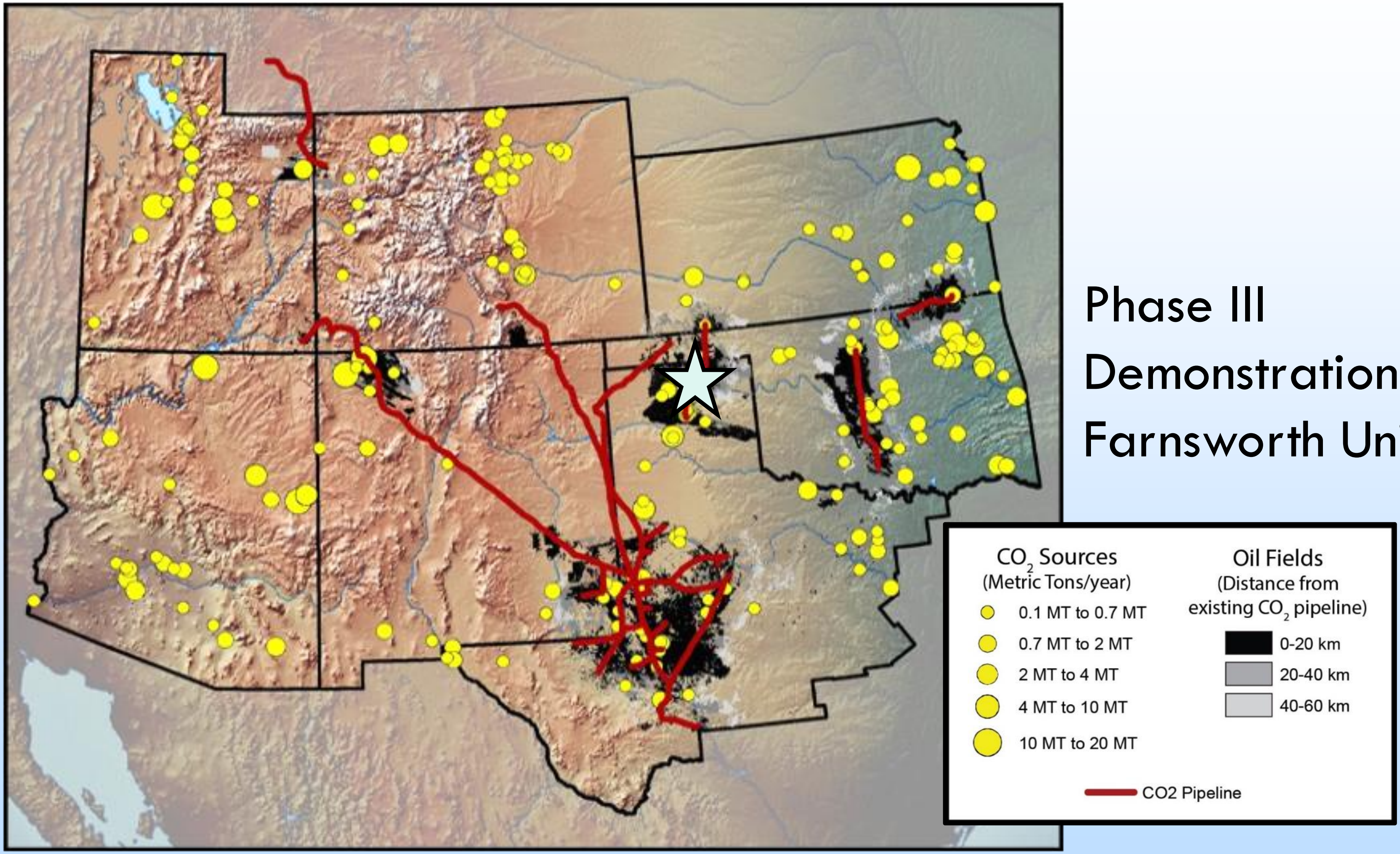
Technical Status: SWP Overview



Phase III Demonstration: Farnsworth Unit

Technical Status: Project Goals

- SWP's Phase III: large-scale EOR-CCUS demonstration
- General Goals:
  - One million tons CO_2 storage
  - Optimization of storage engineering
  - Optimization of monitoring design
  - Optimization of risk assessment
- Blueprint for CCUS in southwestern U.S.

Technical Status: Project Site

- Farnsworth field discovered in 1955.
- About 100 wells completed by the year 1960.
  - Field was unitized in 1963 by operator Unocal
  - Water injection for secondary recovery started in 1964.

Property	**Value**
Initial water saturation	31.4%
Initial reservoir pressure	2218 PSIA
Bubblepoint Pressure	2073 PSIA
Original Oil in Place (OOIP)	120 MMSTB (60 MMSTB west-side)
Drive Mechanism	Solution Gas
Primary Recovery	11.2 MMSTB (9 %)
Secondary Recovery	25.6 MMSTB (21 %)
Tertiary Recovery	16 MMSTB (13 %)

Technical Status: Sources

Anthropogenic CO_2 Supply:

~100,000 Metric tons CO_2/year

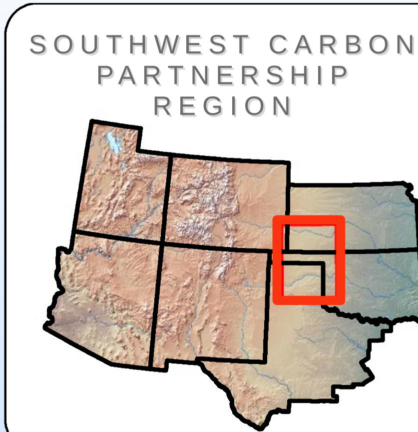
Legend

- Utiilization & Storage
- Carbon Capture
- Transportation
- Oil Fields

Other CO_2 Sources

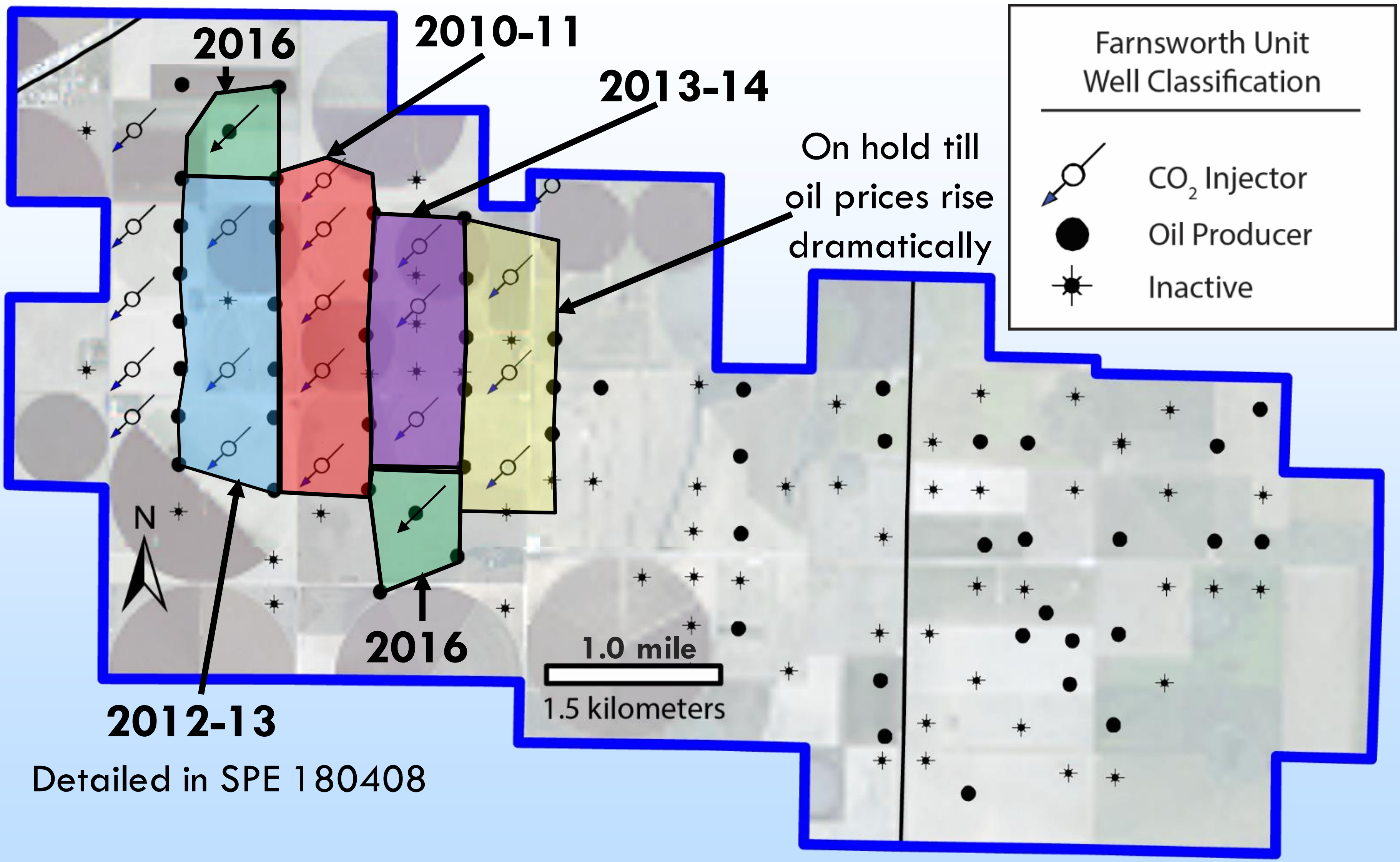
- 0.1 to 0.7 MT/yr
- 0.7 to 1.8 MT/yr
- 1.8 to 4 MT/yr
- 4 to 10 MT/yr
- 10 to 20 MT/yr

http://www.conestogaenergy.com/arkalon-ethanol



www.agrium.com

Technical Status: Injection Patterns



Detailed in SPE 180408

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Accomplishments: Characterization

Characterization Working Group Members and Roles

Lead – Martha Cather, PRRC
Co-Lead – Paige Czoski, PRRC

Geology
Martha Cather, PRRC
Ryan Leary, NMT EES

Students
Spencer Hollingworth, NMT

Wellbore Integrity
Tan Nguyen, NMT PE
Ting Xiao, UU
Reid Grigg, PRRC
George El-Kaseeh, PRRC
Jason Heath, Sandia

Fluid/Rock Interactions
Alex Rinehart, NMT EES
Andrew Luhmann, Wheaton
Jason Heath, Sandia
Hamid Rahnema, NMT

Students
Jason Simmons, NMT
Sam Otu, NMT
Zhidi Wu, UU

Geophysics
Paige Czoski, PRRC
Robert Balch, PRRC
Bob Will, PRRC
George El-Kaseeh, PRRC
Christian Poppeliers, Sandia
Lianjie Huang, LANL

Students
Noah Hobbs, NMT
Alan Horton, NMT

Accomplishments: Characterization

Task 7 – Post-Injection MVA & Risk Assessment:

Achievements

7.1.2 Monitor Subsurface Pressure and Temperature: Replaced old downhole P/T gauges and DTS in observation well (#13-10). Deployed memory P/T gauges in injection well #13-10A.

7.1.6 Assess Risks of Microseismicity: Replaced old microseismic borehole array in well #13-10. Installed new surface array with 20 microseismic recording stations.

7.1.8 Conduct Fluid accounting: FWU has now injected 1.76 Mmt and stored .84Mmt CO_2

7.2.1 Conduct Fluid/Rock Interaction Studies: Two students completed theses; one focused on two rock units' responses to brine and CO_2 at different flow rates – fluid/rock interaction analysis, another focused on 3-phase relative permeability.

