Southwest Regional Partnership on Carbon Sequestration (SWP)

DE-FC26-05NT42591

Phase III Demonstration: Farnsworth Unit

Robert Balch[1]
Brian McPherson[1,2]
[1]New Mexico Institute of Mining and Technology
[2]University of Utah

Mastering the Subsurface through Technology Innovation & Collaboration:
Carbon Storage & Oil and Natural Gas Technologies Review Meeting
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Acknowledgements

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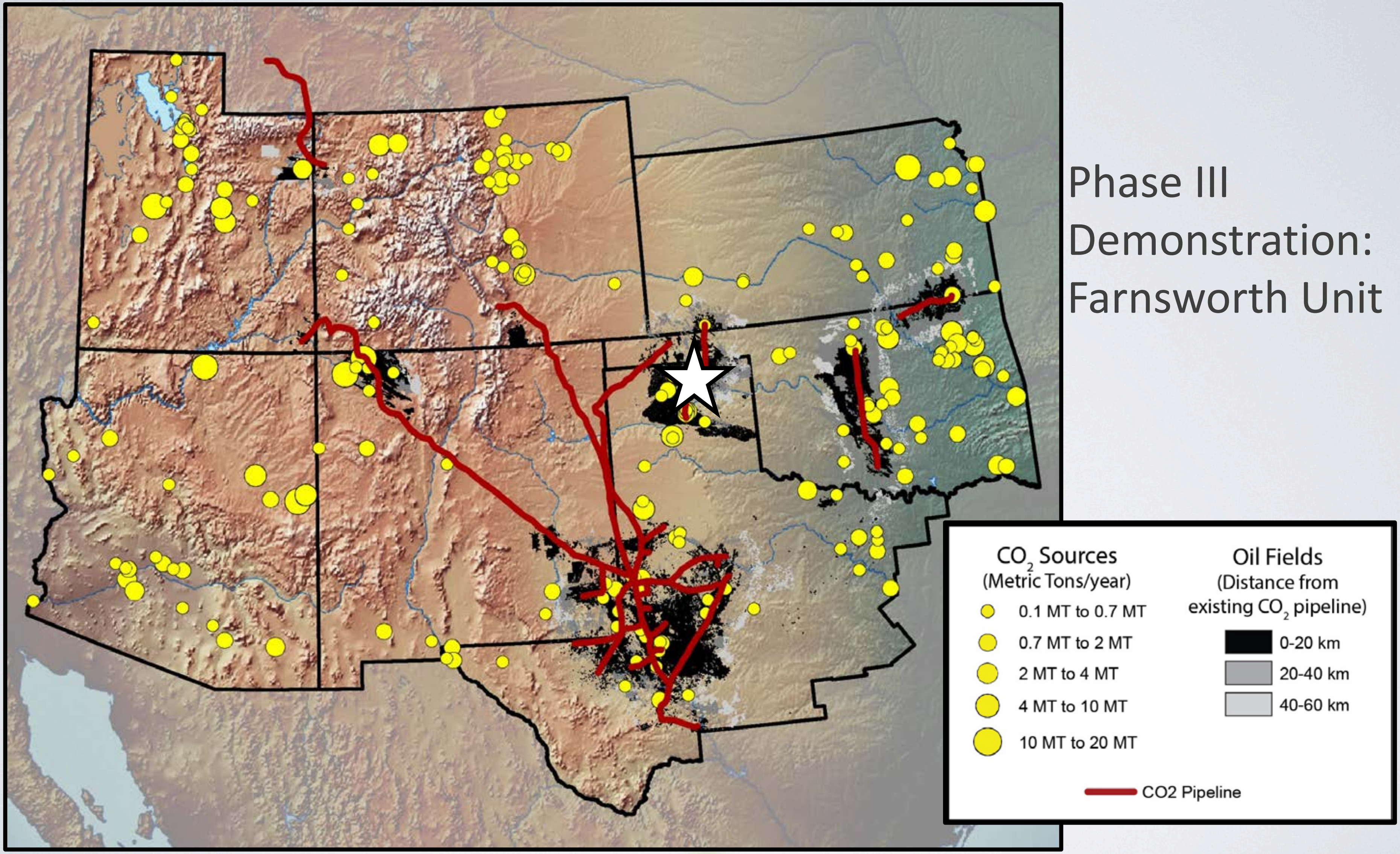
We gratefully acknowledge the contributions of more than 50 SWP scientists and engineers!

