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

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

August 26-30, 2019

ACKNOWLEDGEMENTS

AND MANY STELLAR SCIENTISTS AND ENGINEERS

WHO MAKE THIS PROJECT TRULY TERRIFIC

(EXTRA THANKS TO WORKING GROUP LEADERS)

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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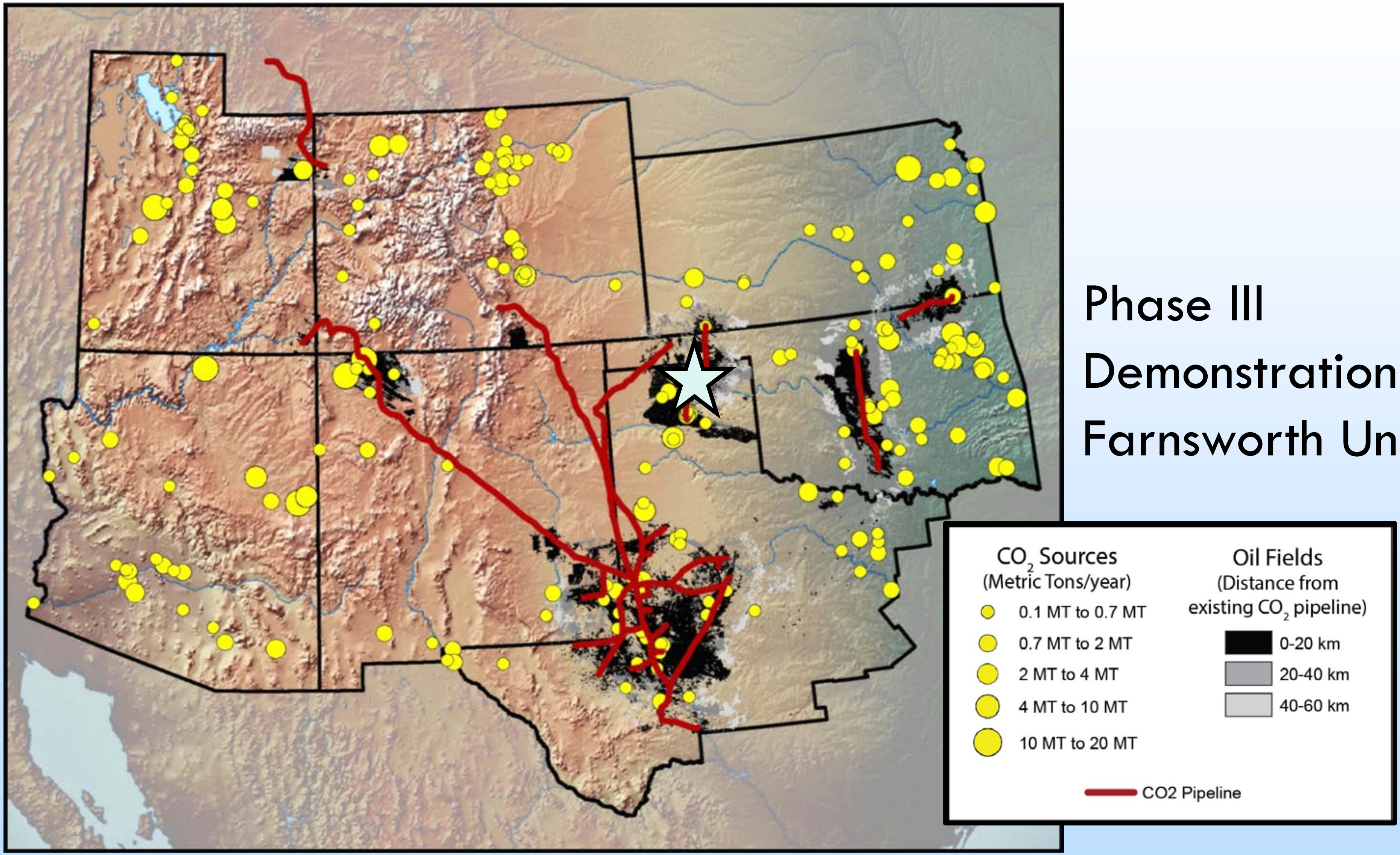
Technical Status: SWP Overview



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

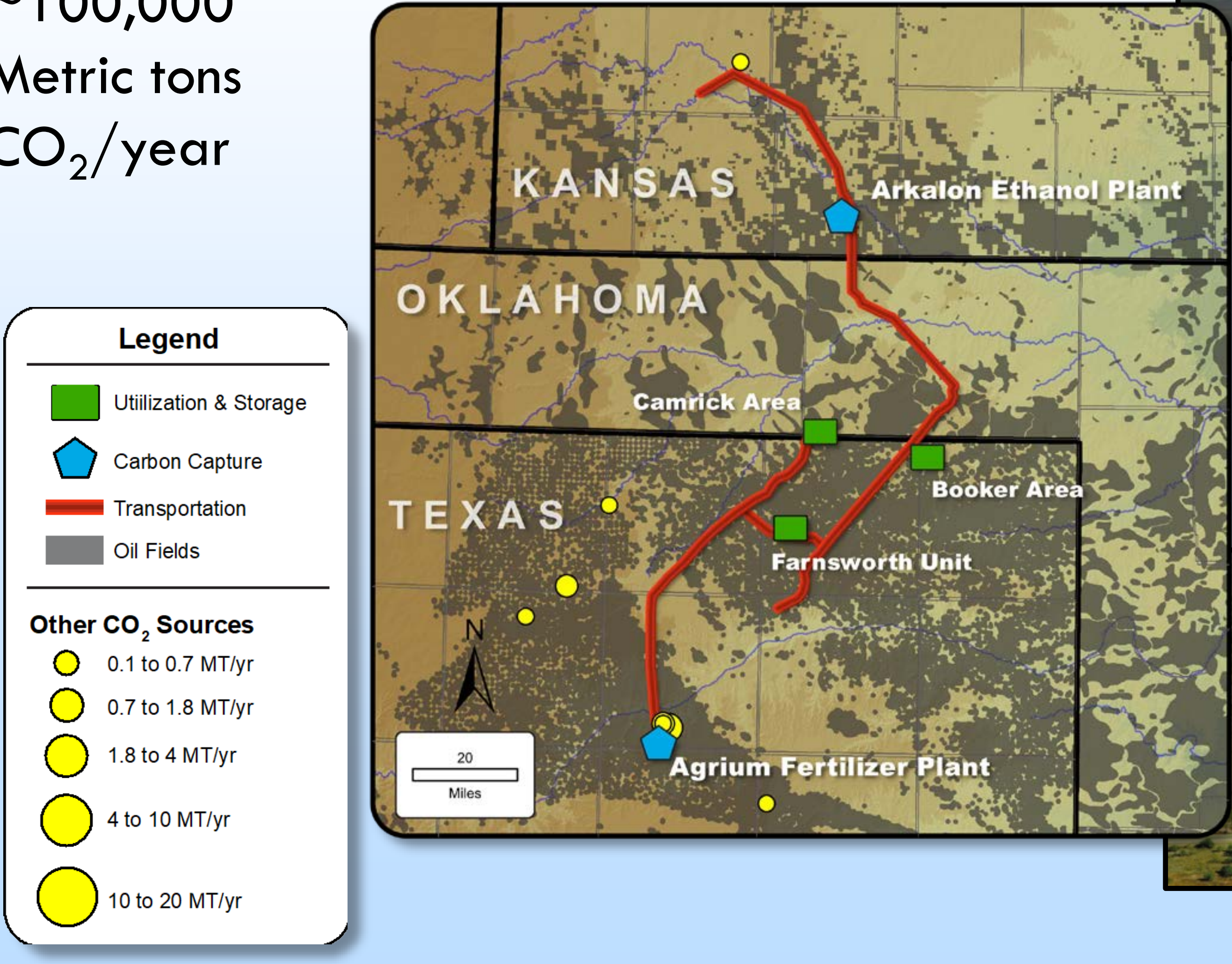
- Farnsworth field discovered in 1955.
- About 100 wells completed by the year 1960.
  - Field was unitized in 1963 by operator Unocal
  - Water injection for secondary recovery started in 1964.

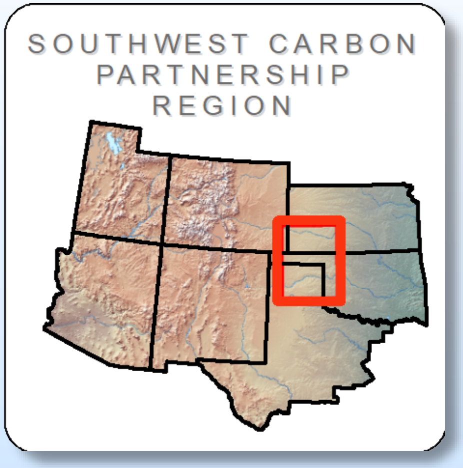
Property	Value
Initial water saturation	31.4%
Initial reservoir pressure	2218 PSIA
Bubblepoint Pressure	2073 PSIA
Original Oil in Place (OOIP)	120 MMSTB (60 MMSTB west-side)
Drive Mechanism	Solution Gas
Primary Recovery	11.2 MMSTB (9 %)
Secondary Recovery	25.6 MMSTB (21 %)
Tertiary Recovery	16 MMSTB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

Technical Status: Sources

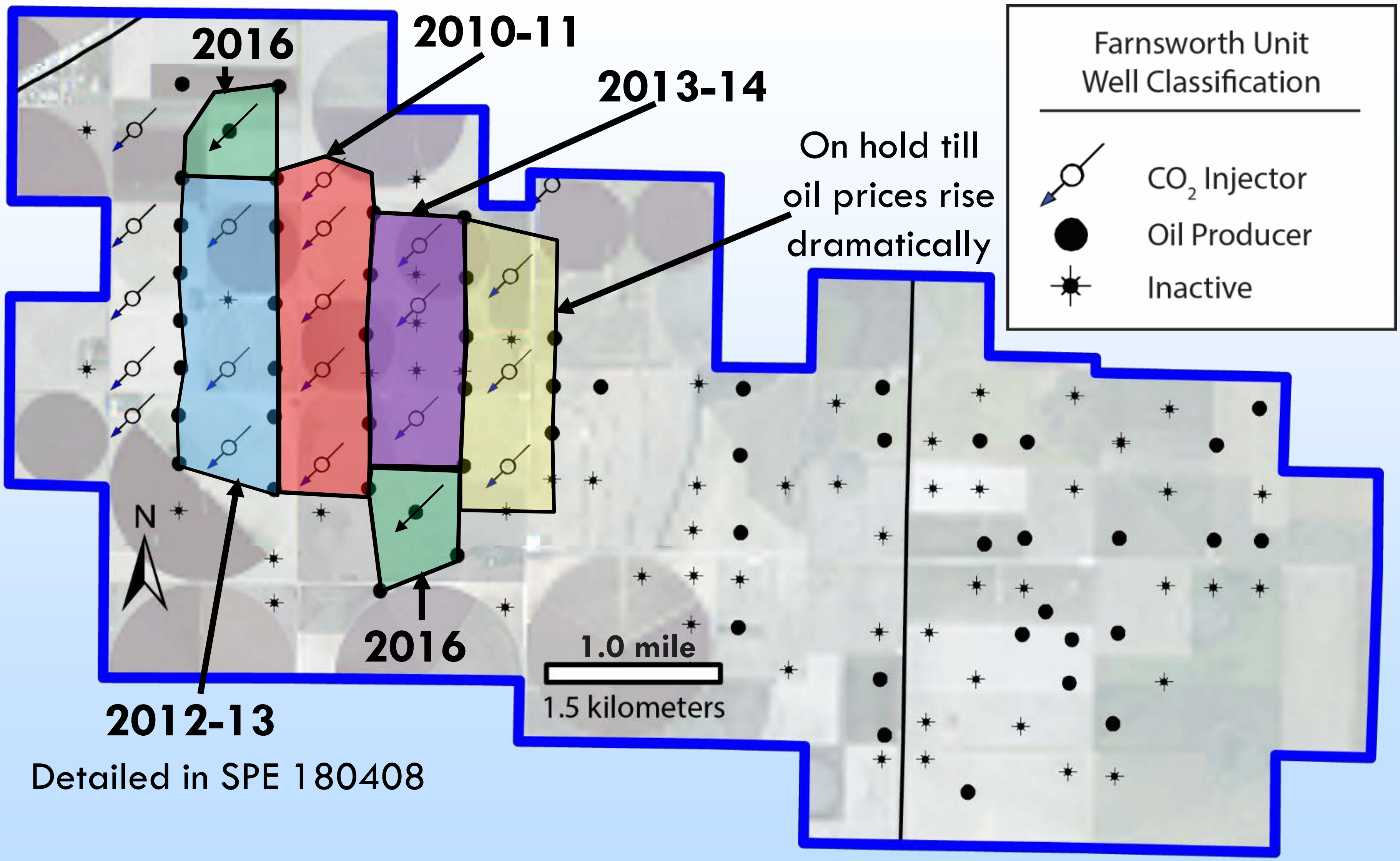
Anthropogenic CO_2 Supply:

~100,000 Metric tons CO_2/year





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).

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Accomplishments: Characterization

Publications – Combined Characterization and MVA

- El-kaseeh G., Czoski P., Will R., Balch R., Ampomah W., and Li X. (2108) Time-lapse vertical seismic profile for CO_2 monitoring in carbon capture, utilization, and sequestration/EOR, Farnsworth project *SEG Technical Program Expanded Abstracts* 2018, 5377-5381. https://doi.org/10.1190/segam2018-2995747.1
- Kumar A., K. Chao, R. Hammack, W. Harbert, W. Ampomah, R. Balch, and L. Garcia (2018), Surface-seismic monitoring of an active CO2-EOR operation in the Texas Panhandle using broadband seismometers, Annual Meeting of the Society of Exploration Geophysicists (SEG), 3027-3031, https://doi.org/10.1190/segam2018-2997451.1. [*Peer-reviewed Conference Paper]
- Kutsienyo E.J., Ampomah W., Sun Q., Balch R.S., You J., Aggrey W.N., and Cather M. (2019). Evaluation of CO_2-EOR Performance and Storage Mechanisms in an Active Partially Depleted Oil Reservoir: *SPE Europec at 81st EAGE Conference and Exhibition*, London, UK, June 3-6. SPE-195534-MS. https://doi.org/10.2118/195534-MS
- Rasmussen, L., Fan, T., Rinehart, A., Luhmann, A., Ampomah, W., Dewers, T., Heath, J, Cather, M., and Grigg, R. (2019). Carbon Carbon Storage and Enhanced Oil Recovery in Pennsylvanian Morrow Formation Clastic Reservoirs: Controls on Oil/Brine and Oil/CO2 Relative Permeability from Diagenetic Heterogeneity and Evolving Wettability. Submitted to Energies, Special Issue "CO2 EOR and CO2 Storage in Oil Reservoirs" (Sue Hovorka, Guest Editor), May 2019
- Wu Z., Luhmann A.J., Rinehart A.J., Mozley P.S., Dewers T.A., Heath J.E., and Majumdar B.S. Chemo-mechanical alterations induced from CO_2 injection in carbonate-cemented sandstone: An experimental study at 71°C and 290 bar. *Journal of Geophysical Research-Solid Earth*, in revision.
- PLUS 11 MAJOR CONFERENCE PRESENTATIONS!