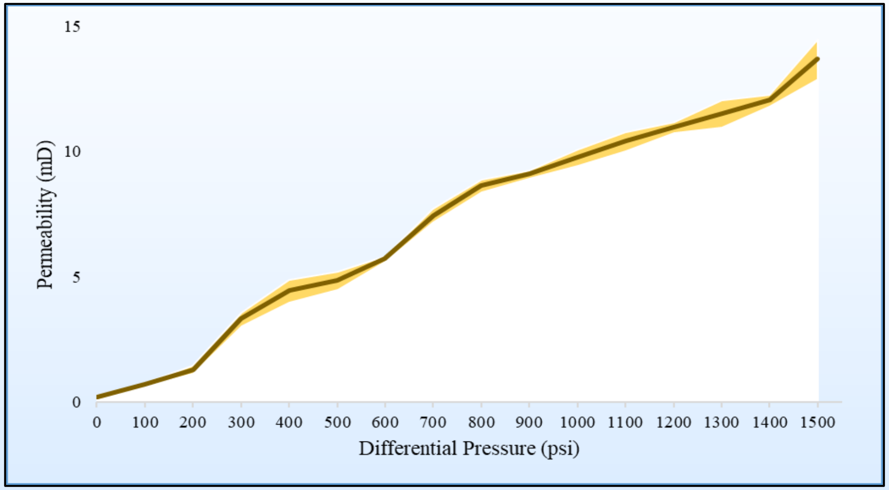
7.2.4 Refine interpretations of existing seismic data: Reviewed and Refined structural and stratigraphic interpretations using improved processing (depth imaging).

7.3.1 Refine Geologic Model: Release of new geologic model including improvements to stratigraphic interpretations and picks of sub-Morrow units (critical for effective structural modeling).

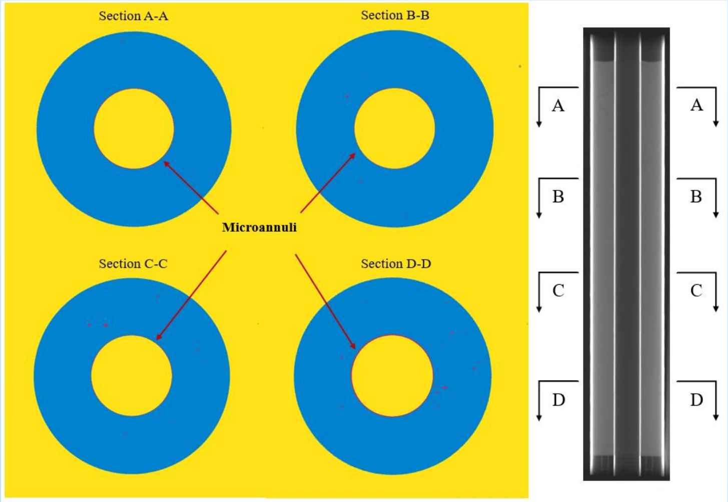
Accomplishments: Characterization

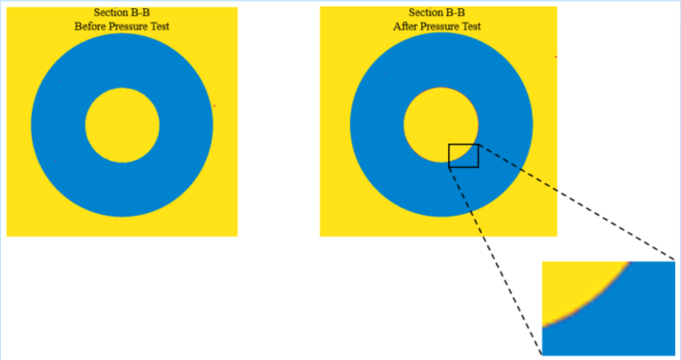
Selected Progress: Wellbore integrity

- Experiments and X-ray CT scans for micro-annulus along the cement casing interface
- $CaCl_2$ (a cement additive) is corrosive to steel casing
- Lab results were upscaled for field risk assessment



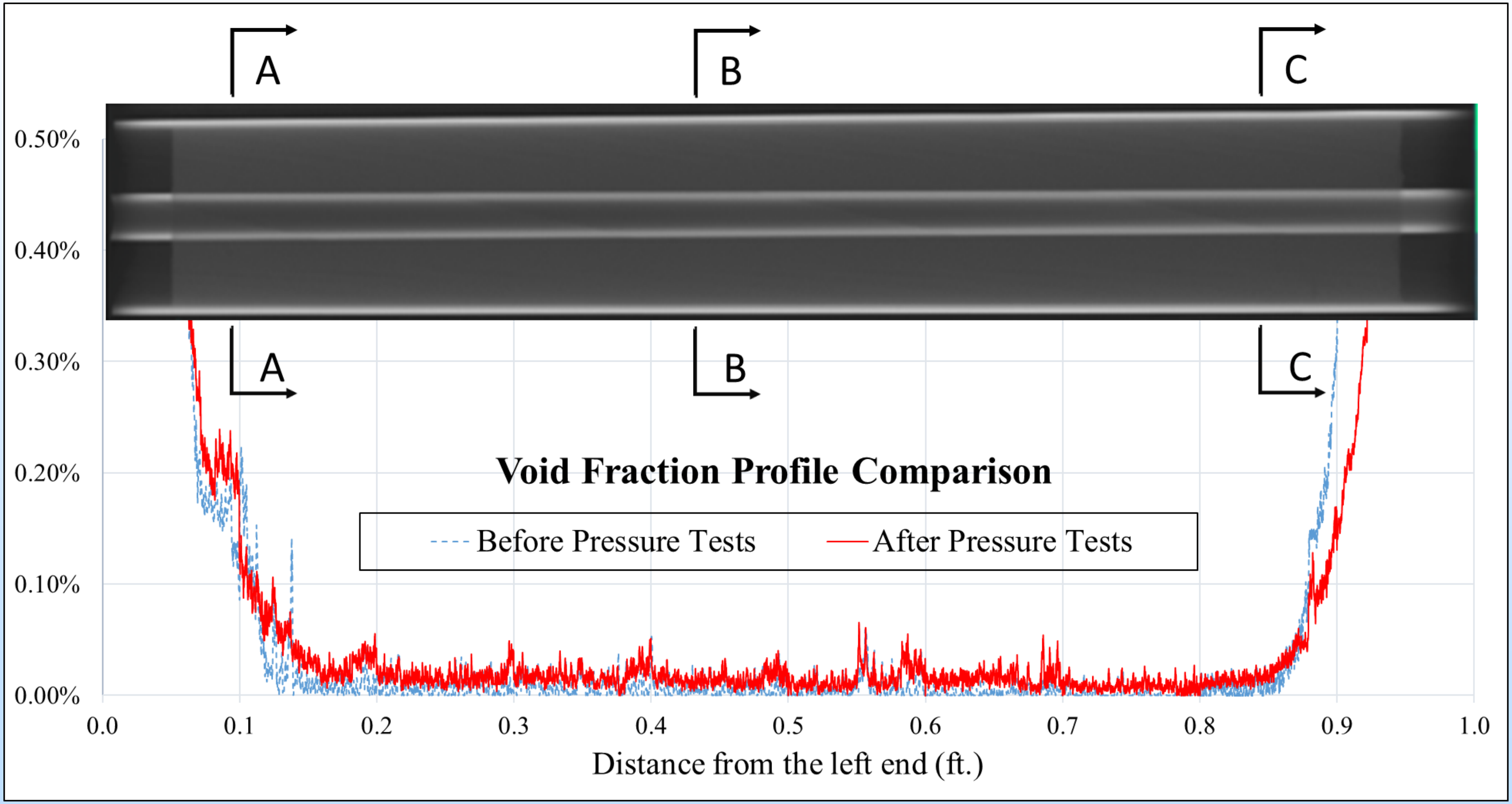
The degree of damage (micro-annulus size) was quantified by permeability measurements





Accomplishments: Characterization

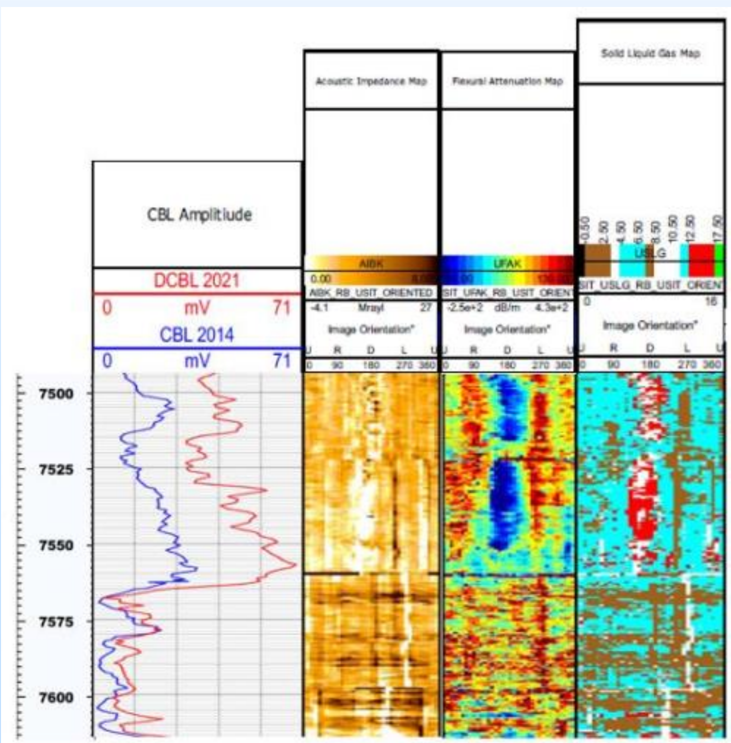
Selected Progress: Wellbore integrity

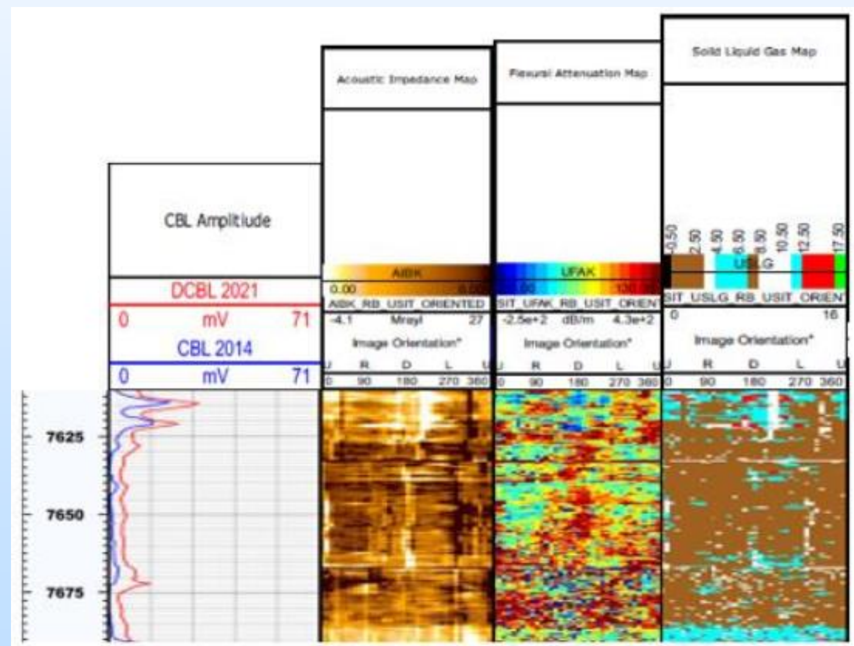


Accomplishments: Characterization

Selected Progress: Wellbore integrity

- Risk analysis was conducted with 20 well historical data and CBL
- Well 13-14 CBL was compared between 2014 and 2021
- No significant damage showed in cement