Outline

- **Introduction to the SWP**
- **Introduction to Farnsworth Unit**
- Major tasks:
  - Geologic Characterization
  - MVA
  - Simulation
  - Risk
- Conclusions and ongoing work

The Southwest Partnership



Phase III Demonstration: Farnsworth Unit

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.

Project Site: Farnsworth Unit

- 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	20-150 PSIA
Original Oil in Place (OOIP)	120 MMSTB (60 MMSTB west-side)
Drive Mechanism	Solution Gas
Primary Recovery	11.2 MMSTB (9.3%)
Secondary Recovery	25.6 MMSTB (21.3%)

Project Site: Farnsworth Unit

Anthropogenic CO_2 Supply:

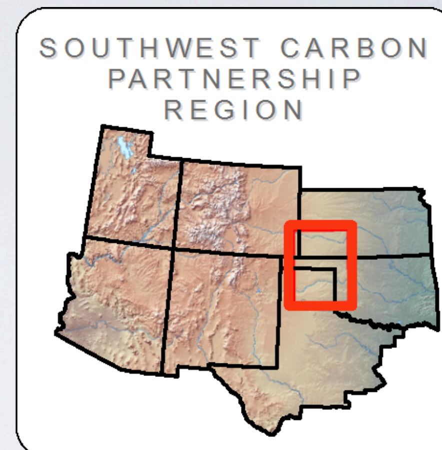
500-600,000 Metric tons CO_2/year for four fields

Legend

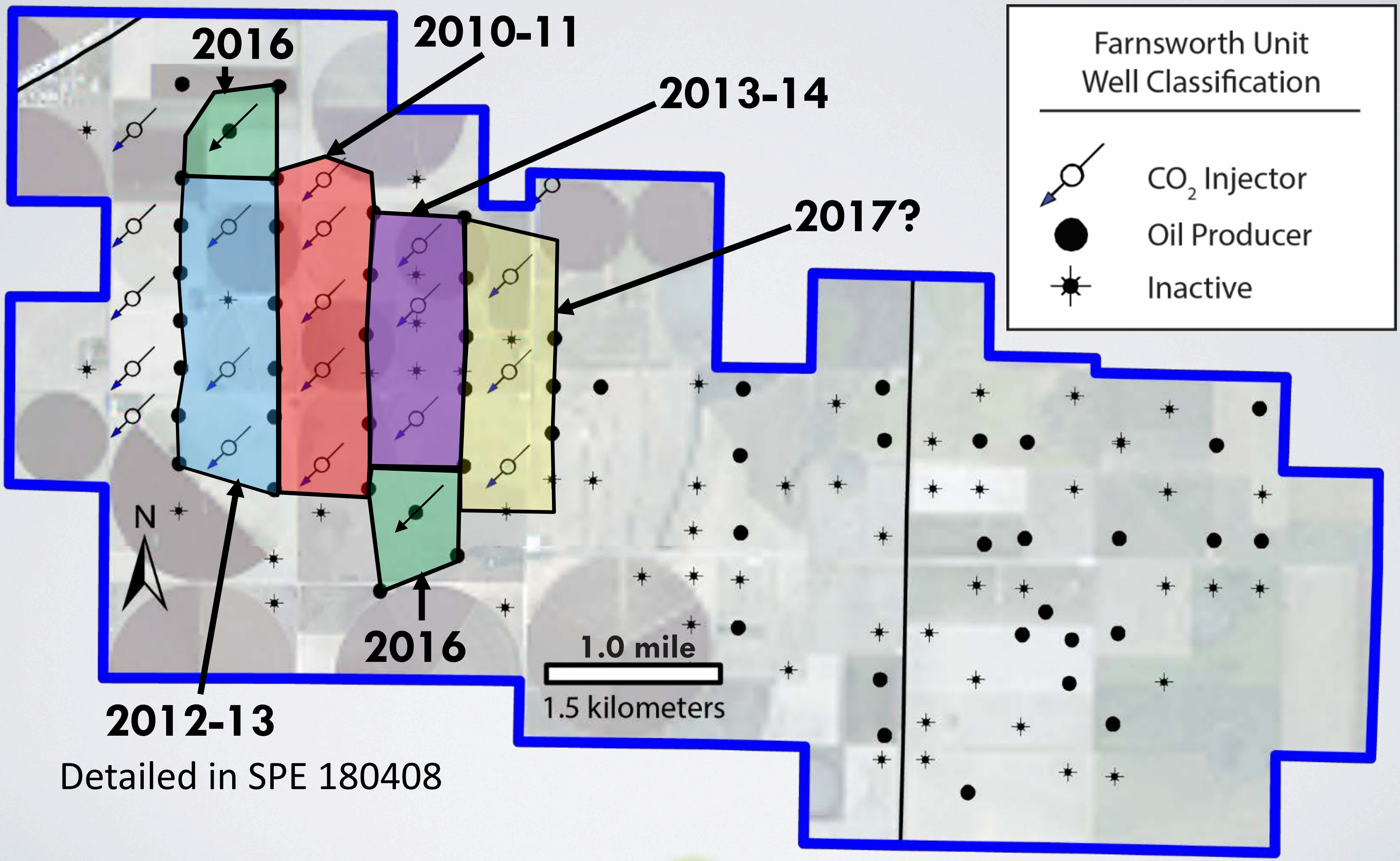
- Utiilization & Storage
- Carbon Capture
- Transportation
- Oil Fields