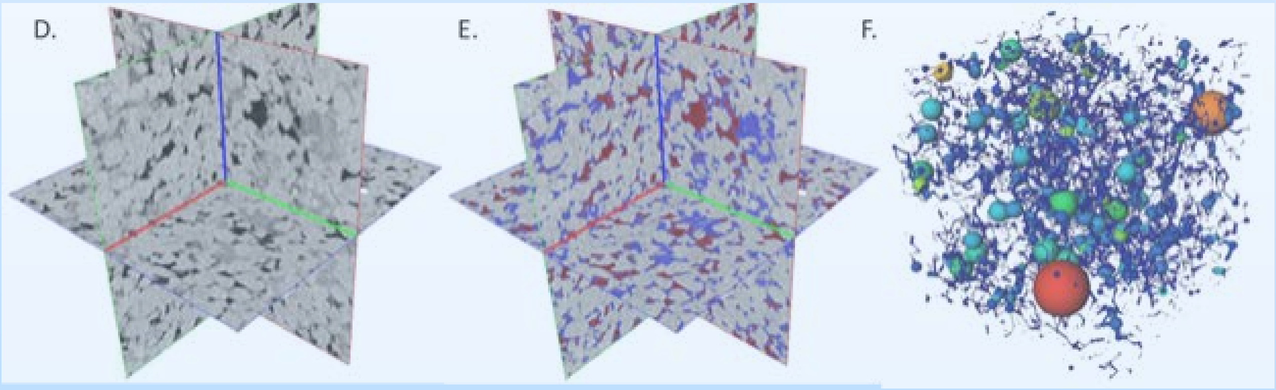
Accomplishments: Characterization

Selected Progress: Fluid/Rock Interactions

- Heterogeneity of the Morrow B reservoir was classified into five “hydraulic flow units” (hydrostratigraphic units) based on pore scale investigations.
- Two of these units evaluated with flow experiments to evaluate potential geomechanical impacts of CO_2-rich fluid-rock interaction

POSTER!!

- Chemo-mechanical degradation is largely controlled by the cement texture and composition



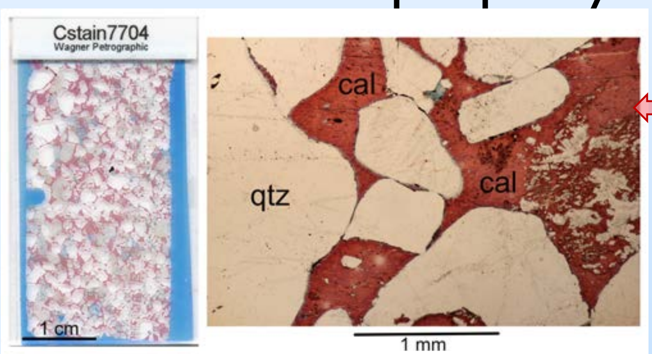
Tomographic images with interpreted pore networks built from those images (sphere size scaled to pore size)

Accomplishments: Characterization

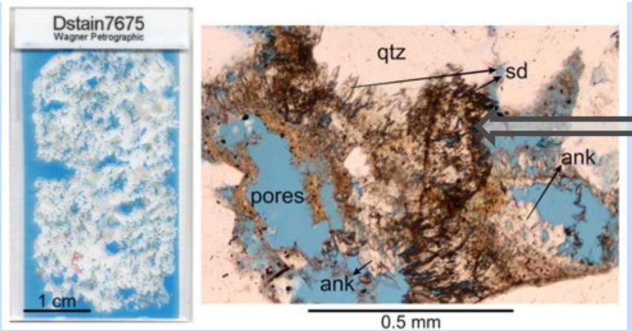
Selected Progress: Fluid/Rock Interactions

- CO_2-induced dissolution in disseminated ankerite-siderite-cemented sandstone yields little change in permeability and mechanical properties.
- CO_2-induced dissolution in poikilotopic calcite-cemented sandstone yields little to significant permeability and mechanical property changes.

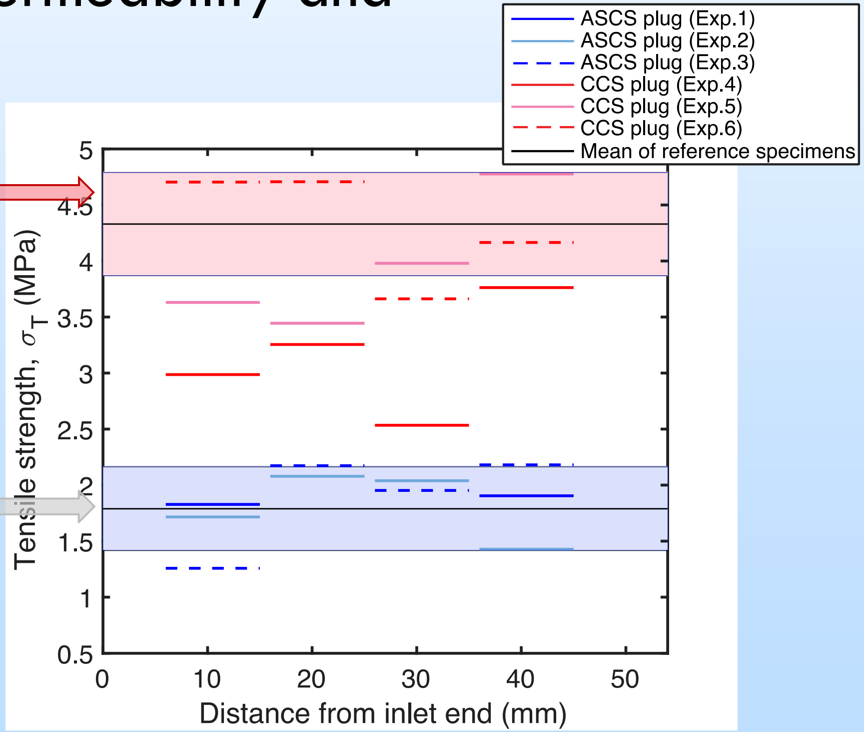
POSTER!!



Calcite cement



Ankerite/siderite cement



Accomplishments: Characterization

Selected Progress: Fluid/Rock Interactions

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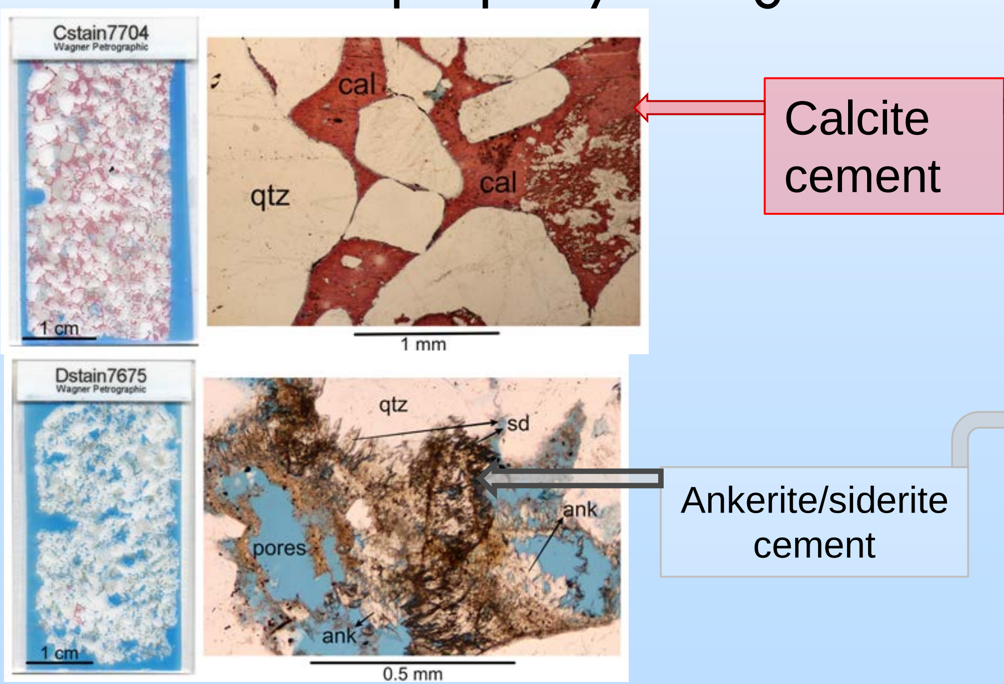
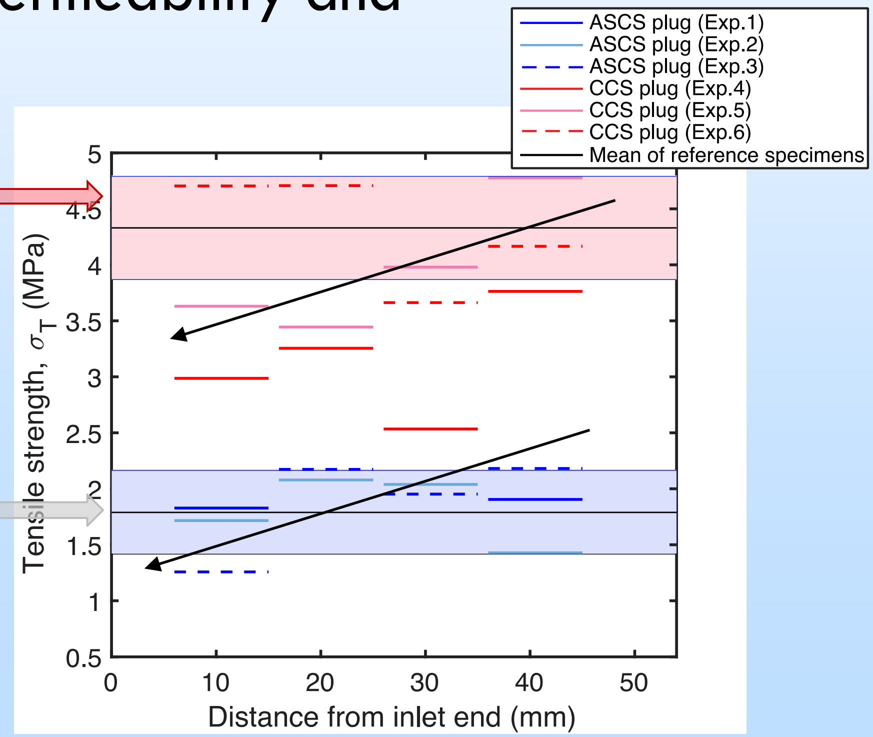




Accomplishments: Characterization

Selected Progress: Relative Permeability

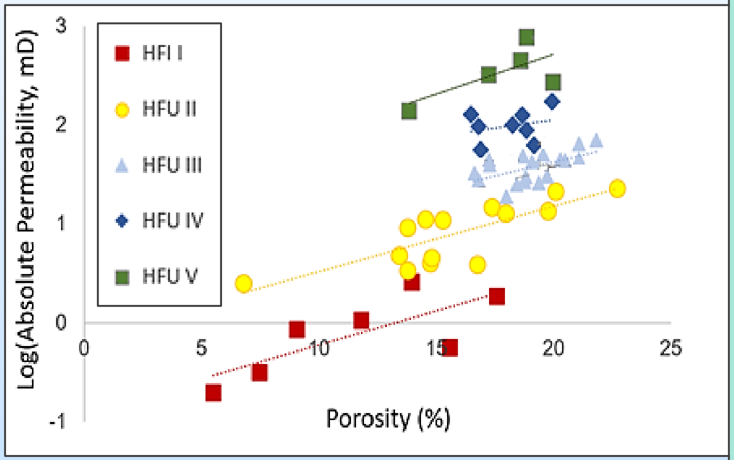
POSTER!!

- Quasi-steady-state oil/brine and oil/CO_2 relative permeability laboratory experiments were performed on various cores within the Morrow B Sandstone to study the effects the heterogeneity on multiphase behavior.
- End member two-phase flow properties, with binary pairs of oil-brine and oil-CO_2, are directly dependent on heterogeneity derived from diagenetic processes
- Both wettability and relative permeability are time-varying and hysteretic with respect to flooding history

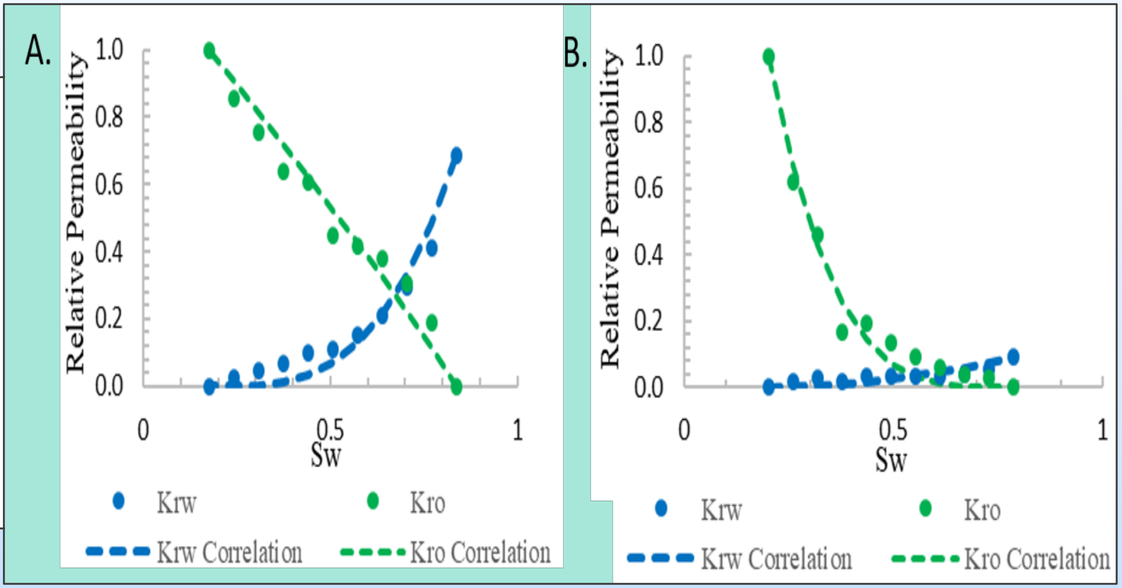
Accomplishments: Characterization

Selected Progress: Relative Permeability

Quasi-steady-state oil/brine and oil/CO_2 relative permeability binary pairs were measured to ascertain 3-phase relative permeability of the Morrow B:



Gas Absolute permeability-porosity relationships measured from Morrow B core plugs obtained in different flow units in well #13-10A at Farnsworth.