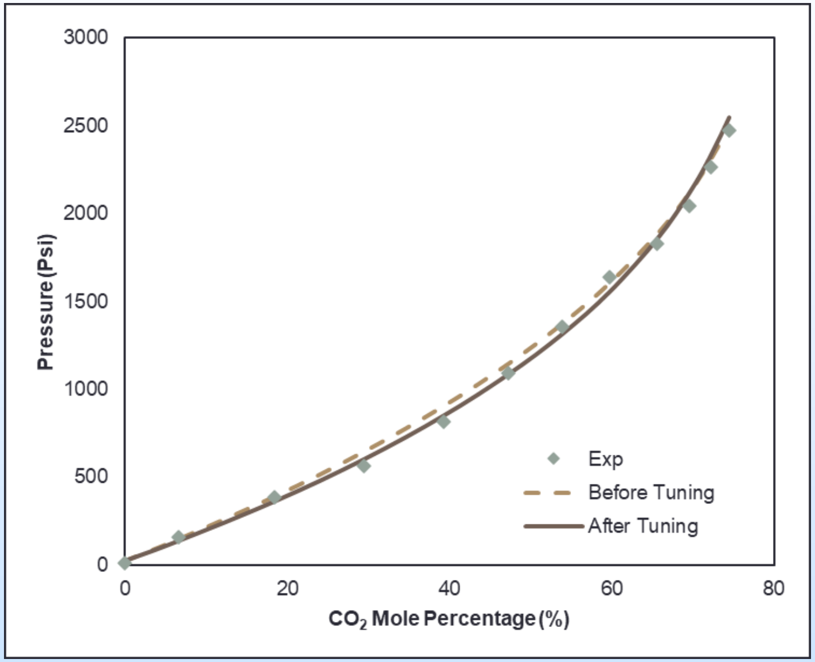


CBL + Isolation Scanner along caprocks,
Well 13-14

Accomplishments: Characterization

Selected Progress: Swelling study

- Swelling tests were performed in laboratory setting to gather experimental data.
- The data were implemented in a compositional software to tune a PVT model.
- After the tuning, simulated swelling data closely matched the experimental data as can be seen from the image.
- Other simulated properties also experienced a good match to experimental data.

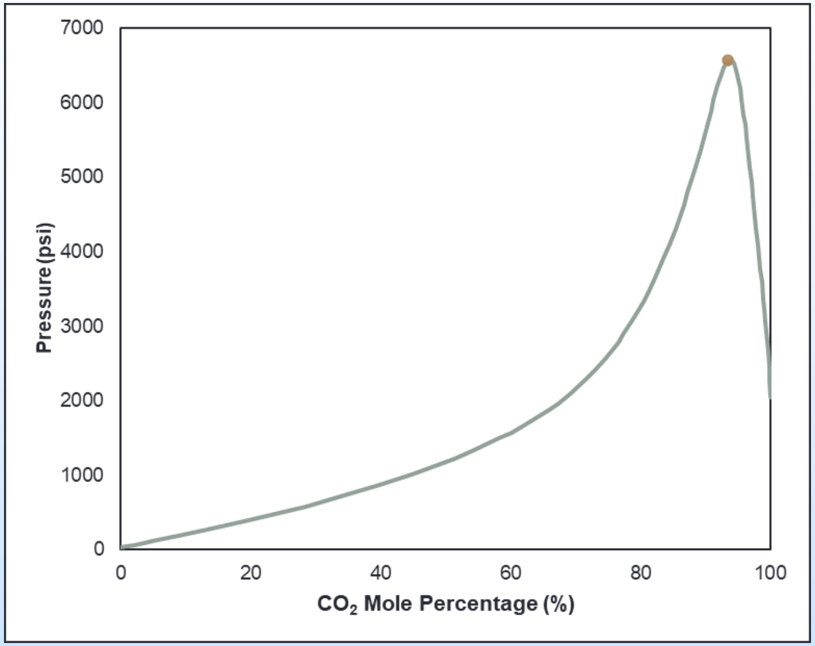


Saturation Pressure vs CO_2 Mole Percentage

Accomplishments: Characterization

Selected Progress: Swelling study

- Using the tuned PVT model, many properties of oil and CO_2 mixtures were estimated at various conditions.
- The relationship between saturation pressure and CO_2 mole percentage was estimated when CO_2 mole percentage ranged from 0% to just below 100%
- This can estimate how much CO_2 dissolved in the liquid phase when the injection pressure is up to around 6,500 psi

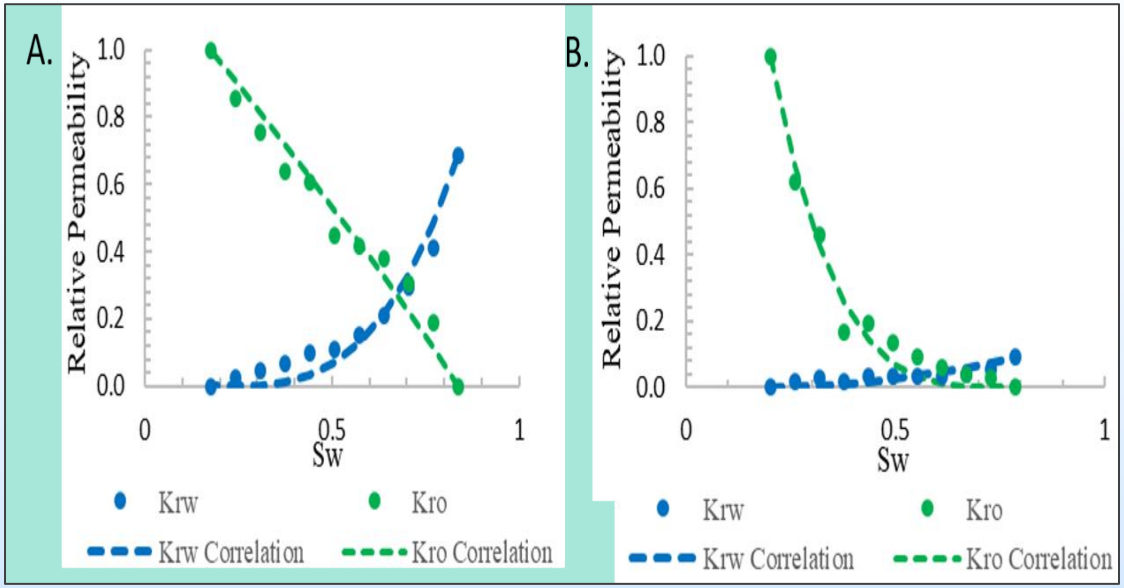


Saturation Pressure vs CO_2 Mole Percentage Prediction

Accomplishments: Characterization

Selected Progress: Relative Permeability

Binary pairs of two-phase relative permeability curves were used to calibrate refined three-phase relative permeability.



History match simulation efforts initially underestimate water injection and production.

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Accomplishments: MVA

MVA Working Group Members and Roles

- Rich Esser
  MVA co-lead
- Tianguang Fan
  Fluid chemistry
- George El-kaseeh
  Field, Seismic, Reservoir
- Martha Cather
  Fluid Accounting
- Pete Rose
  Tracers
- Trevor Irons
  USDW Monitoring & Modeling
- Jianjia Yu
  MVA co-lead
- Paige Czoski
  Seismic Activities
- Aaron Meyer
  Surface & Atmospheric Flux
- Leonard Garcia
  Field Tasks
- Mike Mella
  Tracers
- Robert Balch
  Seismic Activities

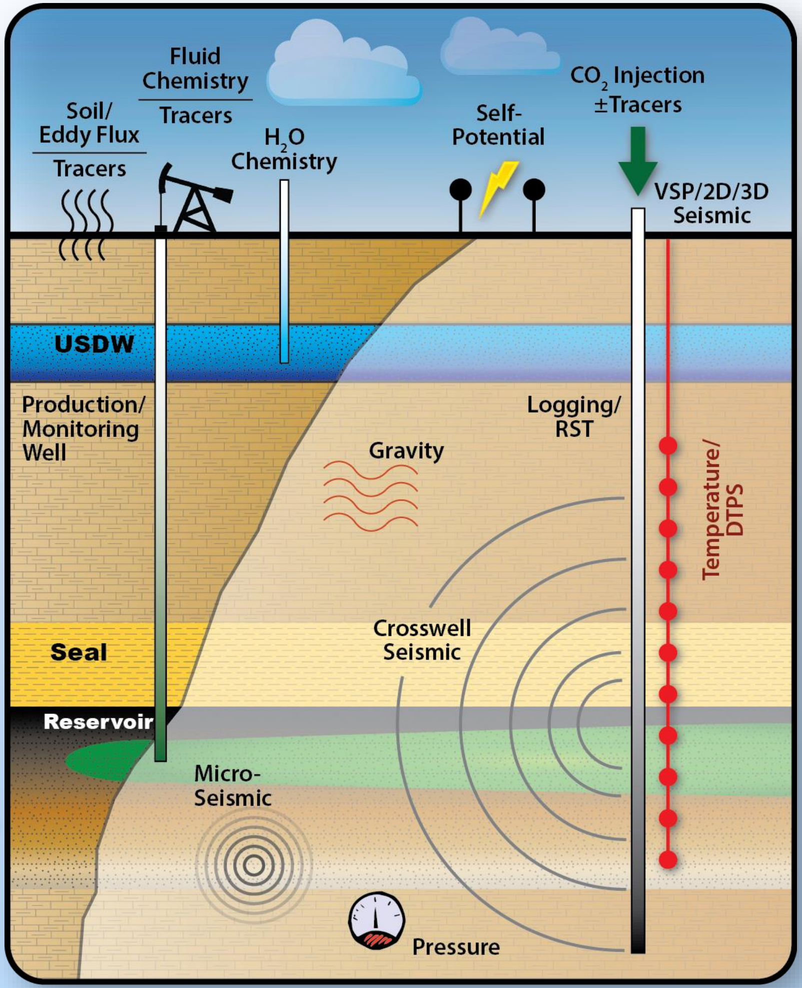
Accomplishments: MVA

Task 6 - Operational Monitoring

- Subtask 6.1 Surface Monitoring
- Subtask 6.2 Subsurface Monitoring
- Subtask 6.3 Seismic Activities

Task 7 – Post-Injection MVA & Risk Assessment

- Subtask 7.1.1 Monitor Surface
- Subtask 7.1.2 Monitor Subsurface P&T
- Subtask 7.1.3 Tracer Recovery
- Subtask 7.1.4 Geophysical Monitoring
- Subtask 7.1.6 Assess Microseismicity
- Subtask 7.1.7 Continue Time Lapse VSP
- Subtask 7.1.8 Conduct Fluid Accounting



Accomplishments: MVA

Significant Achievements

The MVA technologies deployed by the SWP are targeted to provide the data necessary to track the location of CO_2 in the study area, including migration, type, quantity and degree of CO_2 trapping. Monitoring data is used to facilitate simulation and risk assessment, particularly with respect to USDWs, the shallow subsurface, and atmosphere.