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



Active and Currently Planned CO_2 Patterns



Detailed in SPE 180408

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Characterization Accomplishments

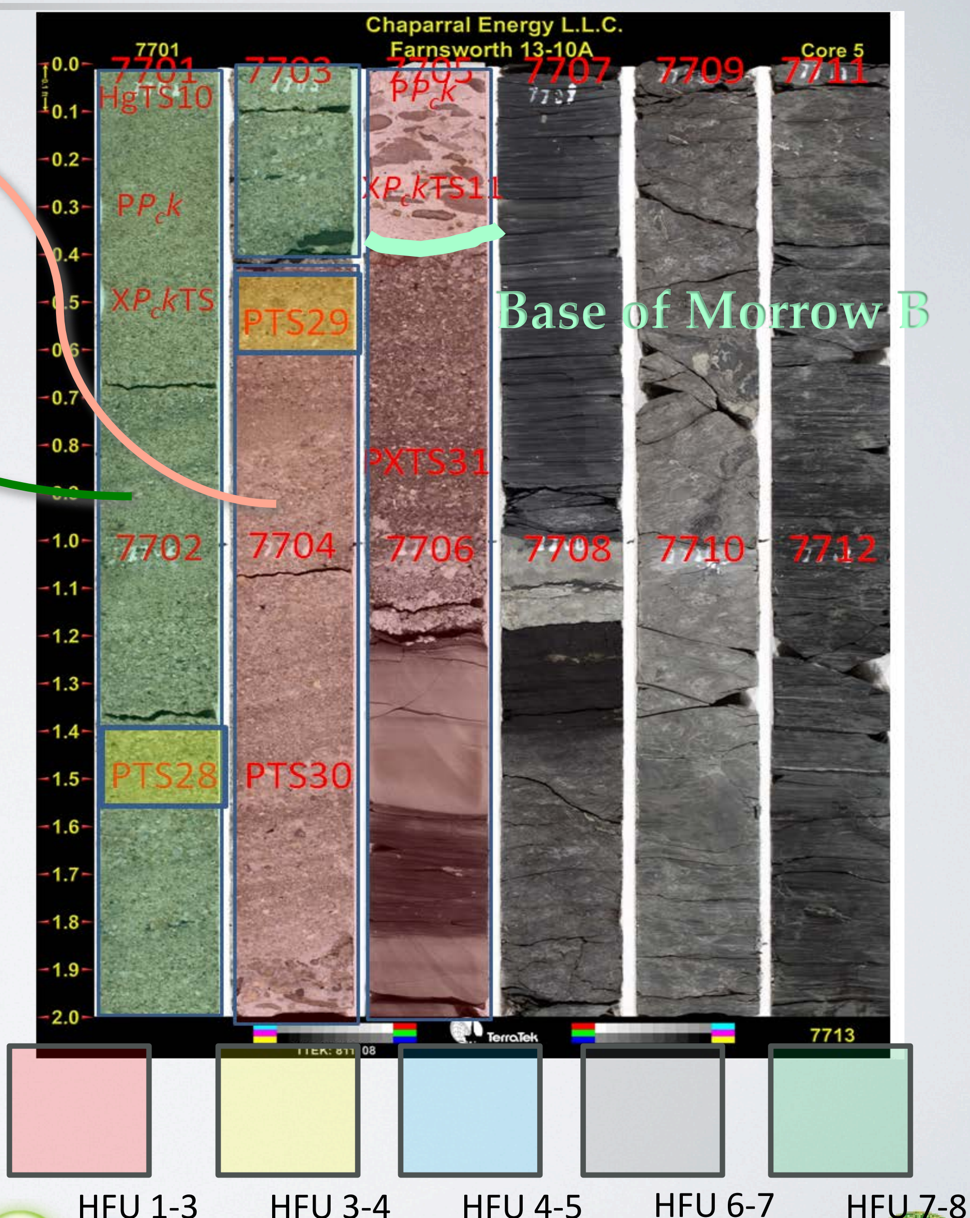
- Hydraulic flow units – can define units based on a refined version of Winland R35 method. These units can be distinguished at scales from microscopic to field scale. **Eight defined for Morrow B; HFUs have been incorporated into the simulation model.**
- **2D seismic lines tied to Booker Field provided insight into regional structure and suggest any potential regional CO_2 migration would be to northwest and risk of leakage appears low (many seals/ no faults to surface)**
- **Basin scale petroleum system modeling has shown that hydrocarbons are likely derived from Atokan black shales in the deeper basin**
- **Caprock integrity evaluated, with a thorough analysis of caprock from microscale through core scale**
- 2nd VSP seismic data shot Dec 2016, and processed spring 2017. **Time-lapse attributes such as NRMS (Normalized Root-Mean Square), Repeatability and Predictability were extracted for 1000 ft around the well 13-10A. From the aforementioned parameters, there is a clear anisotropy that runs NE-SW. This horizontal transverse anisotropy may indicate preferntial flow of CO_2 in this orientation.**