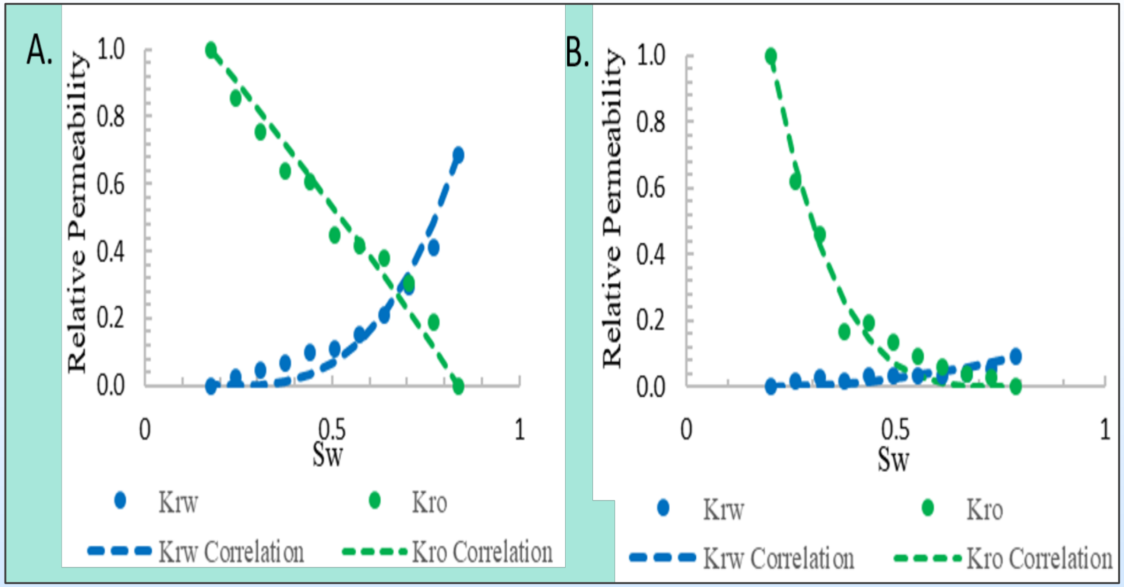
The difference in relative permeability in a clean core (left) and an aged (restored) core (right).

NOTABLE: THESE RESULTS ILLUSTRATE THE NEED TO "AGE" or RESTORE CORE (to original conditions) TO ASCERTAIN ORIGINAL WETTABILITY

Accomplishments: Characterization

Selected Progress: Relative Permeability

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



History match simulation efforts initially underestimate water injection and production.

Accomplishments: Characterization

Selected Progress: Relative Permeability

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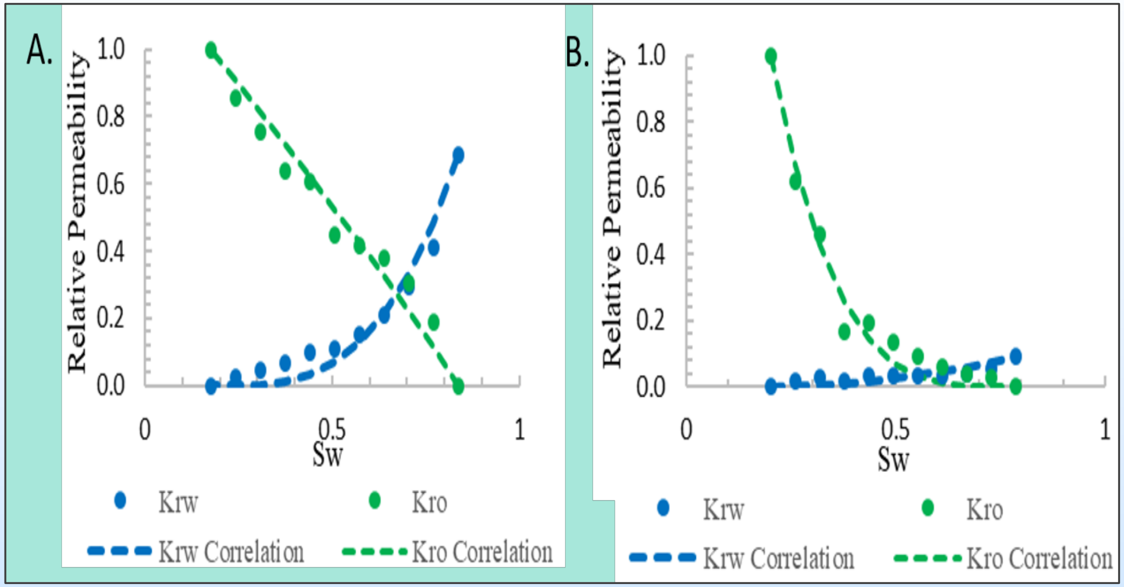

History match simulation efforts initially underestimate water injection and production.

Interpretation: heterogeneous wettability in the Morrow B evolves from oil-wet to strongly water-wetting, creating "fast" pathways that influence and limit sweep EOR/CCUS.

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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

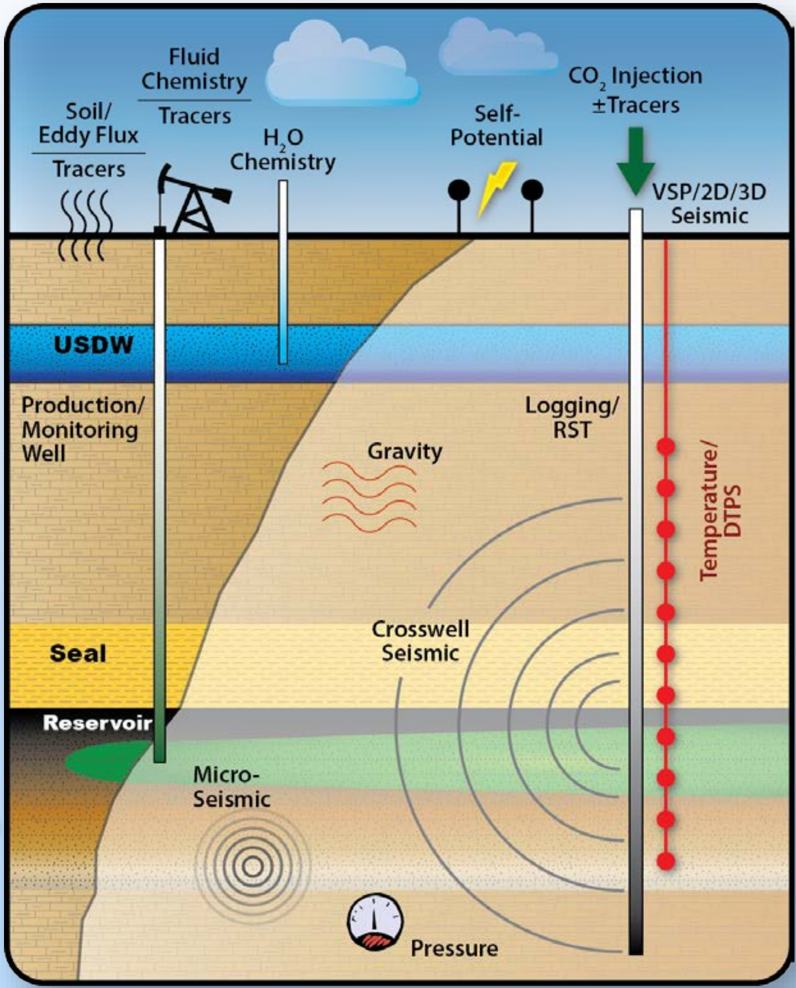
Accomplishments: MVA

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

Selected Progress: Microseismic Array

Task 7.1.6 – Microseismic Monitoring

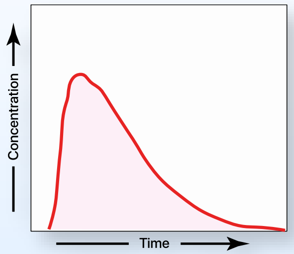
- Sixteen level borehole array - deployed in Dec 2018 (FWU #13-10).
- Twenty surface seismic stations – deployed in July 2019.
- Aid in characterizing the stability and storage of the CO_2 in the reservoir.
- Analysis of both borehole and surface microseismic is starting and will continue to end of project.

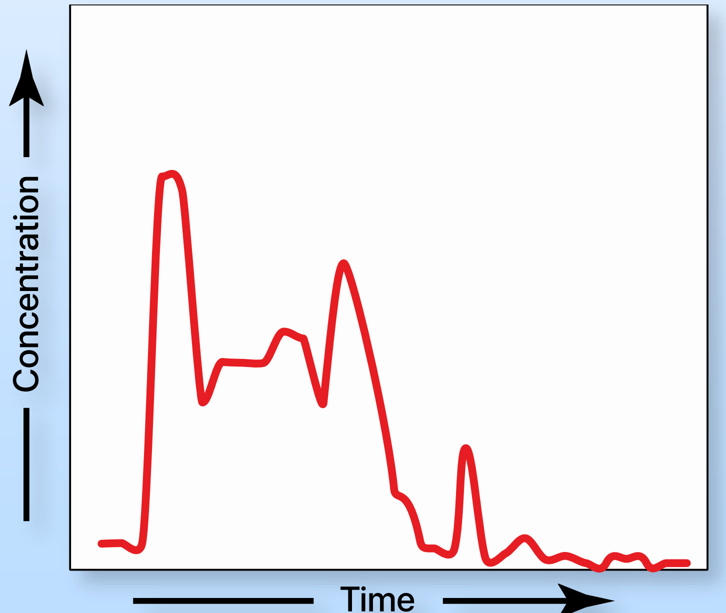
Accomplishments: MVA

Selected Progress: Tracers - Aqueous and Vapor

For Characterization

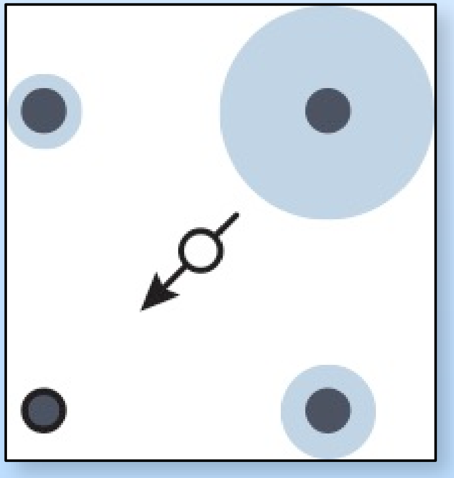
- Well-to-well communication (directions & velocities)
- Reservoir continuity or compartmentalization
- Fracture volume and extent
- Identify and interpret significant faults and/or barriers to flow

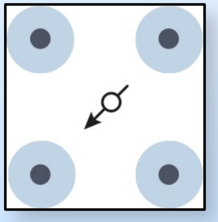




For Monitoring

- 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



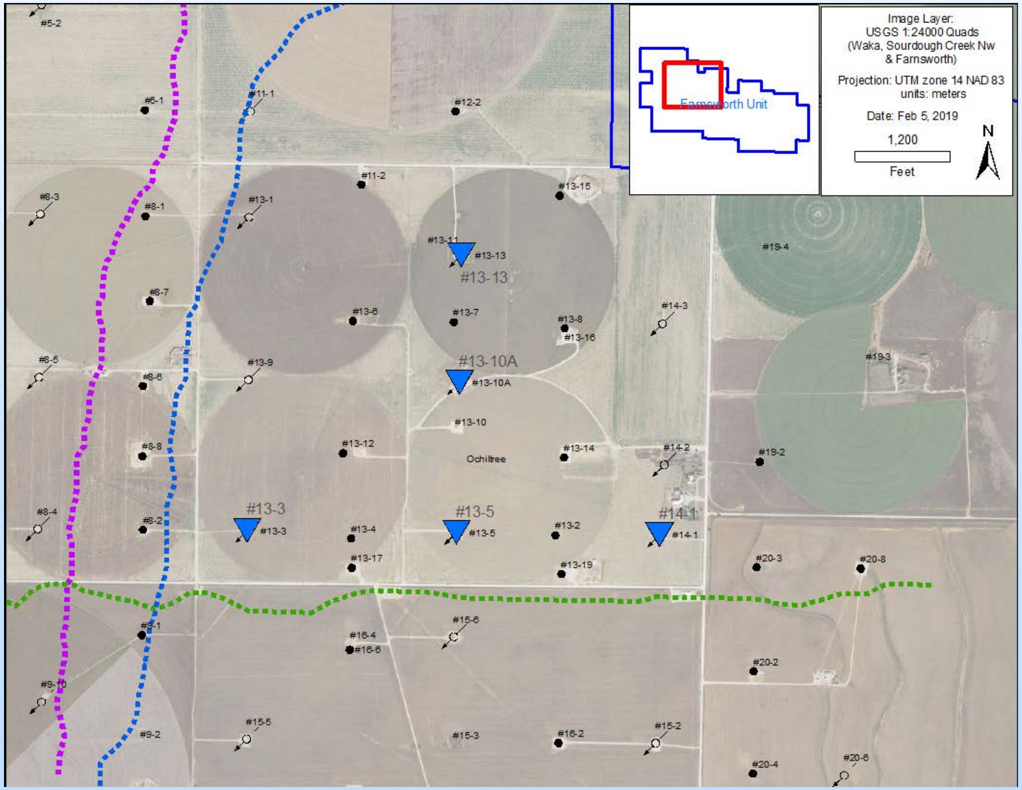


Accomplishments: MVA

Selected Progress: Aqueous Tracers

- 6 aqueous-phase tracers (powder + H_2O) injected into 5 wells to evaluate flow velocities, interwell connectivity, identify heterogeneities

- May 2, 2014
  - Well #13-13: 27.5 kg of 1,6-NDS
  - Well #13-10A: 50 kg of 1,3,6-NTS
  - Well #13-5: 25 kg of 1,5-NDS
- October 16, 2015
  - Well #14-1: 100 kg of 2,7-NDS
- June 15, 2017
  - Well #13-3: 100 kg of the 2,6-NDS
  - Well #13-3:   80 kg of the 2-NS
- Followed by varying lengths of water flood