Detecting CO_2 and/or brine outside Reservoir:

- Groundwater chemistry (USDW)
- Soil CO_2 flux
- CO_2 & CH_4 Eddy Towers
- Aqueous- & Vapor-Phase Tracers
- Self-potential (AIST)
- Distributed Sensor Network (Ok. State)

Tracking CO_2 Migration and Fate:

- *In situ* pressure & temperature
- 2D/3D seismic surveys
- VSP/Cross-well seismic
- Passive/micro seismic
- Fluid chemistry (target reservoir)
- Aqueous- & Vapor-Phase Tracers
- Gravity surveys & MagnetoTelluric (AIST)

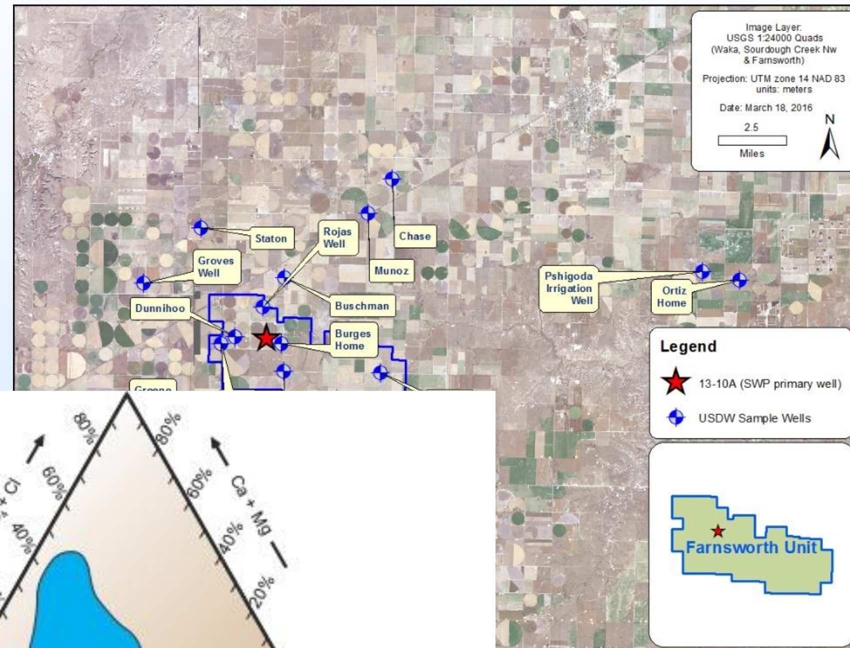
MVA relational database

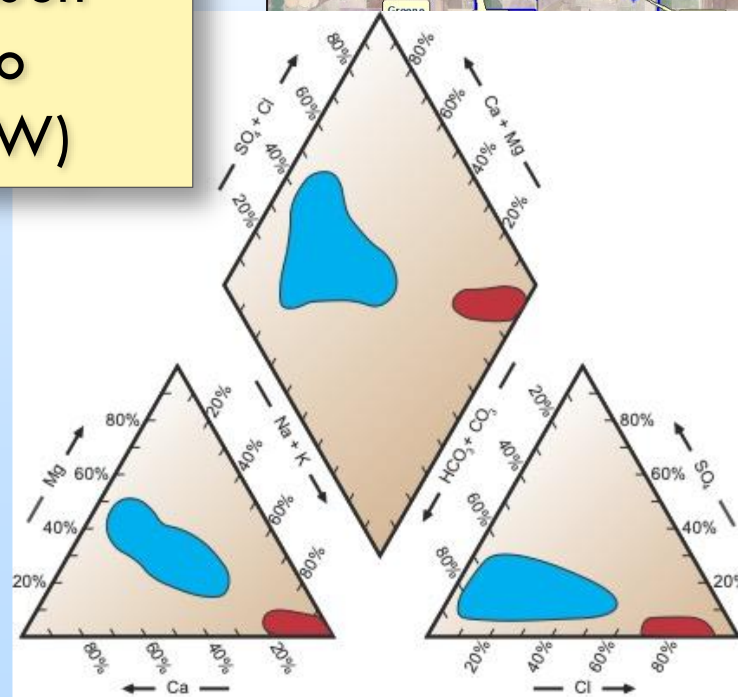
- All SWP non-seismic MVA data in one central location
- Collection of related tables that can be readily queried
- Efficient, Fast
- Complex searching
- Web ready
- Secure

Accomplishments: MVA

Selected Progress: USDW monitoring

- Technology validates spatial and temporal sampling to monitor USDW for potential leakage. No Indication of CO_2, brine or hydrocarbon leakage from depth (into Ogallala aquifer - USDW)





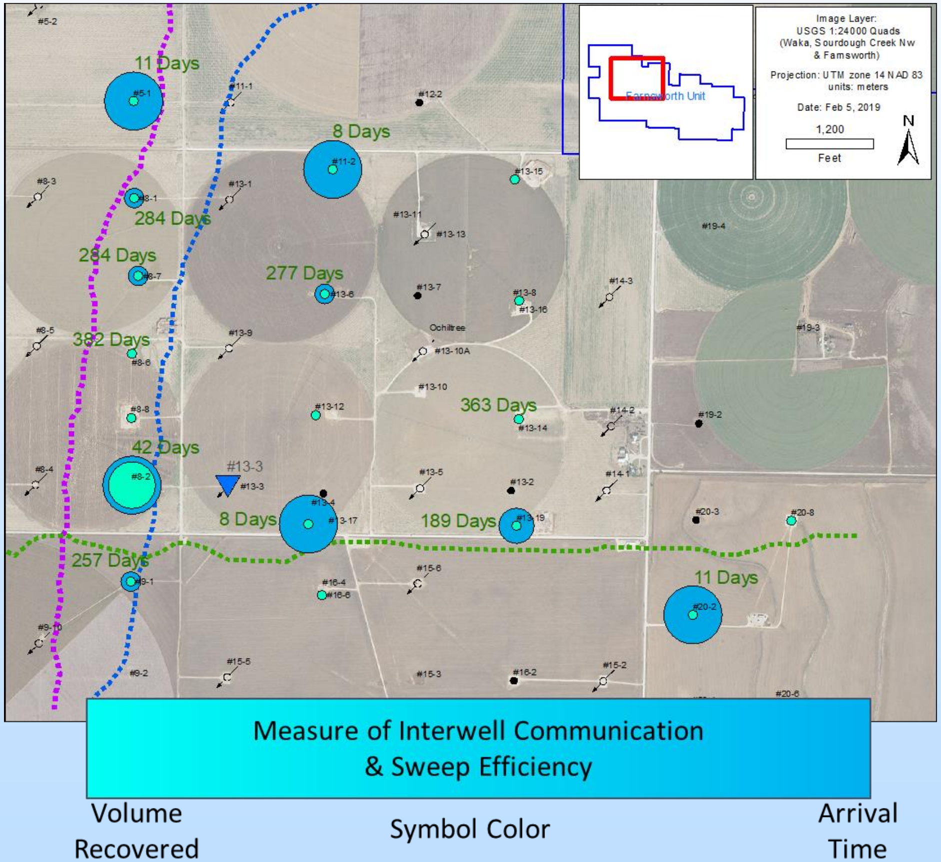
Morrow B water

Ogallala water

Accomplishments: MVA

Selected Progress: Reservoir tracers (aqueous)

- Aqueous-phase tracer slugs (Naphthalene sulfonates) were injected into 5 well patterns to successfully evaluate fluid velocities, interwell connectivity and identify and characterize significant reservoir heterogeneities.
- The injection into FWU #13-3 yielded results indicating significant preferential fluid flow along two adjacent faults.
- Relative tracer recovery along (FWU #8-2 and FWU #20-2) and across faults (FWU #9-1) indicate variable transmissive versus sealed characteristics
- Vapor-phase tracer injection into FWU #13-3 yields similar results, indicating similar flow behavior for water and CO_2 at least in this area of the reservoir.

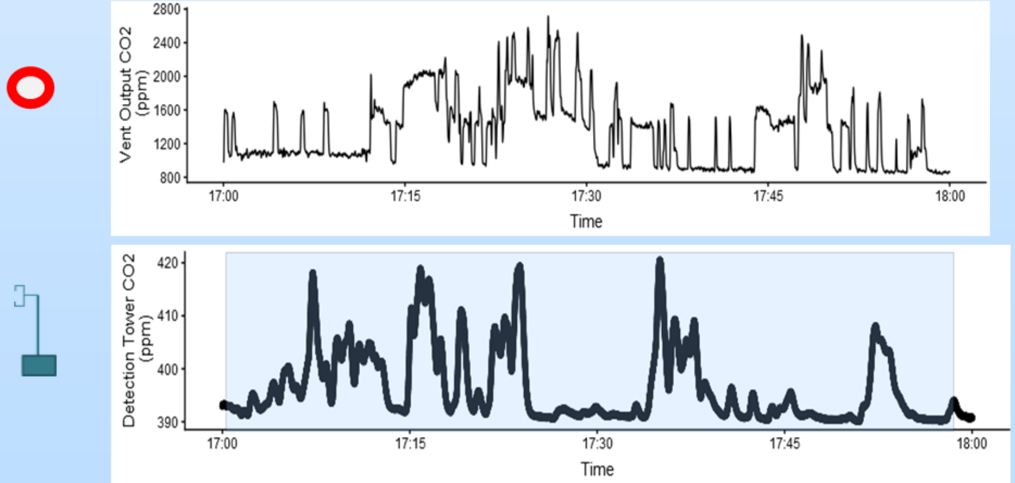


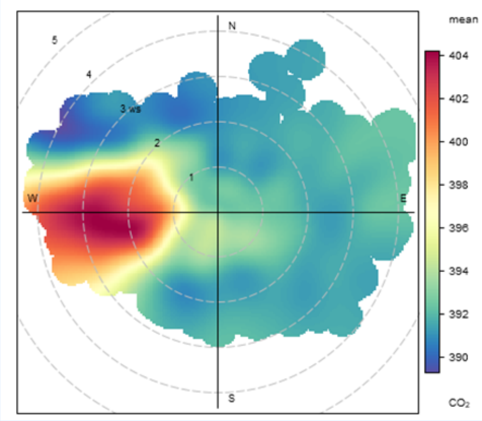
Accomplishments: MVA

Selected Progress: CO_2 surface & atmospheric flux

- Use a known, consistent CO_2 source to develop detection, location, and quantification methods
- Bench experiments, concurrent source measurements, and machine learning methods

Source Location

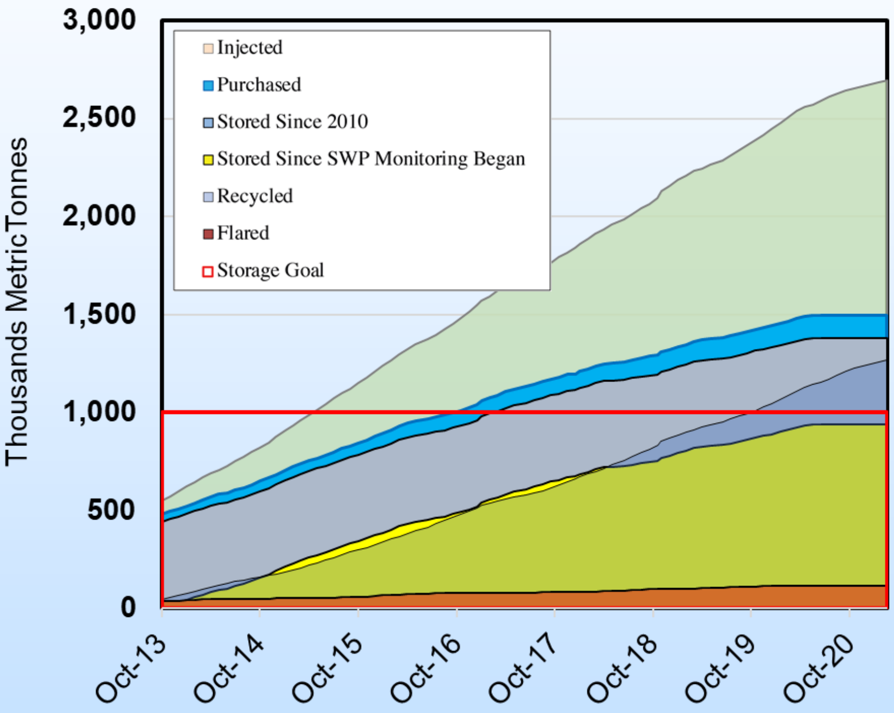




Accomplishments: MVA

Selected Progress: Fluid accounting

- Provided to SWP by Chaparral Energy and Perdure Petroleum
- Daily or Monthly values of CO_2 Purchased, Injected, Produced (Recycled) and Flared
- SWP has not yet accomplished the project goal of 1,000,000 metric tonnes of CO_2 injected (since 2013).
- Since 2010, over 2.5 million metric tonnes of CO_2 have been injected.
- Approximately of the purchased CO_2 50% has been stored.
- 47% has been recycled.
- Purchase and storage rates have slowed as recycling has increased and field expansion has stalled (due to low price of oil).