Example Characterization Result - Hydraulic flow units

HFU 1 associated with the lowest porosity and permeability values.

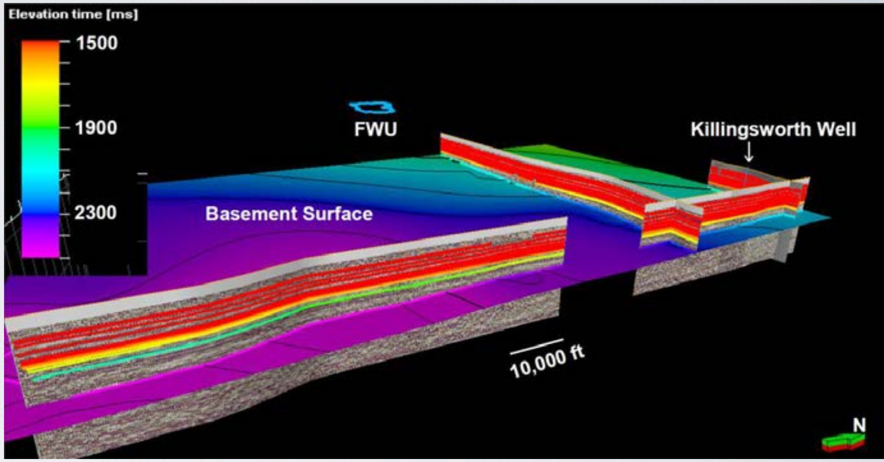
HFU 8 in green interval highlighted indicates the highest porosity and permeability values.