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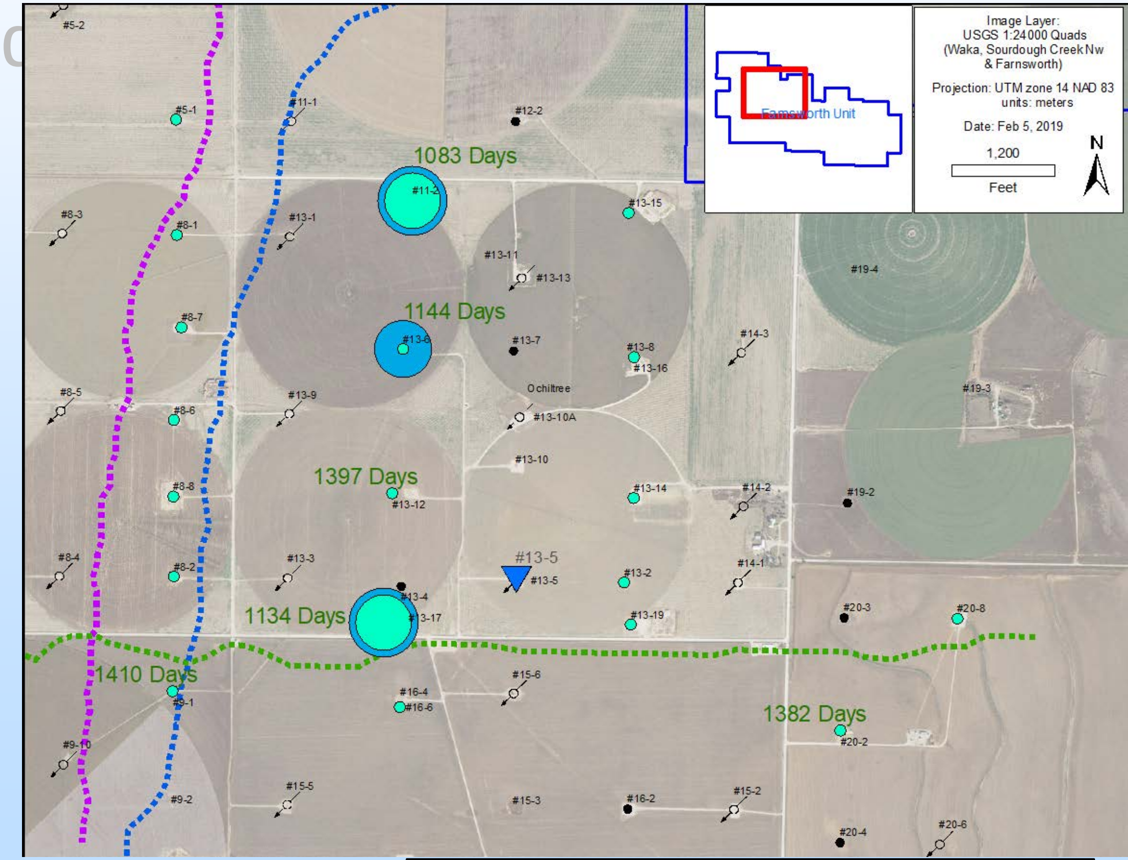

Arrival Times & Volume – Measure of Interwell Comm. & Sweep Efficiency

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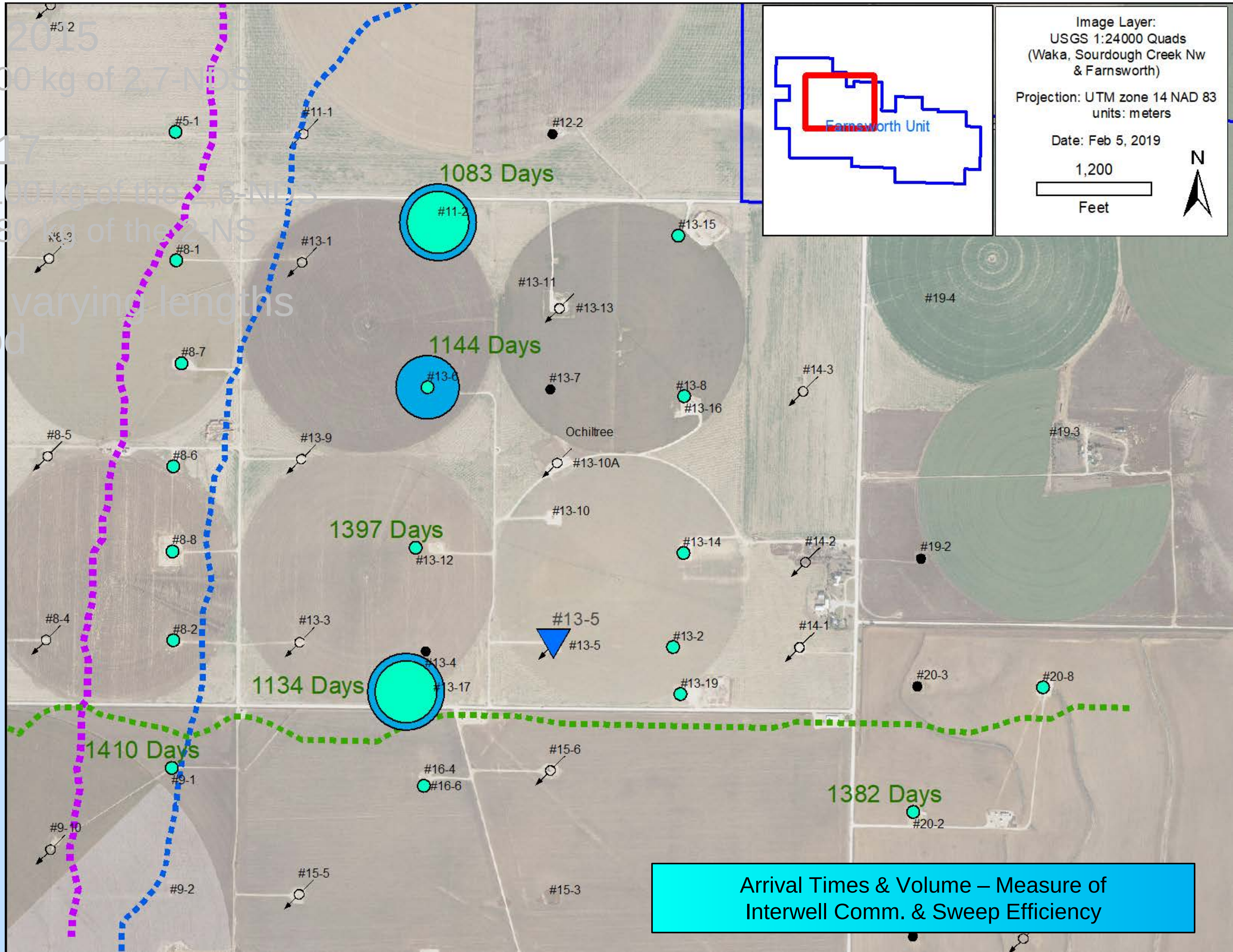

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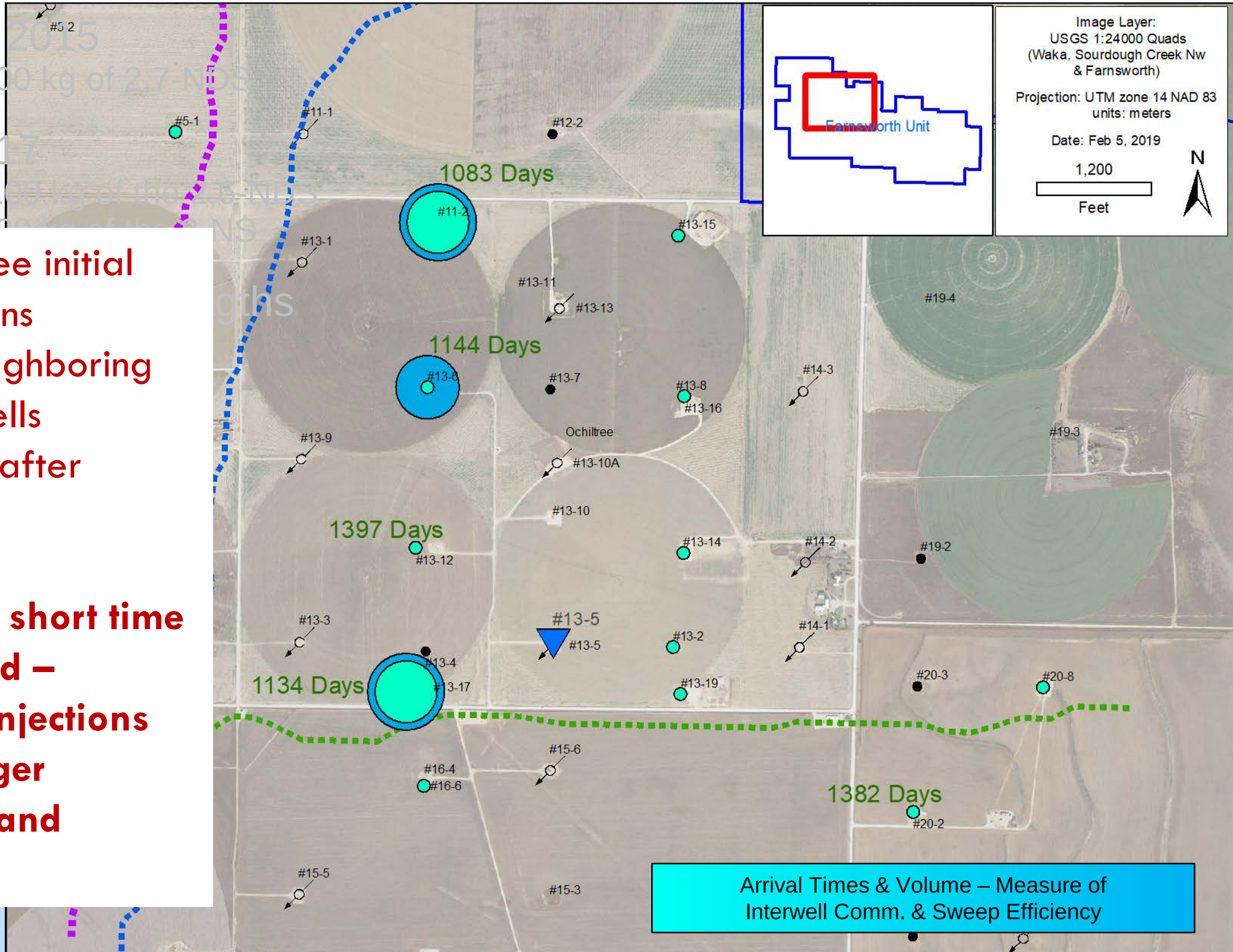
NOTE: All three initial tracer injections arrived at neighboring production wells >1000 days after injection!

Likely due to short time on waterflood – subsequent injections included longer waterfloods and met success



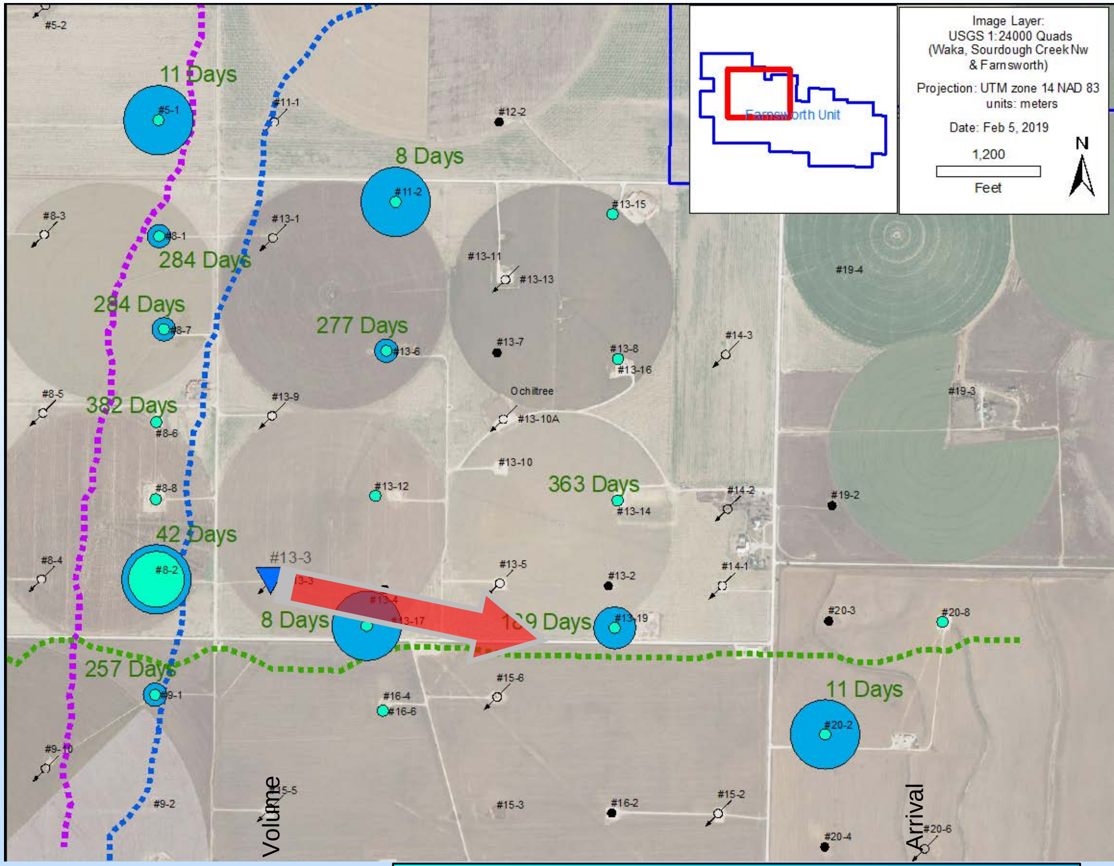
Arrival Times & Volume – Measure of Interwell Comm. & Sweep Efficiency

Accomplishments: MVA

Selected Progress: Aqueous Tracers

Reservoir Tracers
Aqueous Phase

- The latest injection (FWU #13-3) yielded results indicating significant preferential fluid flow along two adjacent "fast pathways".
- Relative tracer recovery along (#8-2 and #20-2) and across possible faults (#9-1) indicate variable transmissive versus sealed characteristics



Arrival Times & Volume – Measure of Interwell Comm. & Sweep Efficiency

#13-3) yielded results indicating significant preferential fluid flow along two adjacent “fast pathways”.