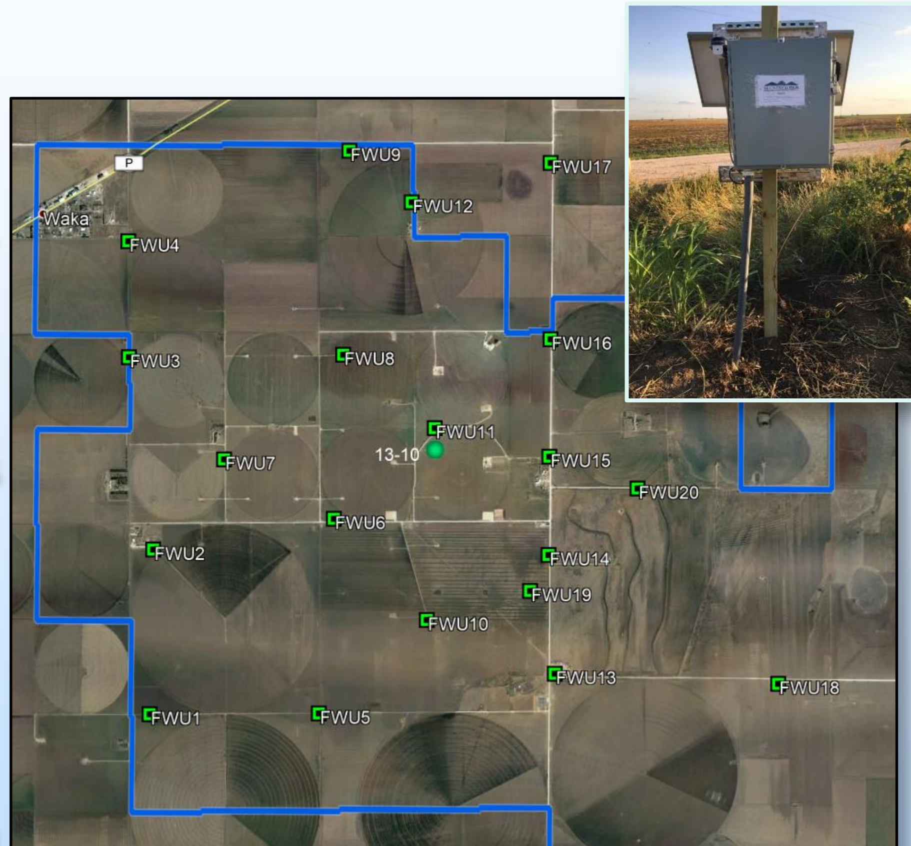


Accomplishments: MVA

Selected Progress: Microseismic Array

Task 7.1.6 – Microseismic Monitoring

- Sixteen level borehole array - deployed in Dec 2018 (FWU #13-10).
- Twenty surface seismic stations – deployed in July 2019.
- Aid in characterizing the stability and storage of the CO_2 in the reservoir.
- Analysis of both borehole and surface microseismic is starting and will continue to end of project.

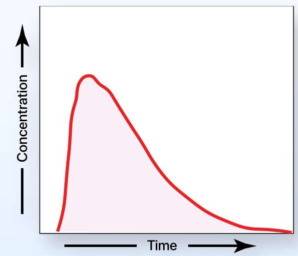


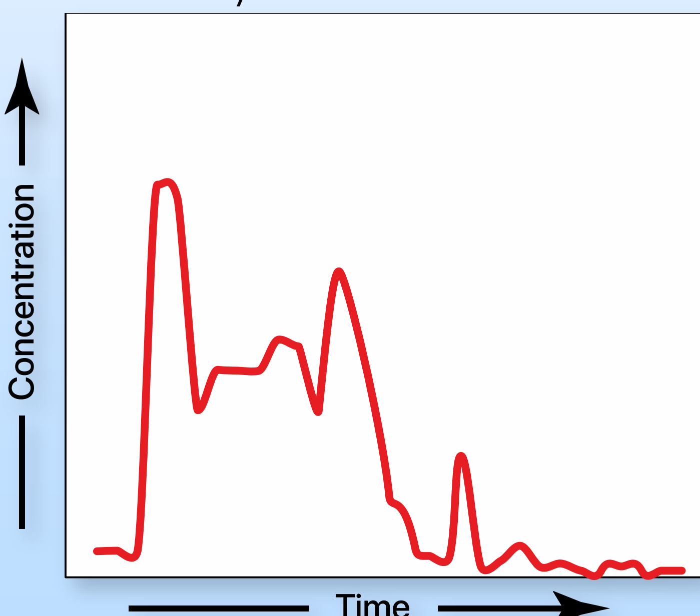
Accomplishments: MVA

Selected Progress: Tracers - Aqueous and Vapor

For Characterization

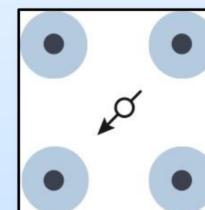
- Well-to-well communication (directions & velocities)
- Reservoir continuity or compartmentalization
- Fracture volume and extent
- Identify and interpret significant faults and/or barriers to flow

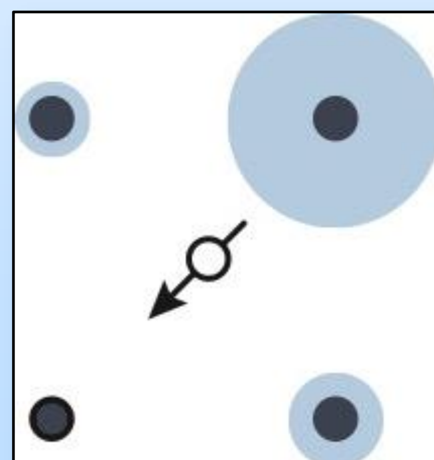




For Monitoring

- Tracers as analogs of CO_2
- Constrain & calibrate flow models and simulations; predict the fate of the injected CO_2
- Monitor tracer leakage to USDW and/or atmosphere as analogue for
  CO_2/brine leakage





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Accomplishments: Simulation

Simulation Working Group Members and Roles

Dr. William Ampomah	History Matching and Optimization
Dr. Nathan Moodie	Relative Permeability Analysis
Dr. Trevor Irons	Relative Permeability Analysis
Prof. Martin Appold	Reactive Transport Modeling
Dr. Mark White	STOMP-EOR Developer/Modeling
Dr. Qian Sun	Numerical Modeling
Dr. Robert Will	Fluid Substitution Modeling

Student Members

Junyu You (PhD)	Optimization
Eusebius Kutsienyo (MS)	History matching
Benjamin Adu-Gyamfi (MS)	Pressure/Rate Transient Analysis

Accomplishments: Simulation

Tasks Addressed

Subtask 7.3.1 Refine Geologic Model

Subtask 7.3.2 Update Reservoir Model

Subtask 7.3.3 Resolve Low-Grade Faults

Subtask 7.3.4 Relative Permeability Analysis

Subtask 7.3.5 Reactive Transport Modeling

Subtask 7.3.6 Conduct Dynamic Reservoir Modeling

Subtask 7.3.7 Fluid Characterization and Substitution Modeling

Subtask 7.3.8 Analyze Production, Pressure and Rate Transient Data

Accomplishments: Simulation

Significant Achievements

- Interpreted wellbore leakage analysis
- Quantified uncertainty of measured/estimated relative perm curves
- Relative Permeability tied to capillary pressure data
- Continued history matching modeling with machine learning workflow
- Continued co-optimization of oil recovery and CO_2 storage
- Simulations of tracers facilitated effective interpretation of faults and flow patterns, including delayed recoveries
- Simulations of tracers without fault zones (in models) corroborated fault zone interpretation
- Quantified mineral dissolution basis of chemo-mechanical interpretations
- Increased resolution of CO2 trapping mechanisms and migration patterns

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Accomplishments: Risk Assessment

Risk Assessment Working Group Members and Roles

- Wei Jia (Co-lead) : Quantitative risk assessment and uncertainty analysis
- Ting Xiao: Quantitative risk assessment
- Si-Yong Lee (Co-lead) : Qualitative risk assessment, geomechanical risk analysis, and prevention & mitigation plan
- Shaoping Chu and Hari Viswanathan : Leakage analysis with NRAP tools
- Ken Hnottavange-Telleen : Risk workshop and risk communication

Accomplishments: Risk Assessment

Tasks Addressed

Subtask 7.4.1 Quantify Risk

- Quantify Geomechanical Risk and Uncertainty
- Extend quantitative brine and CO2 leakage calculations
- Compare leakage risk between CO2-EOR and CO2-storage-only scenarios
- Incorporate Characterization Data for Uncertainty Reduction
- Quantify Risk of CO_2 Intrusion into Sealing Formations
- Quantify storage capacity loss and estimate associated risk