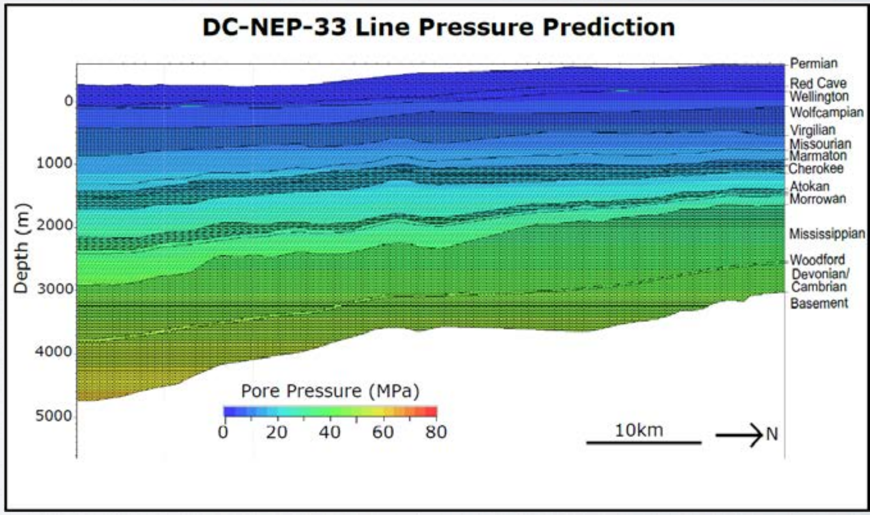
Ts, T – Thin Section
P – Routine Plug analysis
P_c - Capillary pressure



Example Characterization Result – Petroleum System Modeling

- 2D seismic structural interpretations show regional migration is NW to NE
- Migration risk to the surface is low due to a lack of regional scale faulting and lateral continuity of sealing stratigraphy
- Hydrocarbons at FWU migrated hundreds of millions of years ago from the deeper basin Thirteen Finger and upper Morrow Black Shales.
- FWU was discovered as an under pressured reservoir when it should be over pressured. This phenomenon is seen across Northwest Anadarko Basin reservoirs and is attributed to Laramide erosion and groundwater discharge.
- Seal bypass is an area of active research, but is unlikely





Characterization Working Group Goals

Remaining goals

- Complete fluid substitution modeling
- Complete and publish results of caprock integrity studies
- Complete and publish results of micro-scale pore studies

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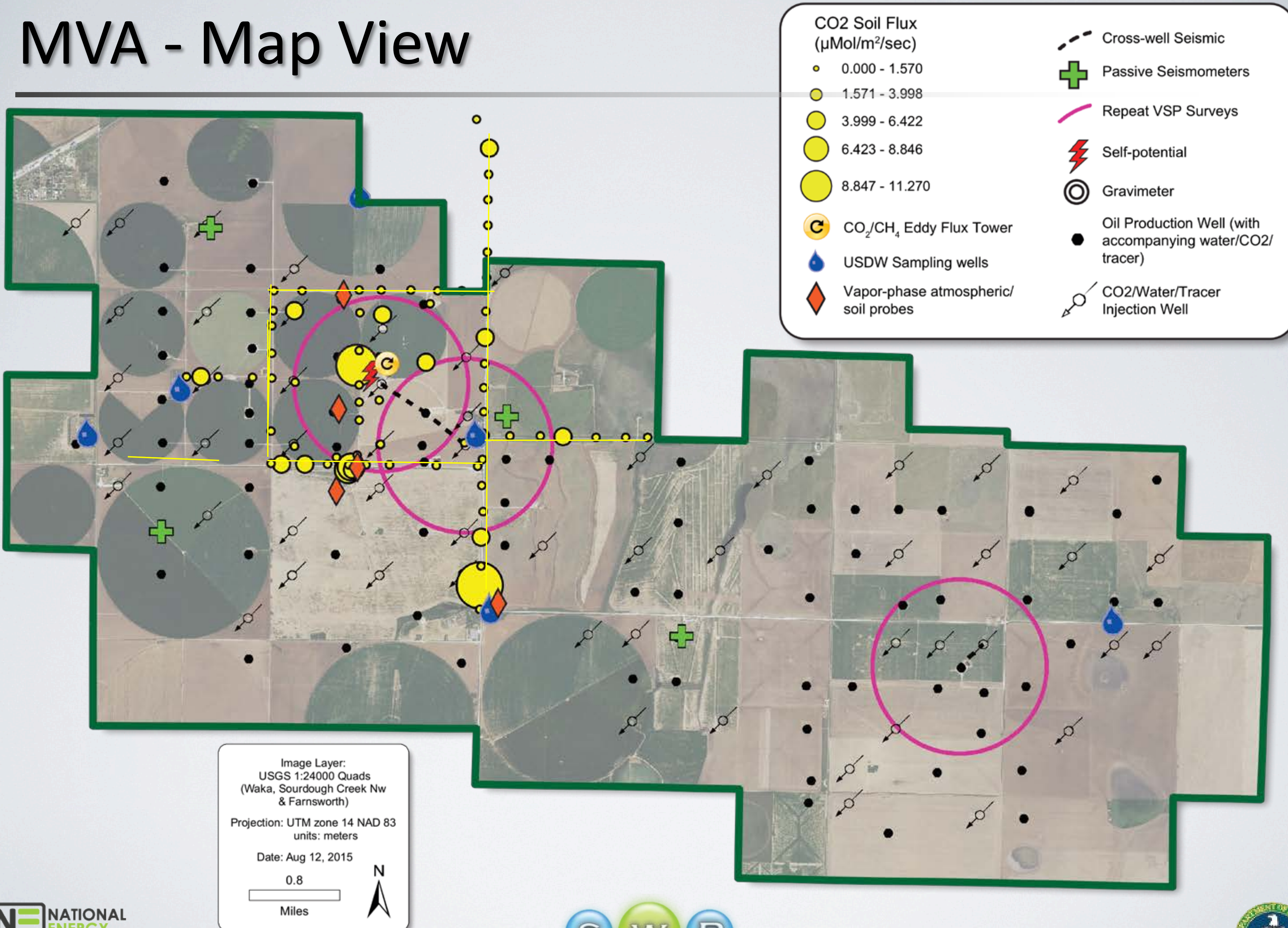
Monitoring (MVA) Working Group Goals