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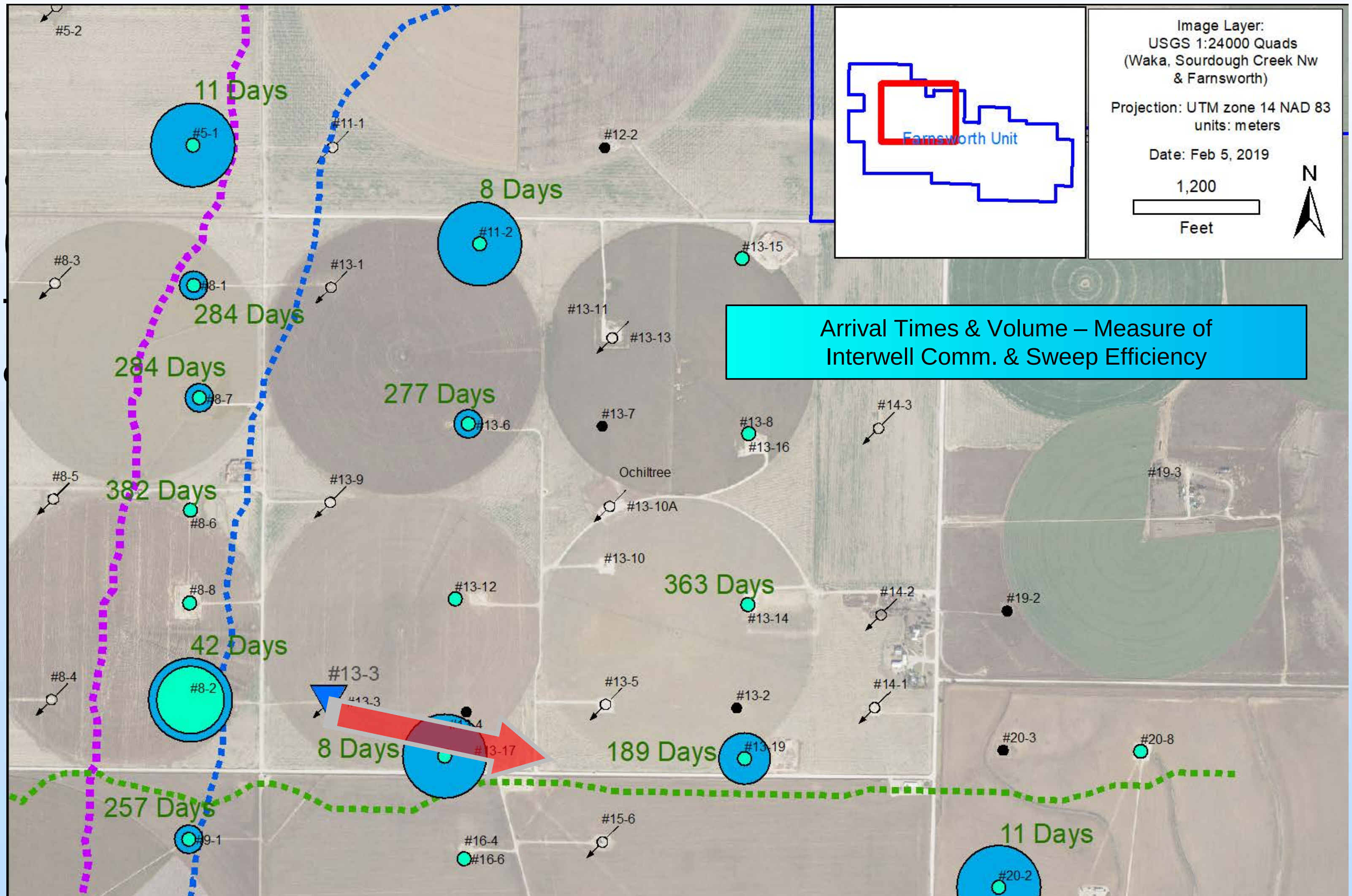
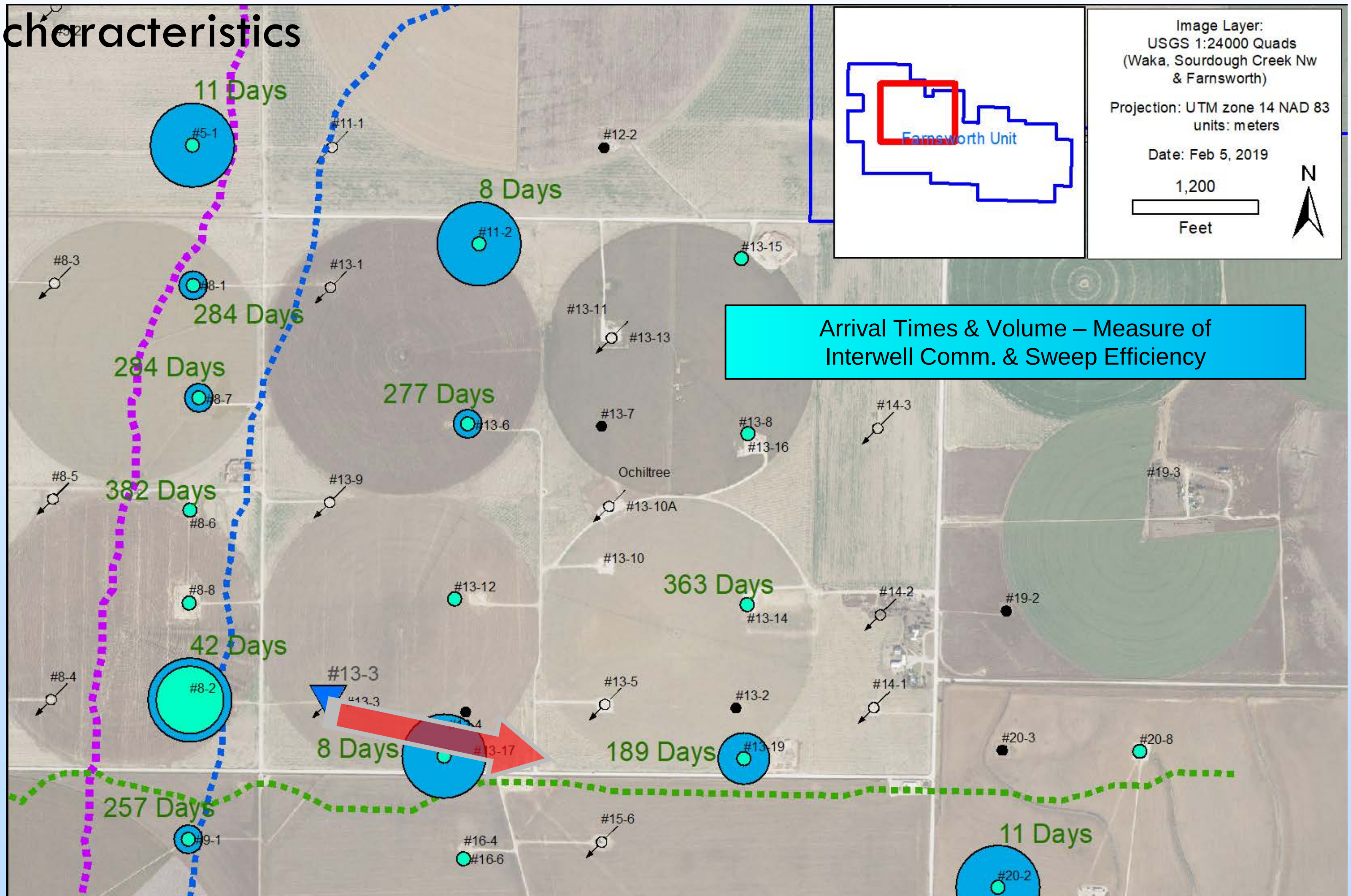


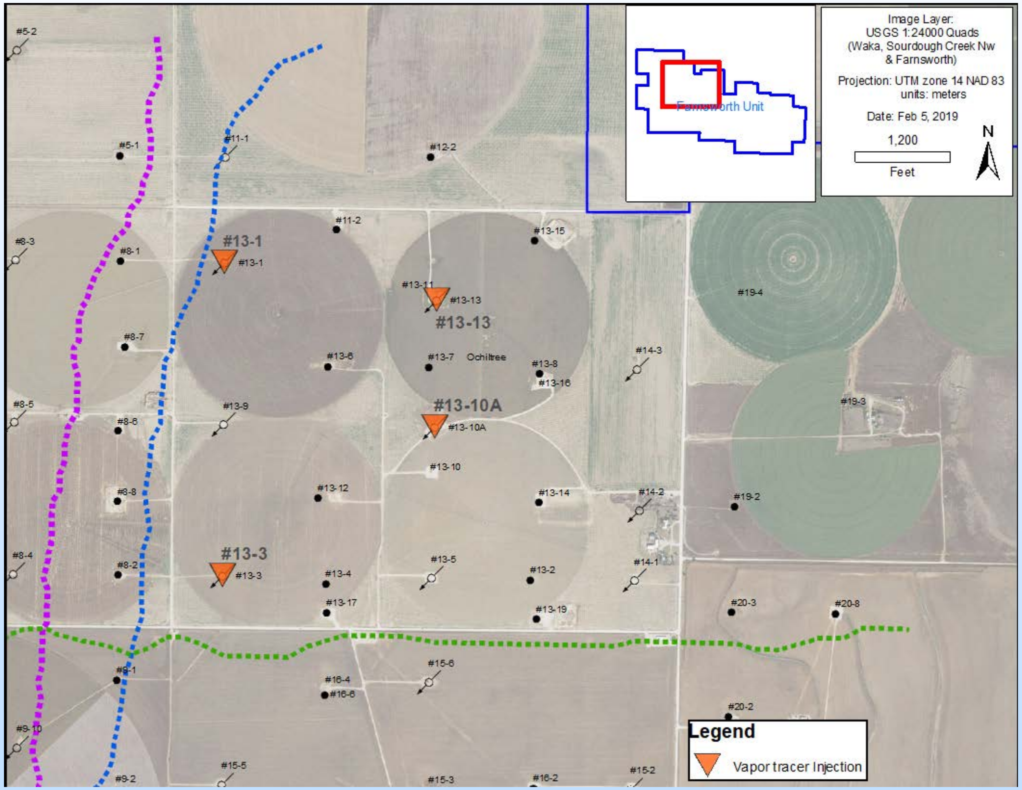
- Relative tracer recovery along (#8-2 and #20-2) and across possible faults (#9-1) indicate variable transmissive versus sealed characteristics



Accomplishments: MVA

Selected Progress: Vapor Tracers

- Four different vapor-phase tracers injected in four different wells to evaluate flow, interwell connectivity, and heterogeneity



May 21, 2015

- **Well #13-13: 2 kg of PTCH**

November 2, 2015

- **Well #13-10A: 1 kg of PDCB**

May 4, 2016

- **Well #13-1: 500 g of the PMCH**
- **Well #13-3: 500 g of the PECH**

Followed by varying lengths of CO_2 flood

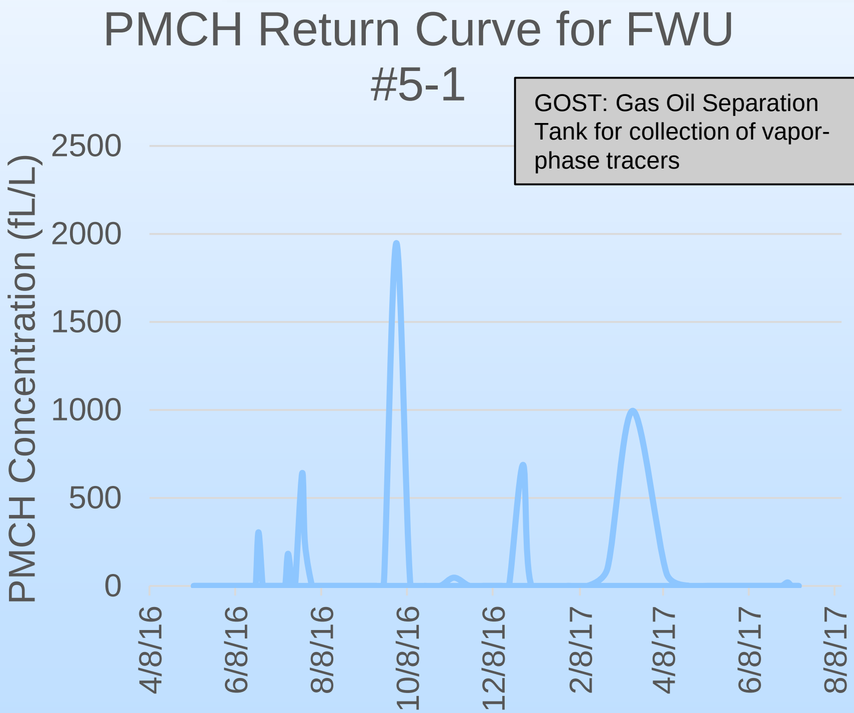
Accomplishments: MVA

Selected Progress: Vapor Tracers

Tracers – Vapor Phase

- Vapor-phase tracer slugs (Perfluorocarbons) in 4 wells
- Vapor tracer in FWU #13-1 corroborated preferential fluid flow along the two faults
- Caveat: vapor tracer recovery is complex (multiple returns)

  = *more uncertainty*
- Despite excellent gas tracer tech, procedures increase costs



Fluctuating vapor-phase tracer return curve for FWU well #8-2 is indicative of most wells sampled.

Presentation Outline

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

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

- Provided basis for NRAP's wellbore leakage analysis
- Quantified variability between measured and 'fitted' relative perm curves
- Relative Permeability tied to (predicated on) capillary pressure data
- Regrid (mesh conversion) software developed for code comparison
- 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

Accomplishments: Simulation

Publications

- Moodie, N., Ampomah, W., Jia, W., Heath, J., & McPherson, B. (2019). Assignment and calibration of relative permeability by hydrostratigraphic units for multiphase flow analysis, case study: CO2-EOR operations at the Farnsworth Unit, Texas. *International Journal of Greenhouse Gas Control*, *81*, 103-114.
- Kutsienyo, E. J., Ampomah, W., Sun, Q., Balch, R. S., You, J., Aggrey, W. N., & Cather, M. (2019, June). Evaluation of CO-EOR Performance and Storage Mechanisms in an Active Partially Depleted Oil Reservoir. In *SPE Europec featured at 81st EAGE Conference and Exhibition*. Society of Petroleum Engineers.
- You, J., Ampomah, W., Kutsienyo, E. J., Sun, Q., Balch, R. S., Aggrey, W. N., & Cather, M. (2019, June). Assessment of Enhanced Oil Recovery and CO Storage Capacity Using Machine Learning and Optimization Framework. In *SPE Europec featured at 81st EAGE Conference and Exhibition*. Society of Petroleum Engineers.
- You, J., Ampomah, W., Sun, Q., Balch, R. S., Kutsienyo, E. J., & Cather, M. (2019, September). Multi-objective Optimization of CO2 Enhanced Oil Recovery Projects Using a Hybrid Artificial Intelligence Approach. In SPE ATCE Canada.
- Trevor P Irons, Brian JOL McPherson, M Andrew Kass, Reliable noise measure in time-gated NMR data, Geophysical Journal International, Volume 215, Issue 2, November 2018, Pages 959–964, https://doi.org/10.1093/gji/ggy318
- Plus six (6) major conference presentations!

Accomplishments: Simulation

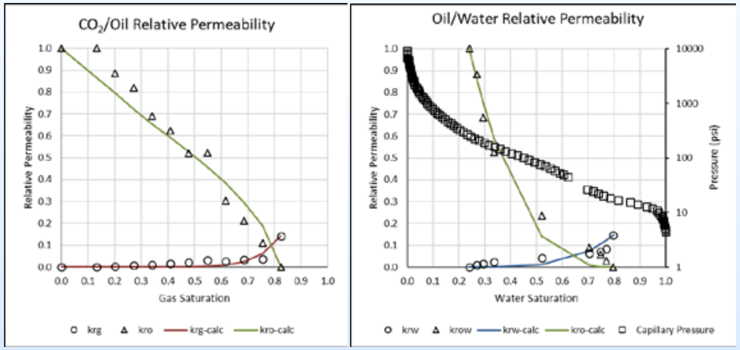
POSTER!!