Subtask 7.4.2 Risk communication

Subtask 7.4.3 Update and Formalize Risk Mitigation Plan

Accomplishments: Risk Assessment

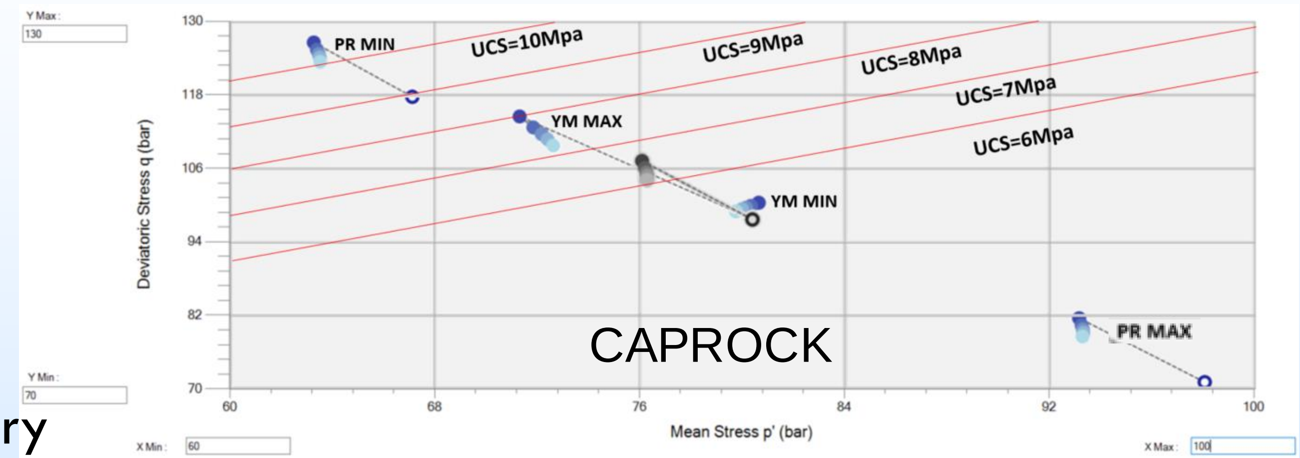
Significant Achievements

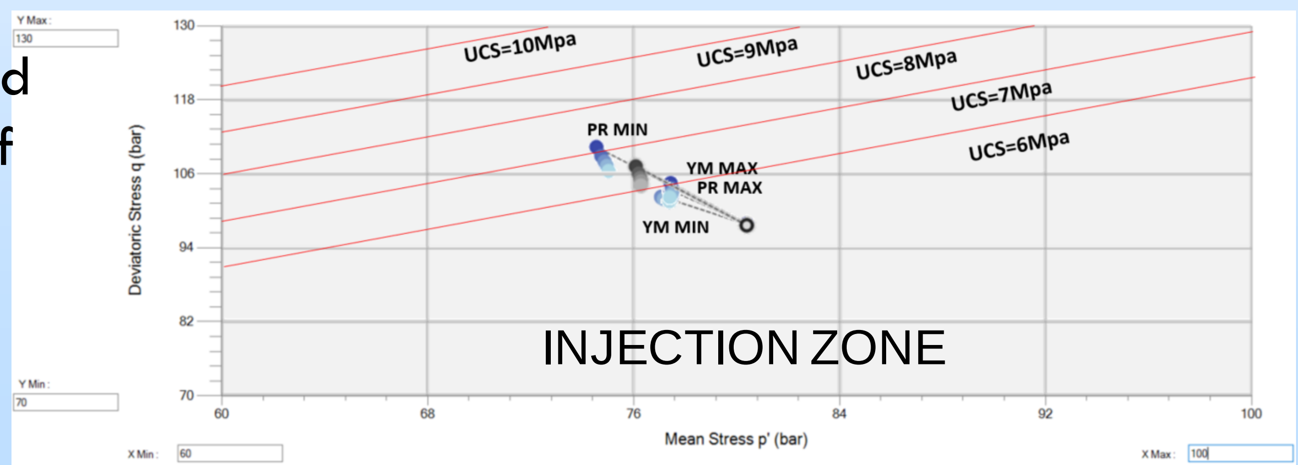
- Summarized risk assessment and management workflow
- Completed sensitivity analysis on elastic and strength properties of caprock and injection formation
- Evaluated impact of mineral reactive surface area on mineral trapping and porosity change at the FWU
- Interpretated the overlying USDW cation release mechanisms
- Completed a draft of the risk communication plan
- Reviewed and updated prevention and mitigation treatments; evaluated each treatment for completeness, effectiveness, and cost
- Performed leakage analysis with NRAP tools
- Six peer-reviewed journal articles and five presentations on national and international conferences

Accomplishments: Risk Assessment

Select Progress: Quantify Geomechanical Risk

- Completed and demonstrated application of multi-laminate model for caprock failure
- Completed preliminary sensitivity analysis;
- Completed sensitivity analysis on elastic and strength properties of caprock (shale) and injection formation (sandstone)





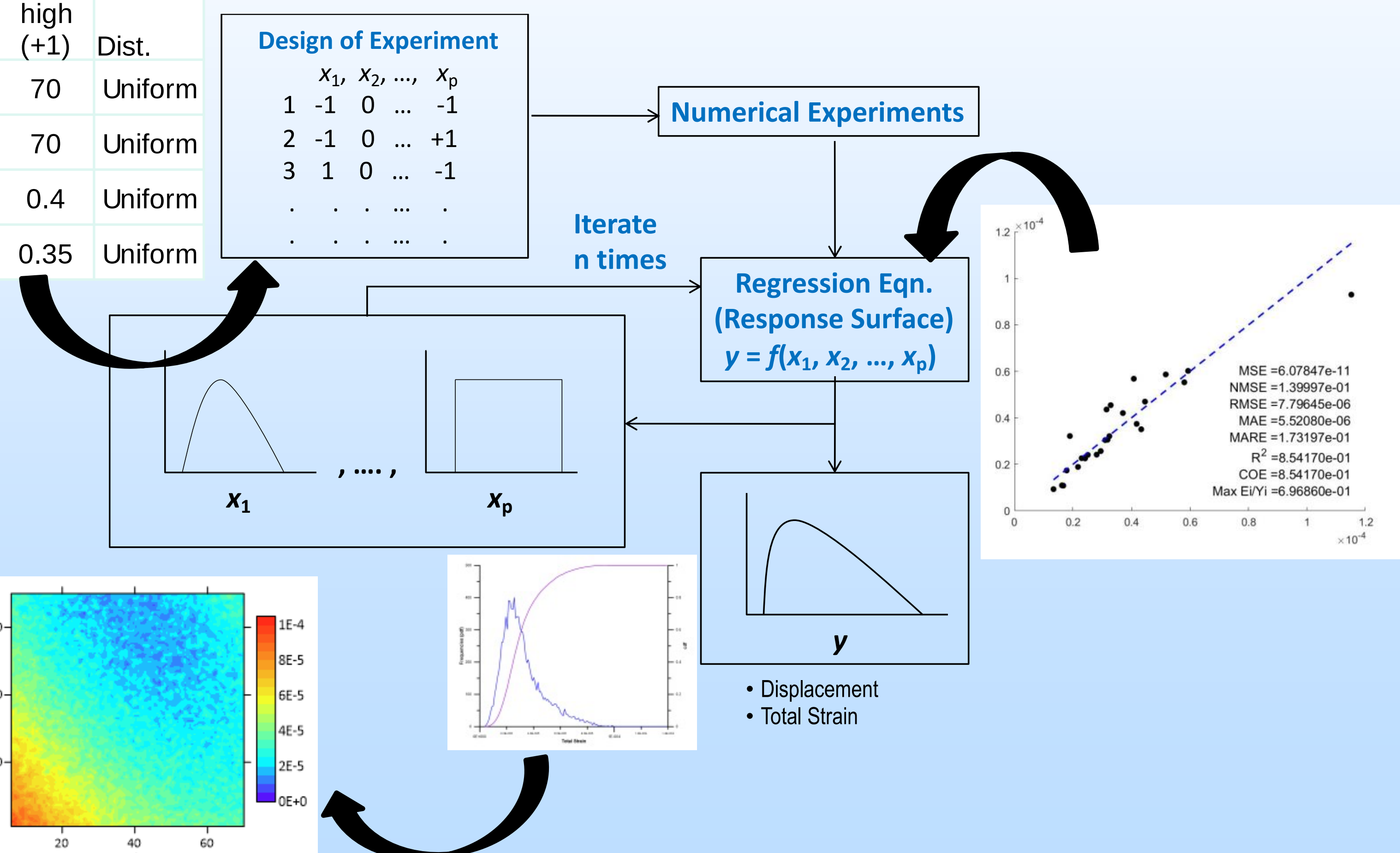
Accomplishments: Risk Assessment

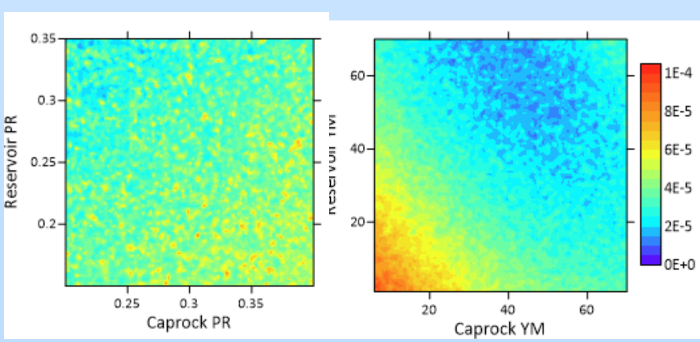
Select Progress: Quantify Geomechanical Risk

- Established geomechanical risk analysis workflow based on Response Surface Methodology (RSM) for vertical displacement & total strain

		low (-1)	med (0)	high (+1)	Dist.
X1	Caprock Young's mod (Gpa)	6	38	70	Uniform
X2	Aquifer Young's mod (Gpa)	1	35.5	70	Uniform
X3	Caprock Poisson's ratio	0.2	0.3	0.4	Uniform
X4	Aquifer Poisson's ratio	0.15	0.25	0.35	Uniform

Box-Behnken Design

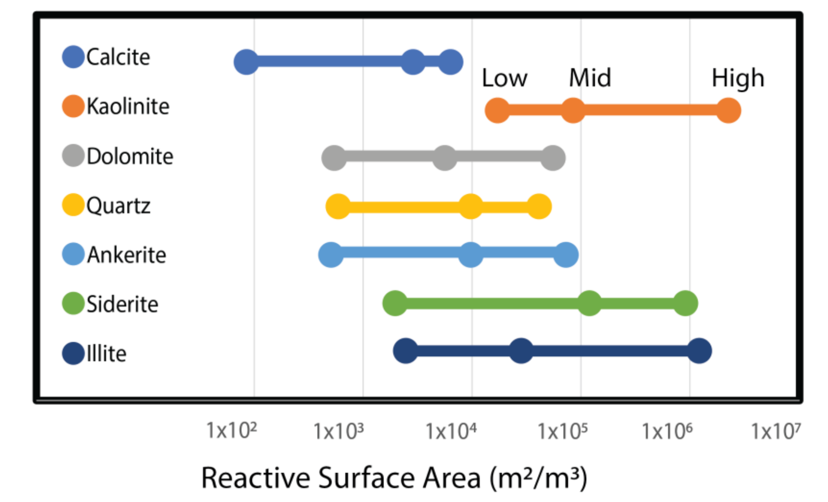




Accomplishments: Risk Assessment

Select Progress: Reactive surface area and mineral trapping

- Identified ranges of reactive surface area (RSA) for seven key minerals in FWU



- Developed a seven-factor Box-Behnken Design (BBD) with 87 simulation cases for uncertainty analysis (-1: Low, 0: Mid, 1: High)

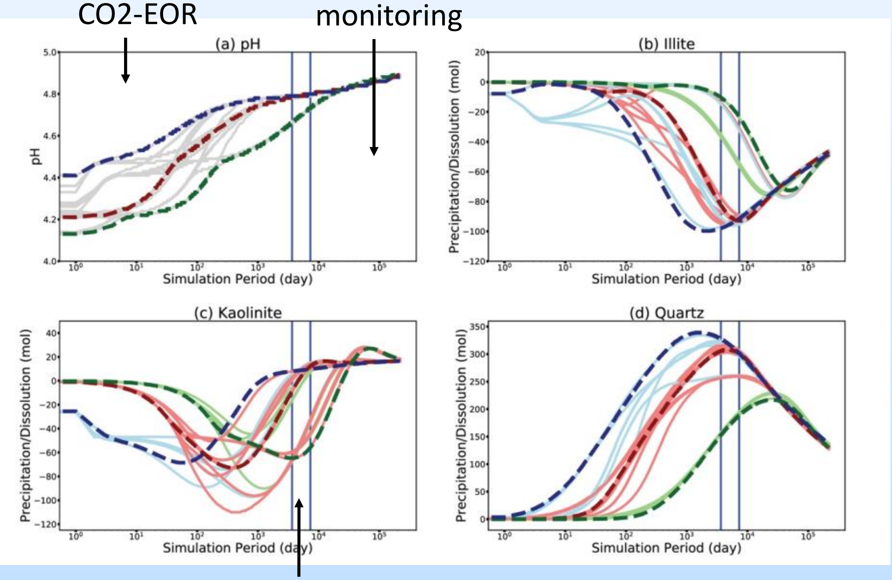
Case No.	Calcite	Kaolinite	Dolomite	Quartz	Ankerite	Siderite	Illite
1	-1	-1	0	0	0	0	0
2	1	-1	0	0	0	0	0
3	-1	1	0	0	0	0	0
4	1	1	0	0	0	0	0
...							
...							
...							
83	0	0	0	0	0	-1	1
84	0	0	0	0	0	1	1
85	0	0	0	0	0	0	0
86	-1	-1	-1	-1	-1	-1	-1
87	1	1	1	1	1	1	1

Jia, W.; Xiao, T.; Wu, Z.; Dai, Z.; McPherson, B. Impact of Mineral Reactive Surface Area on Forecasting Geological Carbon Sequestration in a CO_2-EOR Field. *Energies* **2021**, *14*, 1608. https://doi.org/10.3390/en14061608