As a demonstration project a comprehensive monitoring strategy is in place:

- **Monitoring** – understand CO_2 plume movement over short and long time periods
    - ***Direct monitoring*** tests repeat air and water samples for seeps, leaks, and well-bore failures
    - ***Seismic MVA*** utilizes time lapse seismic data at a variety of scales to image the CO_2 plume over time
- **Verification** – assurance that CO_2 stays in target reservoir, doesn't make it back to atmosphere
- **Accounting** – Accurately measure amount of stored carbon including storage mechanisms

MVA - Map View



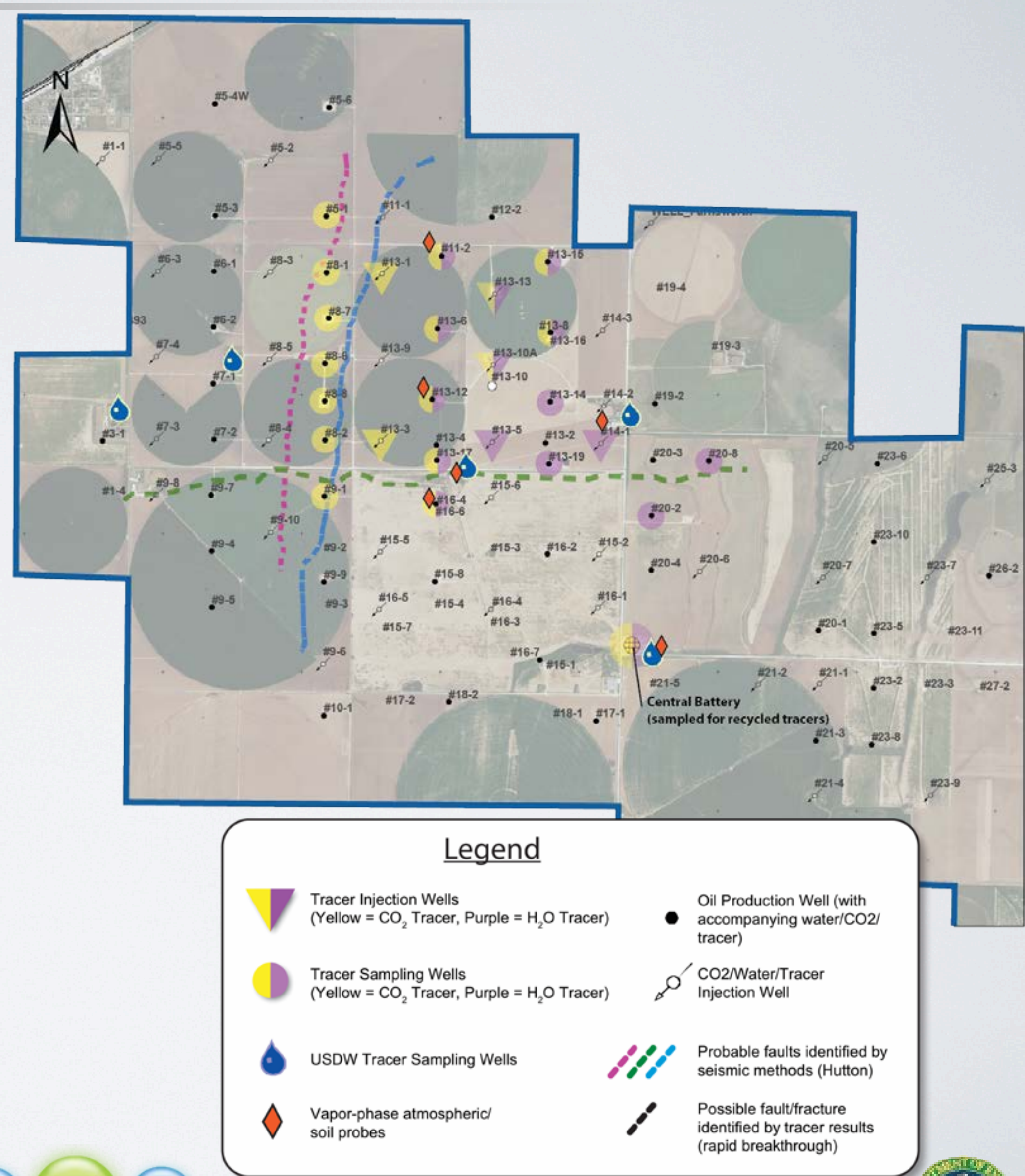
CO2 Soil Flux
(µMol/m²/sec)
0.000 - 1.570
1.571 - 3.998
3.999 - 6.422
6.423 - 8.846
8.847 - 11.270
CO2/CH4 Eddy Flux Tower
USDW Sampling wells
Vapor-phase atmospheric/ soil probes
Cross-well Seismic
Passive Seismometers
Repeat VSP Surveys
Self-potential
Gravimeter
Oil Production Well (with accompanying water/CO2/ tracer)
CO2/Water/Tracer Injection Well
Image Layer:
USGS 1:24000 Quads
(Waka, Sourdough Creek Nw & Farnsworth)
Projection: UTM zone 14 NAD 83
units: meters
Date: Aug 12, 2015
0.8
Miles
N