Select Progress: Relative Permeability

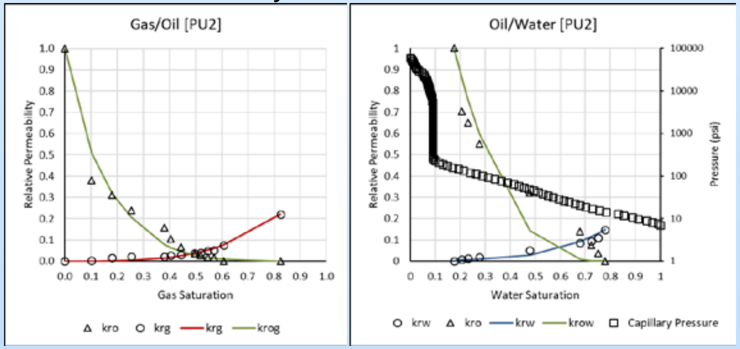
Developed method: three-phase relative permeability curves based on measured mercury intrusion capillary pressure

- Leverage the extensive capillary pressure data set collected by SWP
- Goal: relative permeability relationships when little/no relative permeability data are available

Relative permeability curve fit to Rasmussen and Dewers laboratory data



Relative permeability curve fit to China University of Petroleum laboratory data



Original Algorithms:

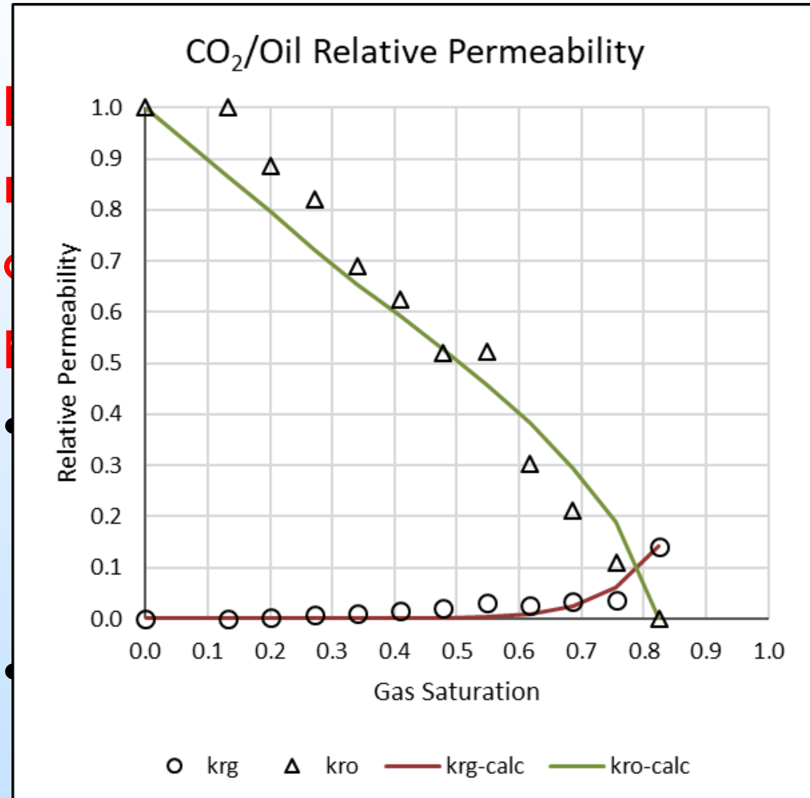
Purcell, W.R., 1949. Capillary pressures - Their measurement using mercury and the calculation of permeability therefrom. Journal of Petroleum Technology 1, 39-48.

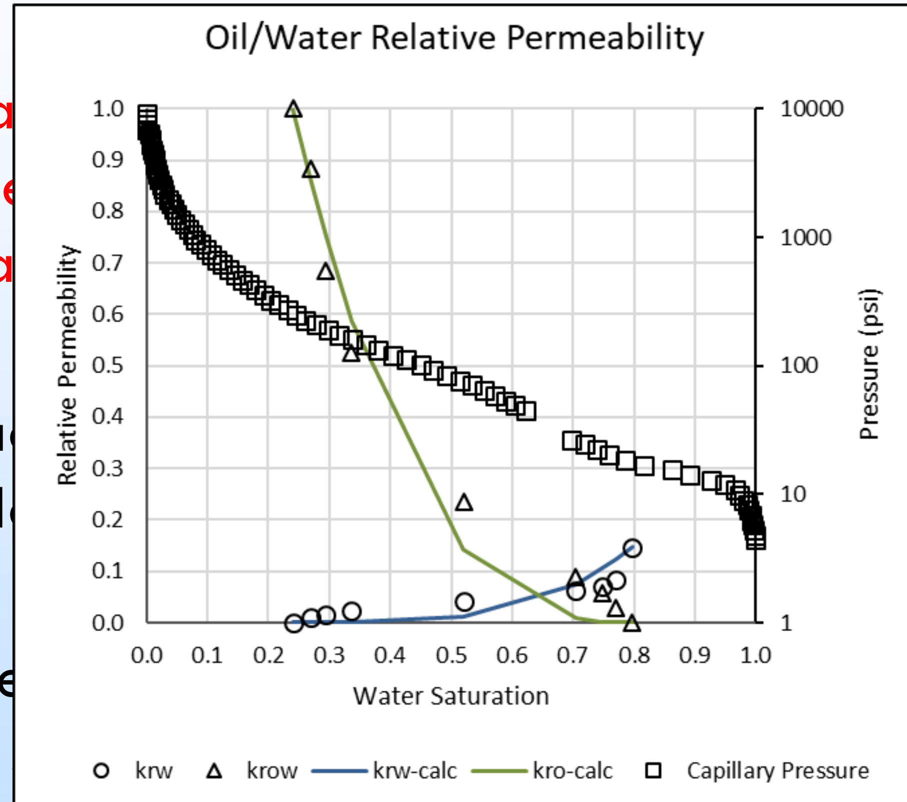
Fatt, I., Dykstra, H., 1951. Relative permeability studies. Journal of Petroleum Technology 3, 249-256.

Accomplishments: Simulation

POSTER!!

Select Progress: Relative Permeability





when little/no relative permeability data are available

Original Algorithms:

Purcell, W.R., 1949. Capillary pressures - Their measurement using mercury and the calculation of permeability therefrom. Journal of Petroleum Technology 1, 39-48.

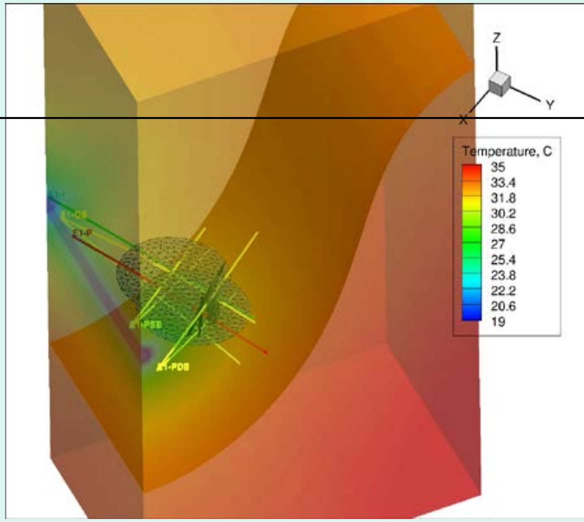
Fatt, I., Dykstra, H., 1951. Relative permeability studies. Journal of Petroleum Technology 3, 249-256.

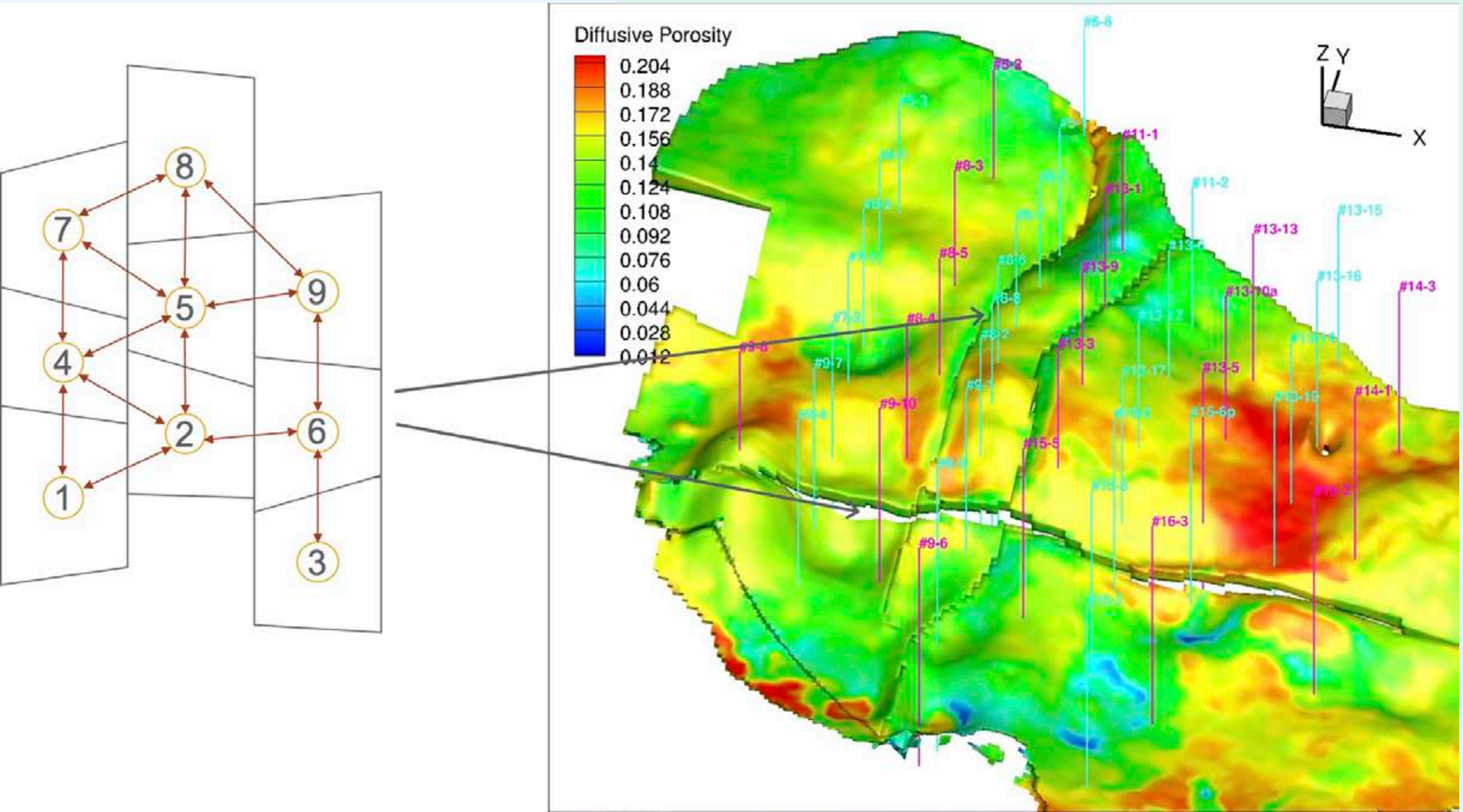
Accomplishments: Simulation

Select Progress: fault slip capability

(improve solute transport)

- Development of embedded fault and z-slip fault models in STOMP-EOR to capture solute transport across and along fault zones in FWU

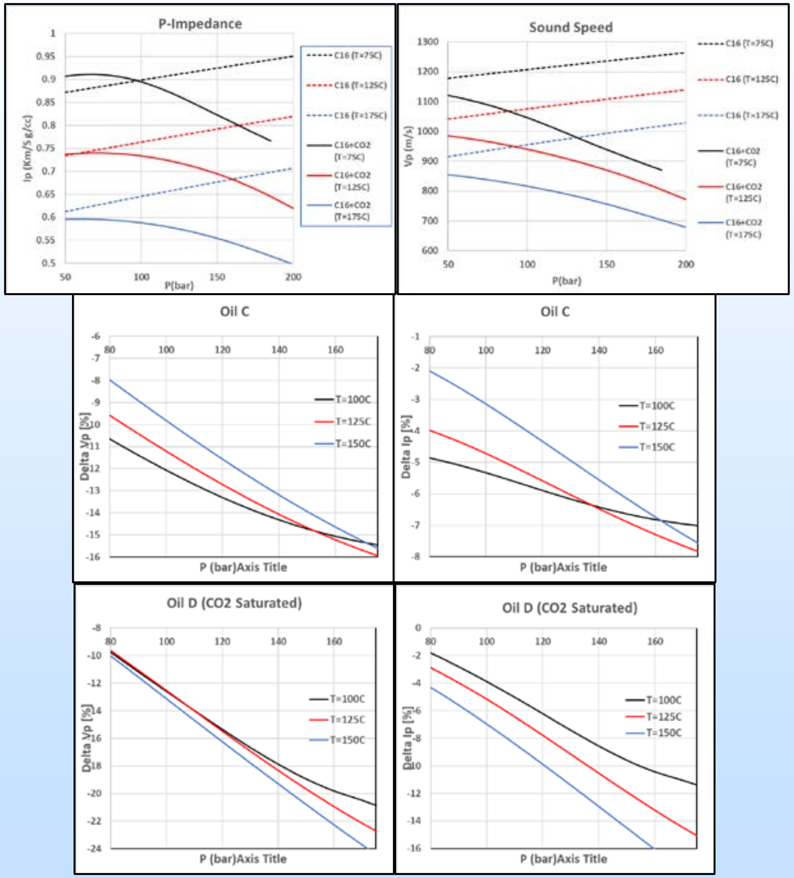




Accomplishments: Simulation

Select Progress: time-lapse seismic / fluid integration

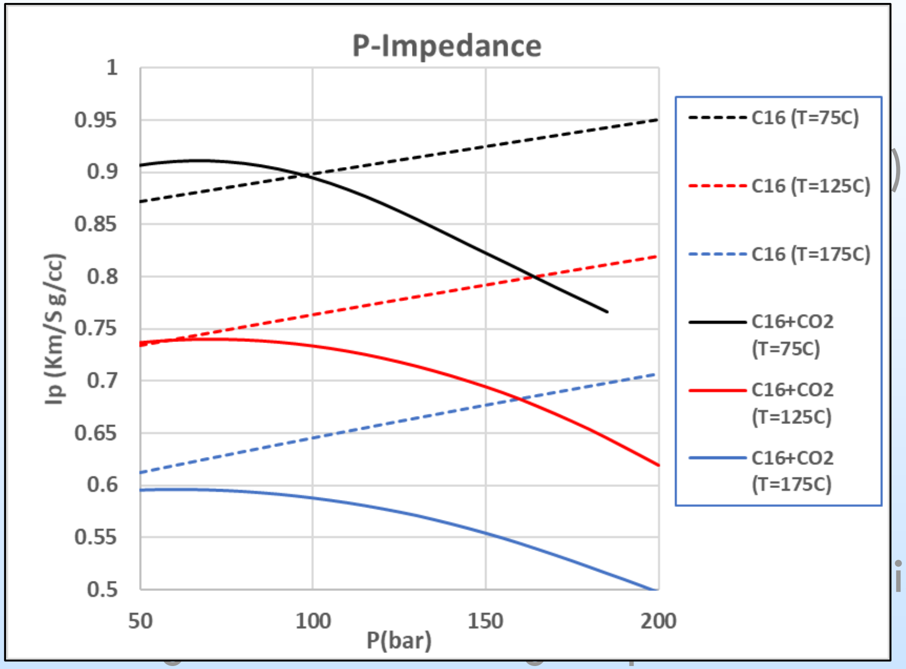
- Benchmarked fluid thermophysical property models workflow against previous work (with NIST SUPERTRAPP)
- Developed custom fluid modeling sequence for sensitivity analysis in SUPERTRAPP
- Integrated FWU fluid properties with seismic properties from available GC and conventional compositional analysis using custom modeling sequence.