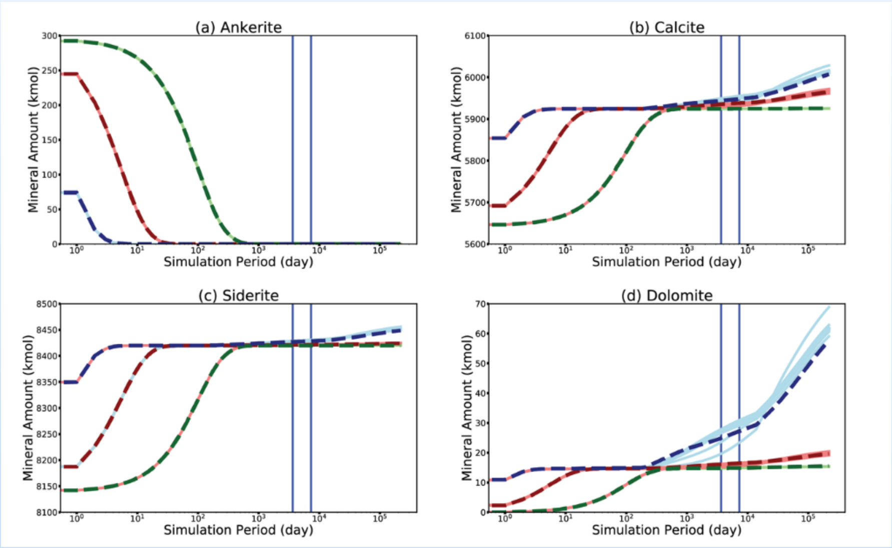
Accomplishments: Risk Assessment

Select Progress: Reactive surface area and mineral trapping

- The inter-dependency effects of mineral RSA values are stronger in the silicate mineral reactions and almost not observed in the carbonate mineral reactions.



pH and silicate minerals



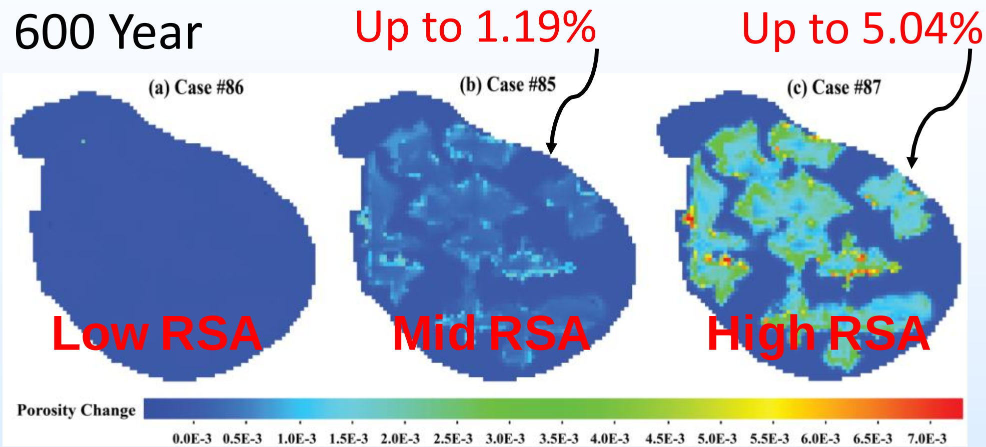
Clustering effect for carbonate minerals

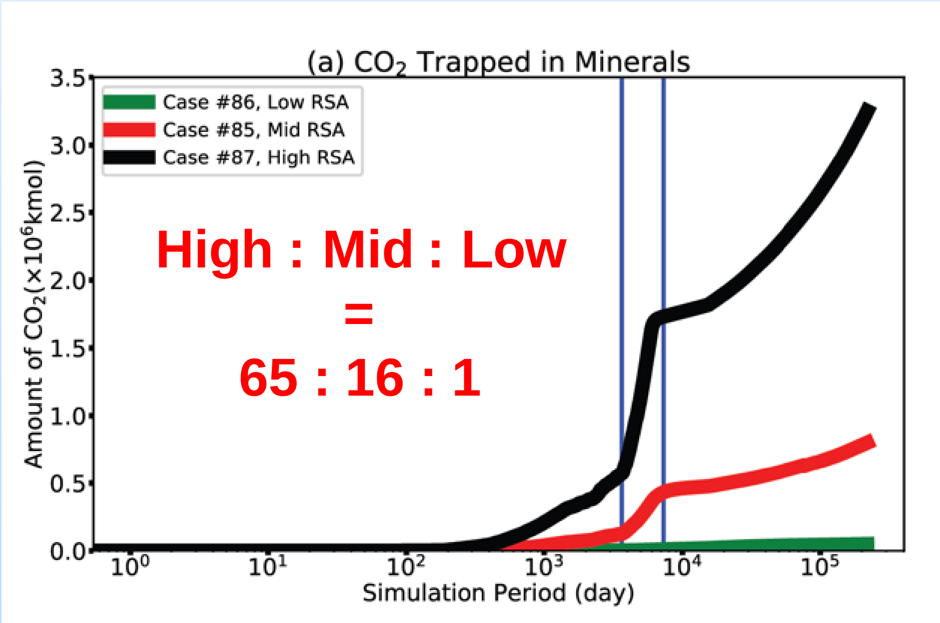
Accomplishments: Risk Assessment

Select Progress: Reactive surface area and mineral trapping

- The low RSA case predicted negligible porosity change and an insignificant amount of CO2 mineral trapping for the FWU model.

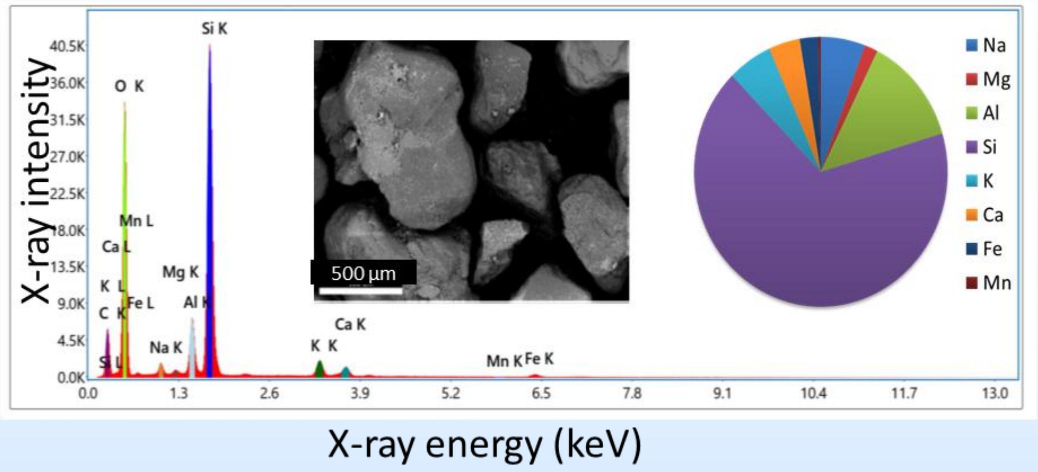
- The mid and high RSA cases forecasted up to 1.19% and 5.04% of porosity reduction due to mineral reactions, and 2.46% and 9.44% of total CO2 trapped in minerals by the end of the 600-year simulation, respectively.





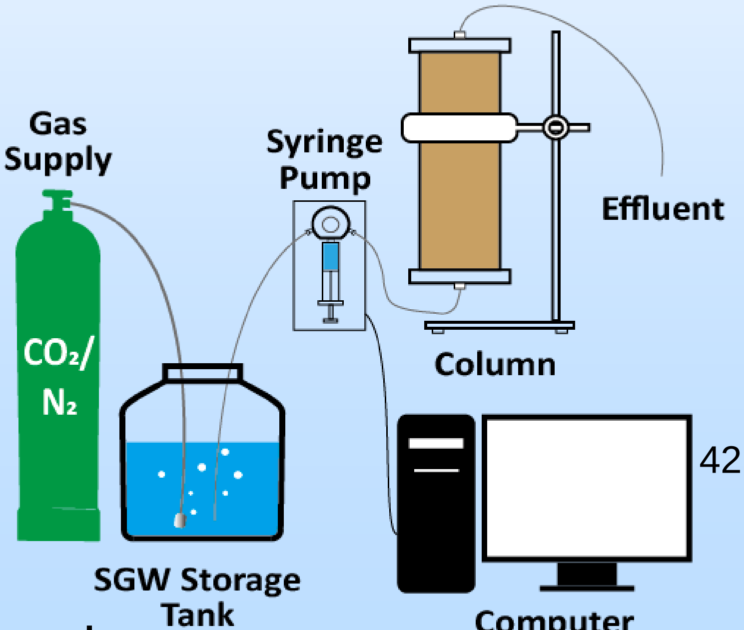
Accomplishments: Risk Assessment

Select Progress: Chemical impacts on the USDW



- Characterization of the Ogallala sand sample.

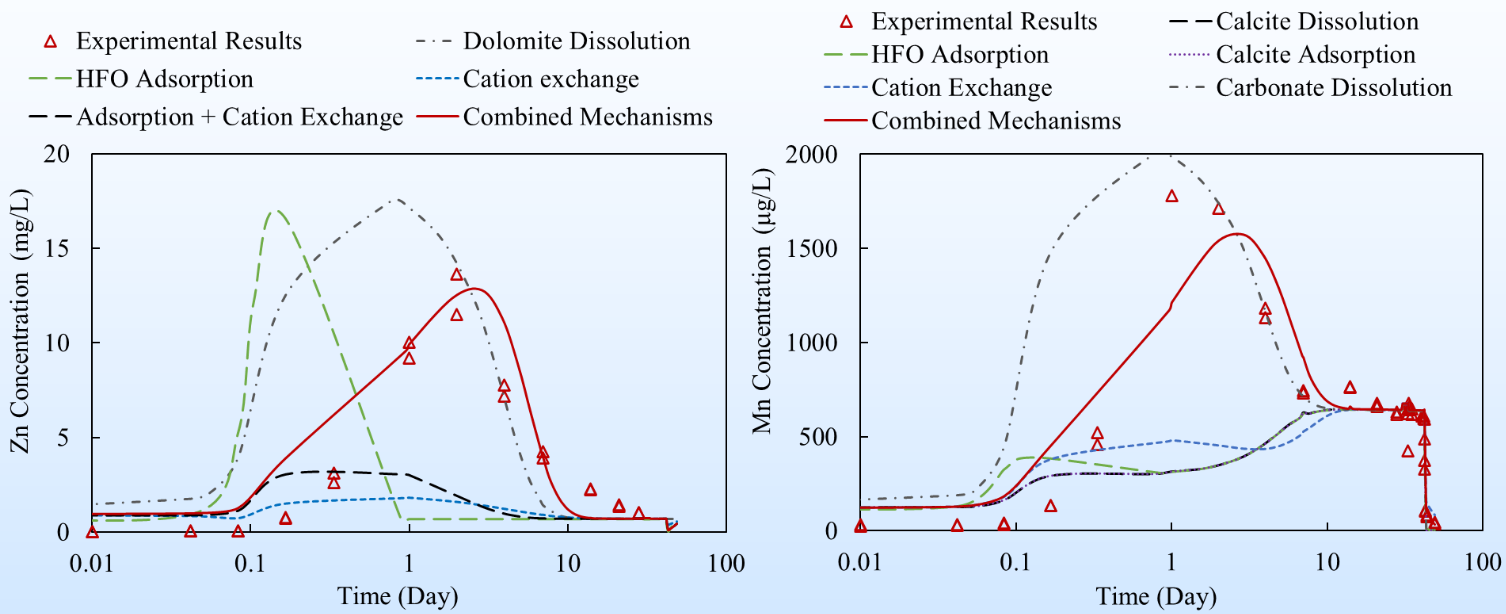
Xiao, T., Jia, W., Esser, R., Dai, Z. and McPherson, B., 2021. Potential Chemical Impacts of Subsurface CO2: An Integrated Experimental and Numerical Assessment for a Case Study of the Ogallala Aquifer. *Water Resources Research*, *57*(5), *https://doi.org/10.1029/2020WR029274*.