Example MVA Result – Tracer Studies

- Tracers (Aqueous- and Vapor-Phase)
  - Determine interwell connections, patterns and directions.
  - Identify heterogeneities including faults/fractures.
  - Fluid Velocities.
  - Constrain and calibrate flow models; predict the fate of the injected CO_2.
  - Detect and quantify CO_2/brine leakage to subsurface/atmosphere.
  - Attempt to determine oil/CO_2 saturation levels and CO_2 storage capacity.
  - Attempt to determine sweep efficiency (tracer concentration history).
  - Confirm other verification methods (e.g. time-lapse seismic).
  - Aqueous Phase: 8 unique naphthalene sulfonates; conservative tracers for injected water (Pete Rose – University of Utah).
  - Vapor Phase: 7 unique perfluorocarbons; conservative tracers that follow gas phase (Sean Sanguinito – NETL).

Example MVA Result – Tracer Studies

- Tracers (Aqueous- and Vapor-Phase)
  - Since 2014, six unique aqueous-phase tracer injections and four unique vapor-phase tracer injections.
  - Mixed results for both.
    - Tracer by-pass and stunted migration (e.g. aqueous-phase tracer by-passed by CO_2 flood).
    - Rapid breakthrough (e.g. vapor-phase tracer by-passing nearby producers, to appear several patterns away). Likely the result of mapped faults in area.
  - High detectability makes a good analog for brine/CO_2 leakage monitoring (no leaks detected).