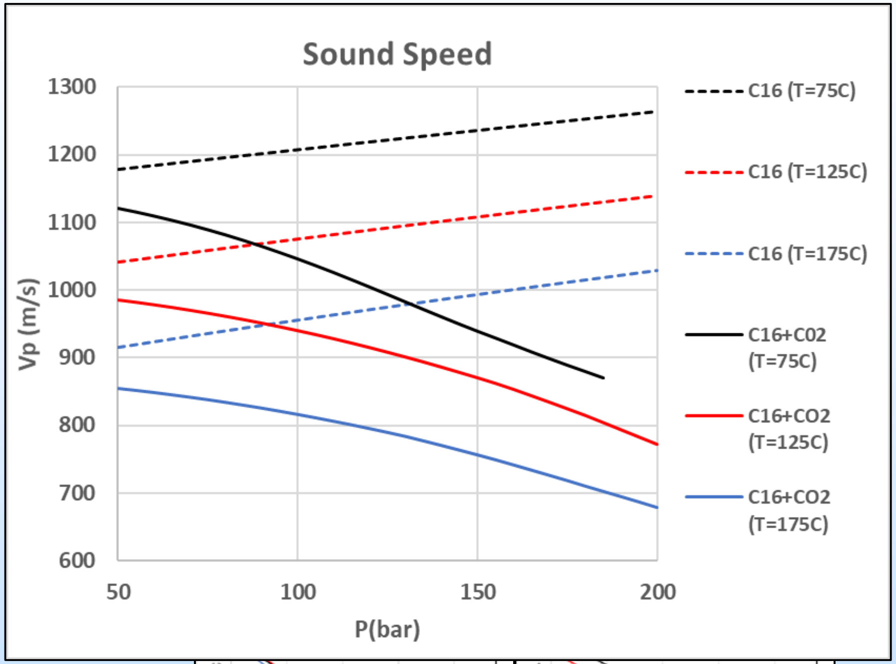


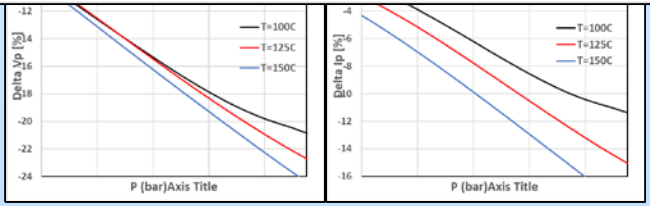
* Bilgin Altundas, Nikita Chugunov, T. S. Ramakrishnan, and Robert Will, (2017), "Quantifying the effect of CO_2 dissolution on seismic monitoring of CO_2 in CO_2-EOR," *SEG Technical Program Expanded Abstracts* : 3771-3775.

Accomplishments: Simulation

Select Progress: time-lapse seismic / fluid integration







Key point: we believe this fluid substitution modeling is essential for meaningful coupling of VSP data with fluid properties, factoring in the pressure and temperature controls on these properties

* Bilgin Altundas, Nikita Chugunov, T. S. Ramakrishnan, and Robert Will, (2017), "Quantifying the effect of CO2 dissolution on seismic monitoring of CO2 in CO2-EOR," *SEG Technical Program Expanded Abstracts* : 3771-3775.

Presentation Outline

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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 6.5 Risk Assessment

- Perform annual FEPs reranking
- Update/refine PDFs/CDFs of the potential risks using updated model with ROMs (including NRAP tools)
- Update Risk Prevention and Mitigation treatments

Subtask 7.4.1 Quantify Risk

- Extend quantitative brine and CO2 leakage calculations
- 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

Accomplishments: Risk Assessment

Significant Achievements

- Completed analysis of 4th risk workshop
- Updated prevention and mitigation treatments accordingly

- Developed preliminary reactive transport model for FWU

- Evaluated chemical-mechanical coupling assessment of caprock integrity
- Conducted column experimental analysis of potential chemical impacts of CO2 intrusion into overlying groundwater aquifer
- Performed leakage analysis with NRAP tools

Accomplishments: Risk Assessment

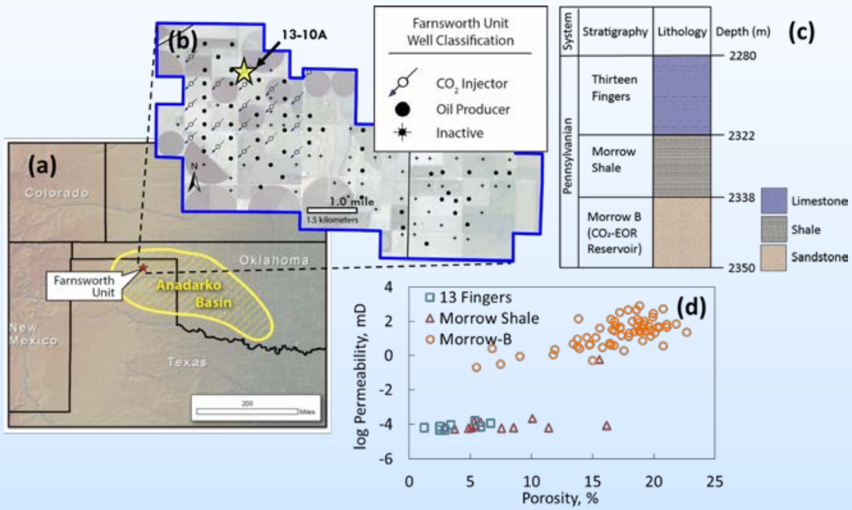
Publications

- Dai, Z., Viswanathan, H., Xiao, T., Hakala, A., Lopano, C., Guthrie, G., McPherson, B., 2019. Reactive transport modeling of geological carbon storage associated with CO_2 and brine leakage. *Science of Carbon Storage in Deep Saline Formations*. Elsevier, ISBN: 9780128127520. doi.org/10.1016/B978-0-12-812752-0.00005-8
- Jia, W., McPherson, B. Multi-phase flow associated with GCS at the field scale. In: P. Newell and A. G. Ilgen (Eds.), *Science of Carbon Storage in Deep Saline Formations: Process Coupling Across Time and Spatial Scales*. Chennai: Elsevier, 2019, pp. 117-143. https://doi.org/10.1016/B978-0-12-812752-0.00006-X
- Jia, W., McPherson, B., Pan, F., Dai, Z., Xiao, T. Uncertainty Quantification of CO_2 Storage Mechanisms Using Bayesian Inference. *International Journal of Greenhouse Gas Control* 71: 104-115. DOI: 10.1016/j.ijggc.2018.02.015.
- Plus four (4) major conference presentations!

Accomplishments: Simulation

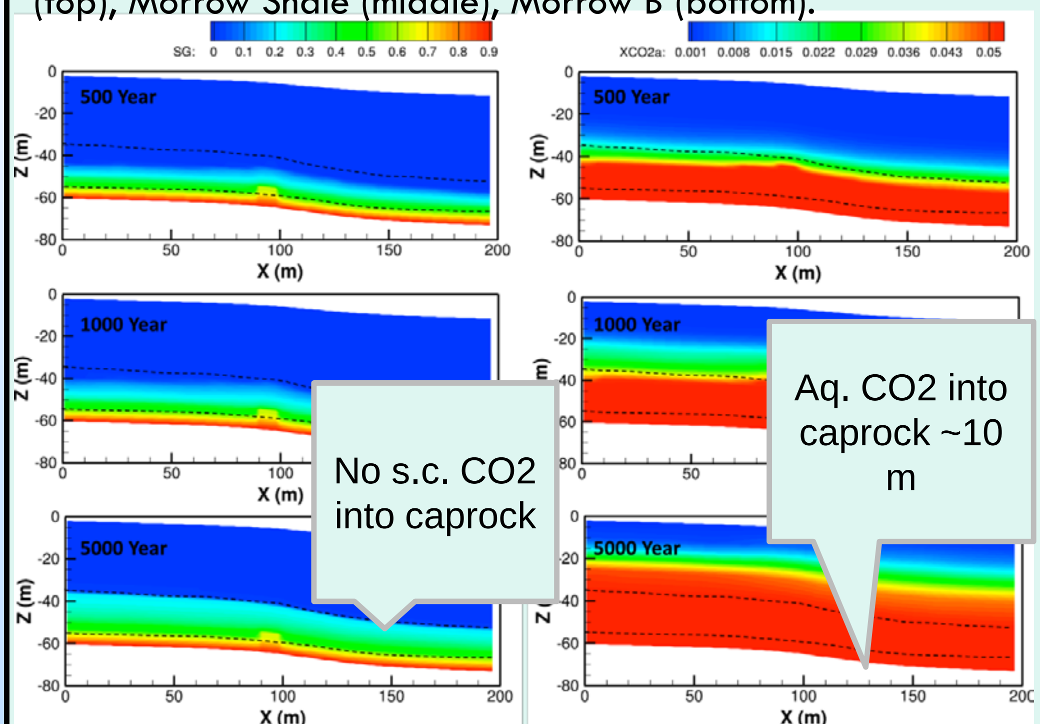
POSTER!!

Select Progress: caprock integrity analysis



- Evaluate the long-term caprock sealing capacity and effects of caprock hydrological and mineralogy heterogeneities on its integrity and CO_2 migration

Simulated spatial distribution of supercritical CO2 (left) and aqueous CO2 (right) in 500 years, 1000 years, and 5000 years. Domains separated with dotted lines: Thirteen Fingers (top), Morrow Shale (middle), Morrow B (bottom).

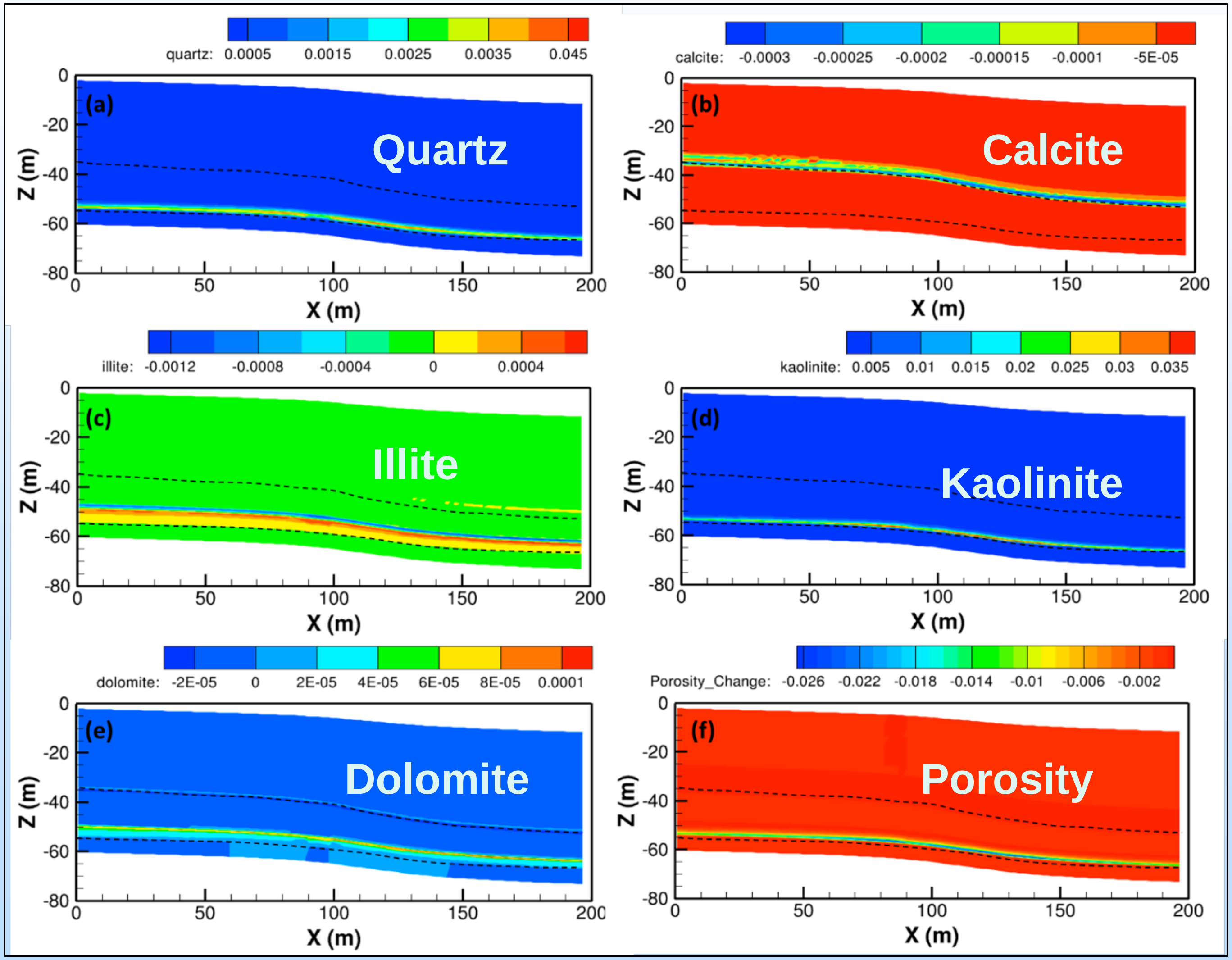


Accomplishments: Simulation

POSTER!!

Select Progress: mineral alterations and sealing efficiency

- Calcite dissolution dominant in Thirteen Fingers.
- Quartz and illite precipitate in Morrow Shale.
- Precipitation increased caprock sealing effectiveness.