- Column experiments

Accomplishments: Risk Assessment

Select Progress: Chemical impacts on the USDW



- Cation exchange and carbonate mineral dissolution are the key mechanisms of cation release.
- Most trace metal show a short-term release and quickly drop to the baseline values, suggesting low risk to impact groundwater quality.
- Manganese and Uranium exhibit a stable release during the experiments, which might impact groundwater quality with CO2 intrusion.

Presentation Outline

- Technical Status
- Accomplishments to Date:
  - Characterization
  - Monitoring, Verification and Accounting
  - Modeling and Simulation
  - Risk Assessment
- **Lessons Learned**
- Synergy Opportunities
- Project Summary

Lessons Learned

Selected lessons learned – "what worked":

- Aqueous phase tracers are very effective for interpreting fast/slow pathways (e.g., faults)
- 3-phase relative permeability derived from capillary pressure is an effective proxy if data lacking
- Wettability evolution may promote "fast" pathways

Lessons Learned

Selected lessons learned – "what did not work":

- Vapor phase tracers are not effective for interpreting flow (multiple returns)
- Most mineralogic changes are too slow to be a factor for CO2-EOR
- Differences in fault modeling approaches (algorithms) provide significantly different storage forecasts
- Better calibration of cement degradation and other geochemical reactions will reduce uncertainty

Presentation Outline

- Technical Status
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Synergy Opportunities

- SWP is collaborating with CUSP and has reached out to the other Regional Initiatives to promote common data sets and tools

- SWP is in dialogue with Unconventional Oil/Gas Reservoir projects to promote common data sets and tools

Presentation Outline

- Technical Status
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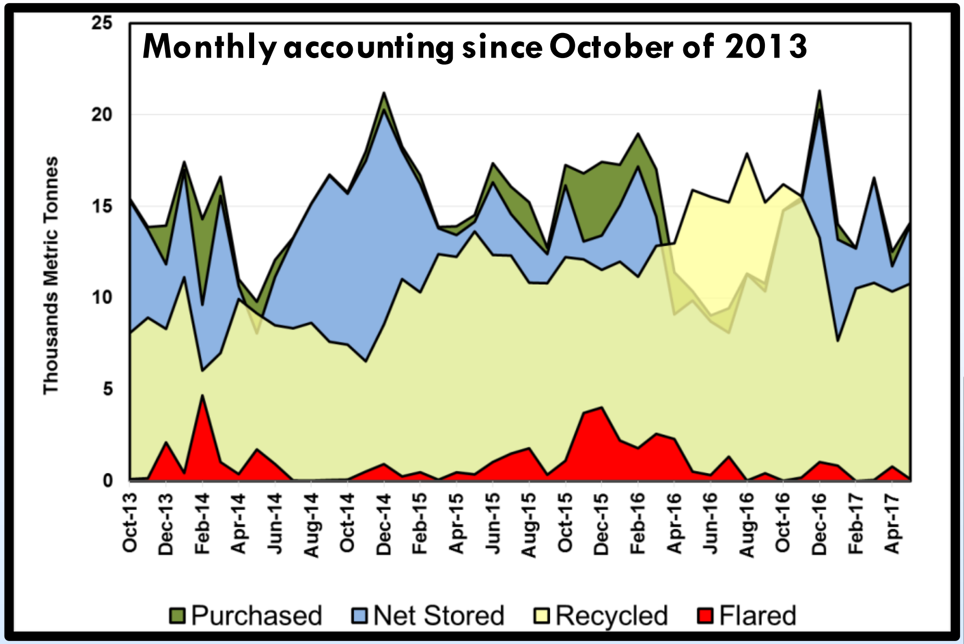
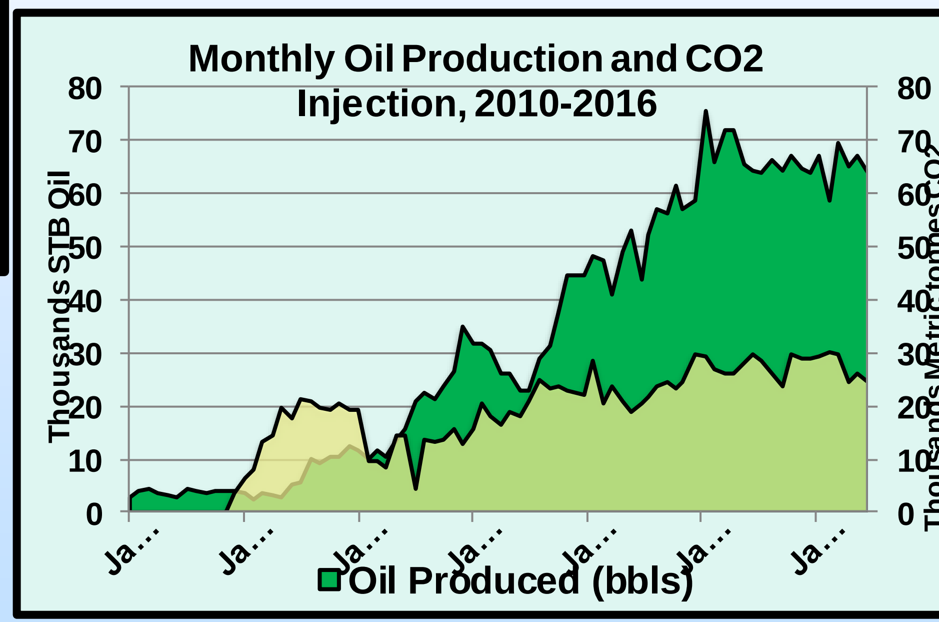
- **Project Summary**

Project Summary



- Average monthly oil rate increased from ~3,500 to ~65,000 BBL's in first 4 years of CO_2 Flood
- Initial production response within 6 months



- Over 1,000,000 tonnes stored since November 2010

- **92.2% of purchased CO_2 still in the system**

Project Summary

- The Southwest Partnership's demonstration project at Farnsworth field highlights enhanced recovery with ~92% carbon storage
- Extensive characterization, modeling, simulation, and monitoring studies have demonstrated long term storage security
- Continuous geologic characterization;
- Annual updated geo-model;
- Continuous history match;
- Continuous monitoring (ongoing);
- Effective best practices for CCS include an effective MVA program
- ***To date and after nearly 3 years of monitoring no leaks to the atmosphere, ground water, or secondary reservoirs have been detected at Farnsworth using a wide array of detection technologies***

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Benefit to the Program

- Identify the program goals being addressed.

- Insert project benefits statement.
  - See Presentation Guidelines for an example.

Project Overview
Goals and Objectives

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

Organization Chart

- Describe project team, organization, and participants.
  - Link organizations, if more than one, to general project efforts (i.e., materials development, pilot unit operation, management, cost analysis, etc.).

- Please limit company specific information to that relevant to achieving project goals and objectives.

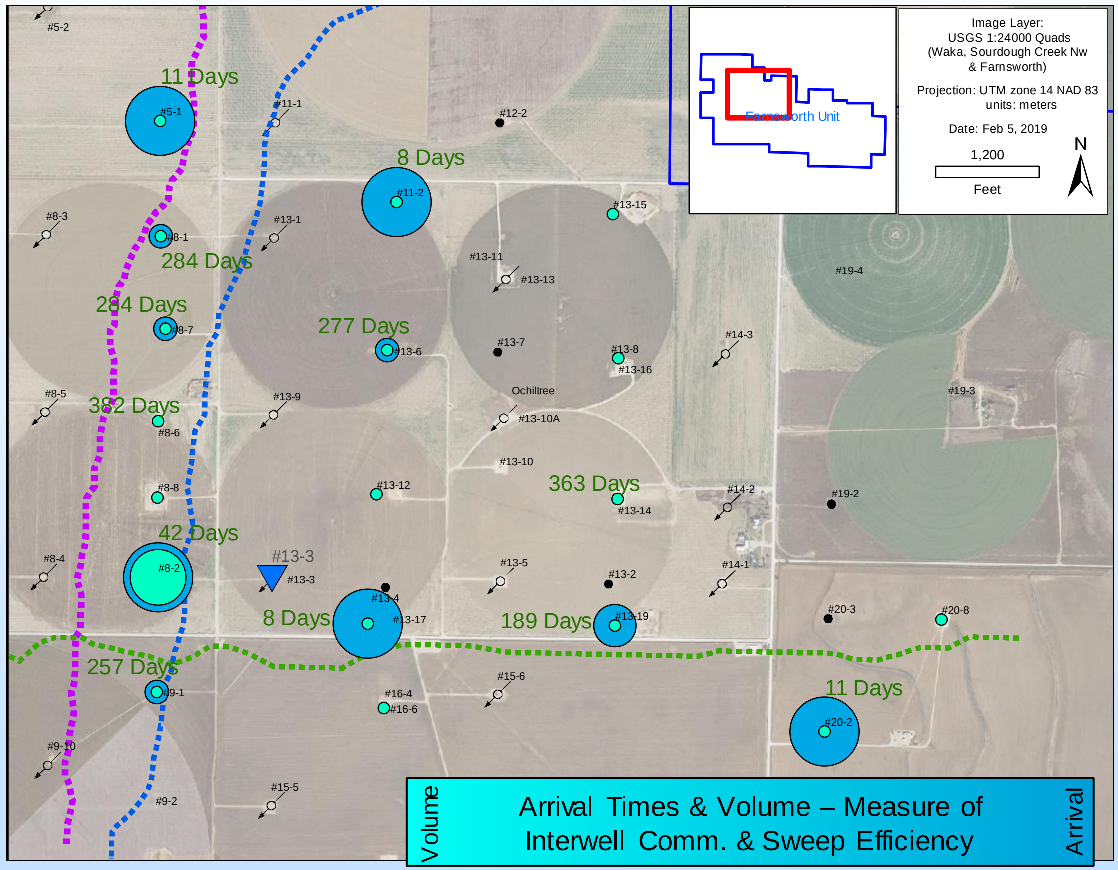
Gantt Chart

- Provide a simple Gantt chart showing project lifetime in years on the horizontal axis and major tasks along the vertical axis. Use symbols to indicate major and minor milestones. Use shaded lines or the like to indicate duration of each task and the amount of work completed to date.

Accomplishments: Characterization

Mini-Talk of MVA Major Findings: Tracers at the FWU

- Aqueous-Phase Tracers – Injection #3
  - FWU well (on water flood) tagged with 2 tracers on June 15, 2017
  - Well #13-3:
    - 2,6-NDS
    - 2-NS
  - 2-NS: “reversibly adsorbing” to evaluate fracture surface area
  - 30 days of waterflood
  - More extensive sampling of production wells
  - Multiple return peaks
  - ~45 days after injection (#8-2), representing 98% of 2,6-NDS/2-NS recovery.
  - Probable signal at #20-3 at 11 days?



Bibliography

– List peer reviewed publications generated from the project per the format of the examples below.

- Journal, one author:
  - Gaus, I., 2010, Role and impact of CO_2-rock interactions during CO_2 storage in sedimentary rocks: International Journal of Greenhouse Gas Control, v. 4, p. 73-89, available at: XXXXXXX.com.
- Journal, multiple authors:
  - MacQuarrie, K., and Mayer, K.U., 2005, Reactive transport modeling in fractured rock: A state-of-the-science review. Earth Science Reviews, v. 72, p. 189-227, available at: XXXXXXX.com.
- Publication:
  - Bethke, C.M., 1996, Geochemical reaction modeling, concepts and applications: New York, Oxford University Press, 397 p.