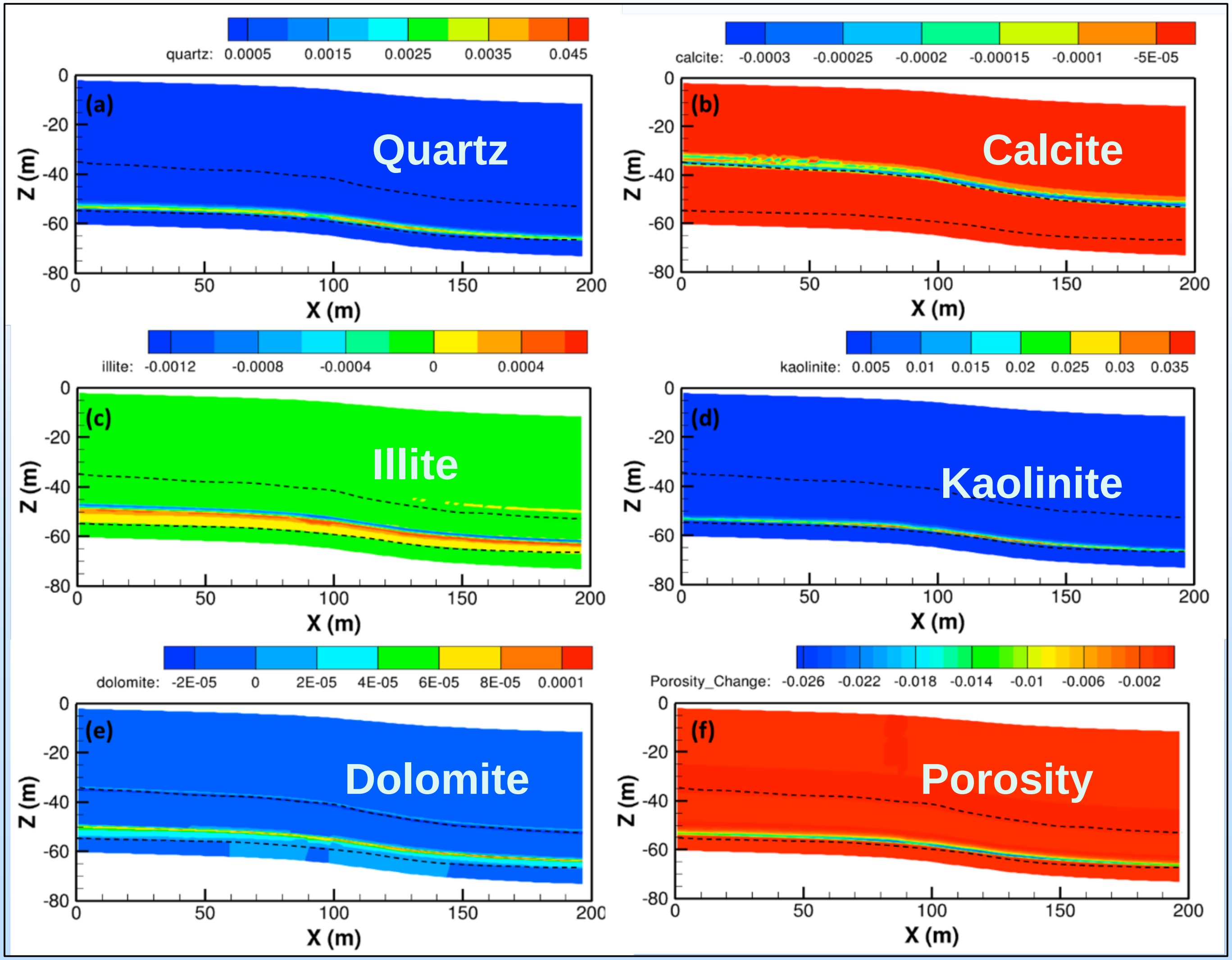


Accomplishments: Simulation

POSTER!!

Select Progress: mineral alterations and sealing efficiency

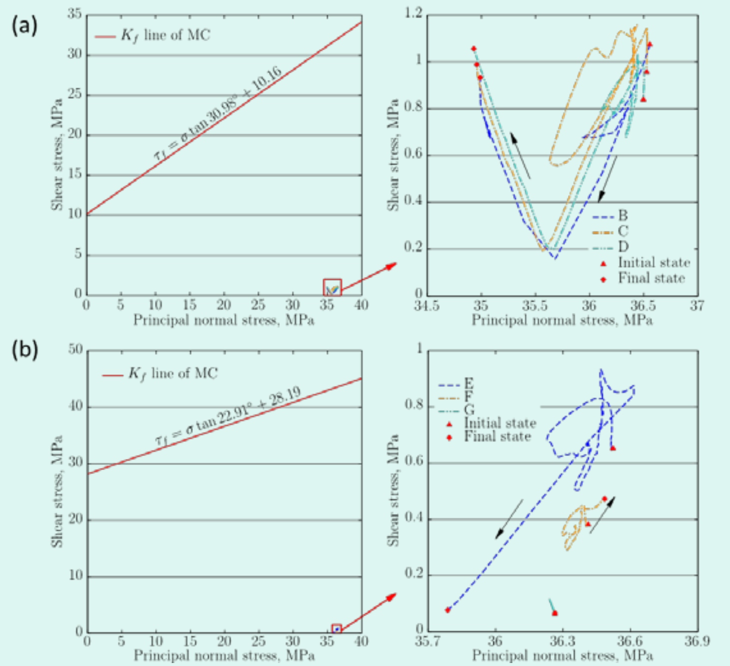
- Mineral alteration is slow significant changes in minerals after 5000 years (!)
- Sealing efficiency increases with porosity reduction
- Porosity decreases ~10% to ~8%, leading to significant reduction of CO2 intrusion in caprock



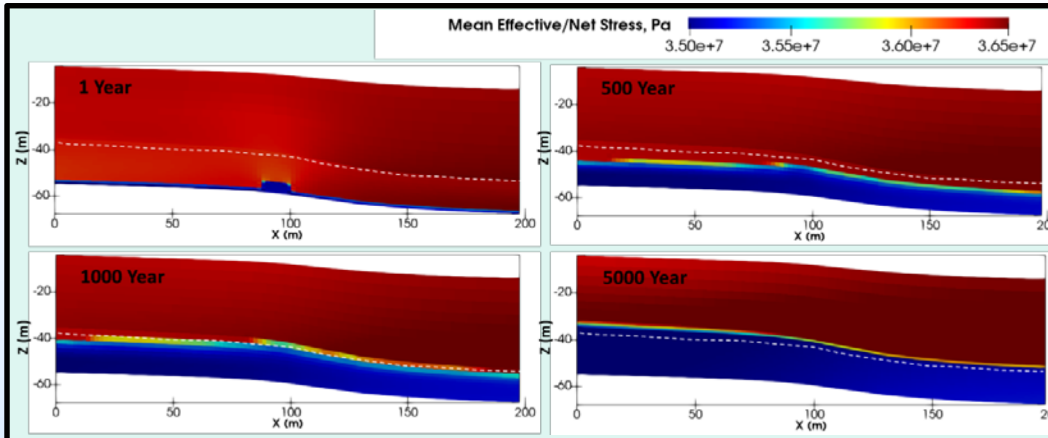
Accomplishments: Simulation

POSTER!!

Select Progress: geomechanical alteration and caprock integrity



Simulated stress paths suggest no shear failure occur and both Thirteen Fingers and Morrow Shale remain mechanically stable.



Simulated distribution of mean effective/net stress in Morrow Shale and Thirteen Fingers limestone at 1, 500, 1000 and 5000 years.

Coupling between chemical changes and geomechanical behaviors:

- Examine pore pressure and effective/net stress for simulations with and without chemical reactions;
- Slight difference observed within one-year simulation;
- Almost identical for longer time period simulations;
- Mineralogy alterations in caprocks has limited impact on mechanical behaviors at FWU.

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- Synergy Opportunities
- Project Summary

Lessons Learned

Selected lessons learned - what worked well:

- Aqueous phase tracers are fabulous for interpreting fast/slow pathways (e.g., faults)
- 3-phase relative permeability derived from capillary pressure is a great proxy if data lacking
- "aging" or restoring core (preceding CO_2 flow experiments with extended oil flow to mimic pre-EOR conditions) confirmed that wettability evolves (from oil-wet to water-wet)
- Wettability evolution may promote "fast" pathways

Lessons Learned

Selected lessons learned – did not work so well or are "null results":

- Vapor phase tracers are so not fabulous for interpreting flow (multiple returns)
- Most mineralogic changes are too slow to be a factor for CO2-EOR, or at least this field
- Differences in fault modeling approaches (algorithms) between STOMP, Eclipse and other simulators a barrier to code comparison
- Better calibration of cement degradation and other geochemical reactions would reduce associated uncertainty

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- Project Summary

Synergy Opportunities

- SWP has reached out to neighboring CarbonSAFE projects to promote common data sets and tools

- SWP has reached out to neighboring RCSP projects to promote common data sets and tools

- SWP has reached out to neighboring Unconventional Oil/Gas Reservoir projects to promote common data sets and tools

Presentation Outline

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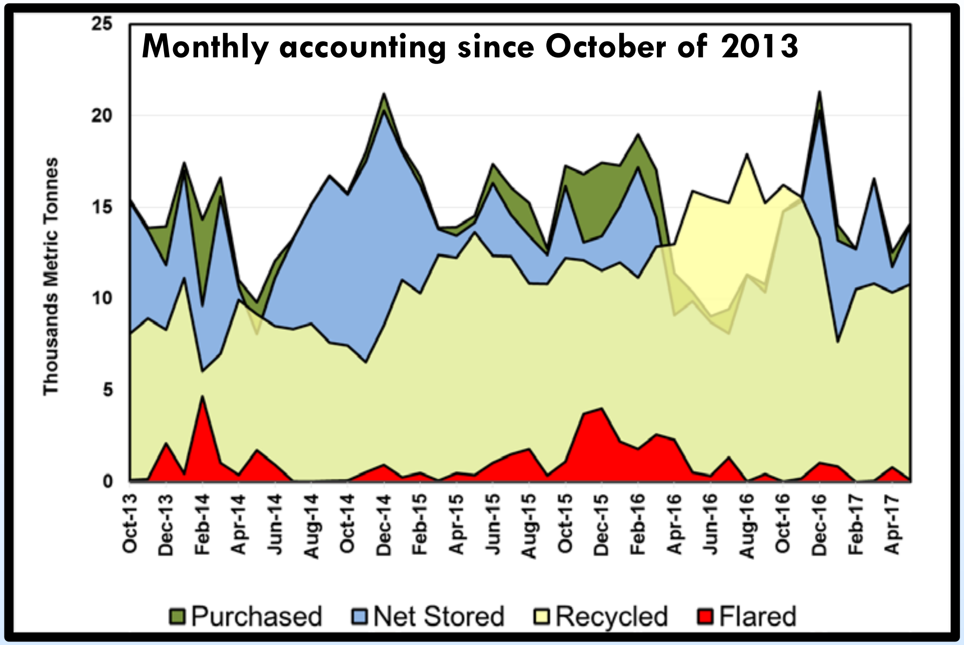
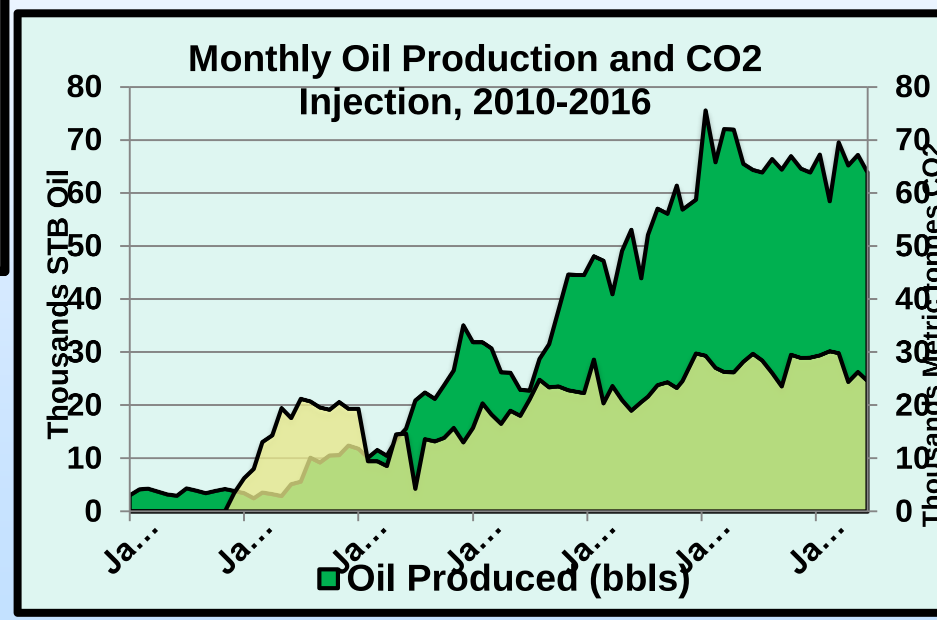
Project Summary



- 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



- 1,050,000 tonnes stored since November 2010
- Over 850,000 tonnes is the "official" storage (since 2013)

- **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.

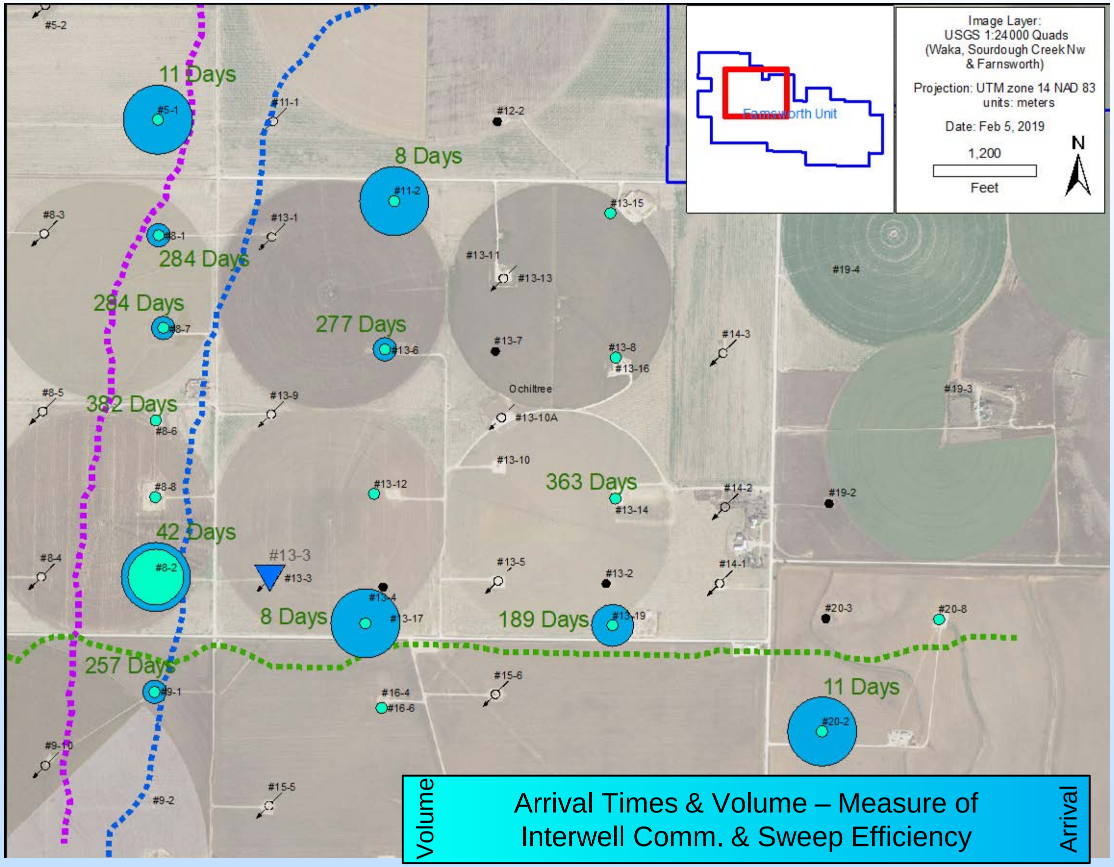
Gantt Chart

- 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.