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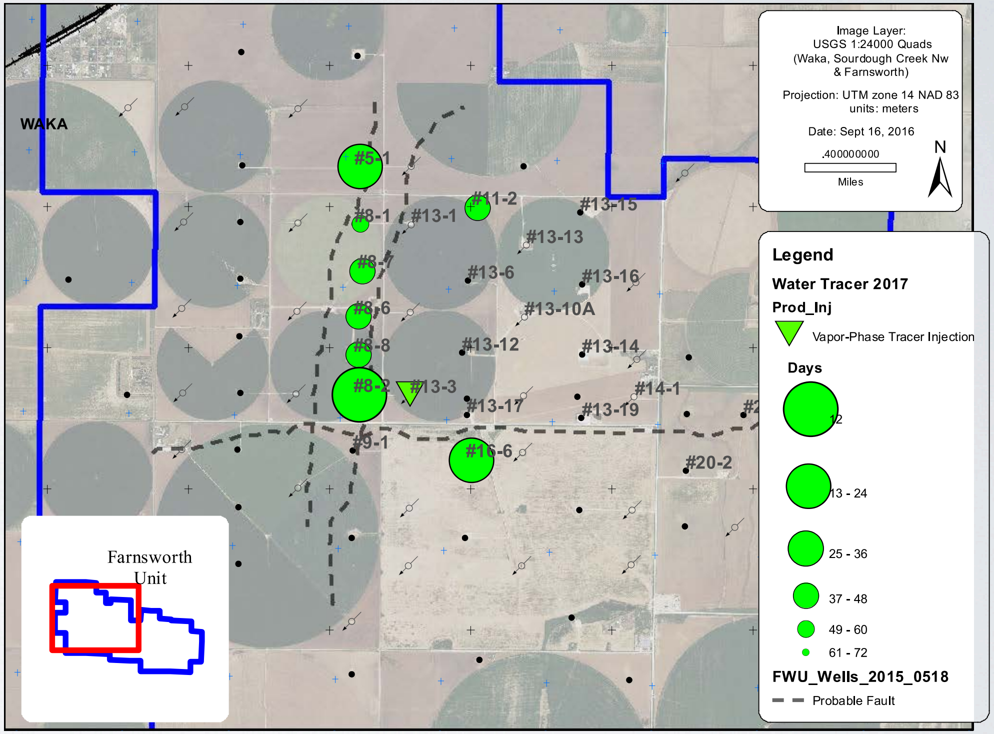

Initial tracer breakthrough (days). Larger circles mark faster breakthrough from injection (inverted triangle). Faults seem to influence breakthrough times.

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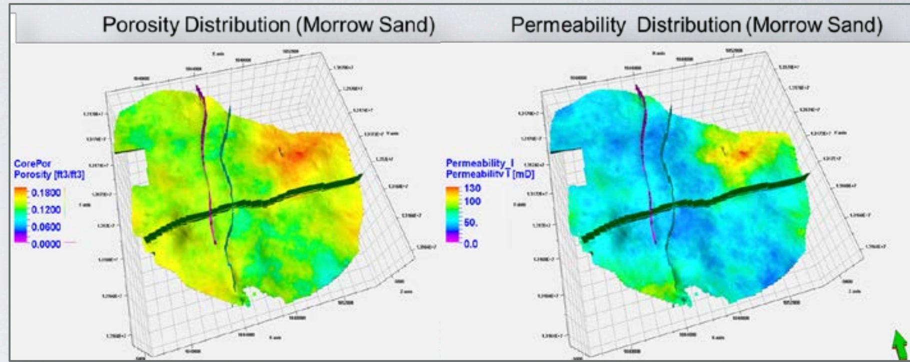
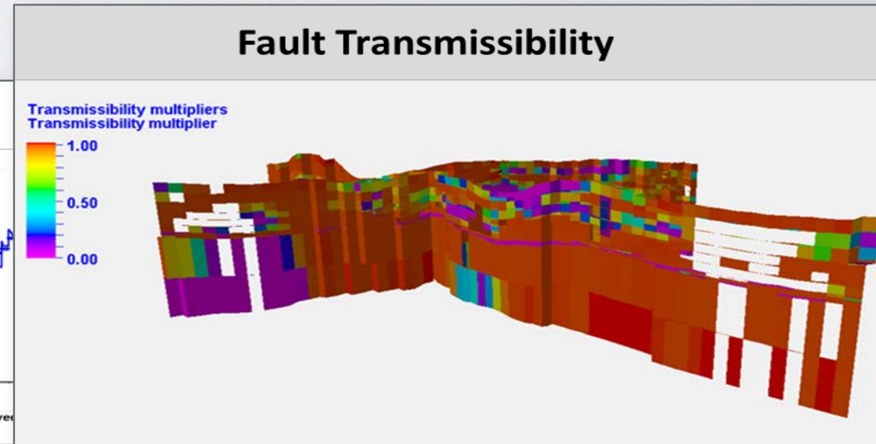
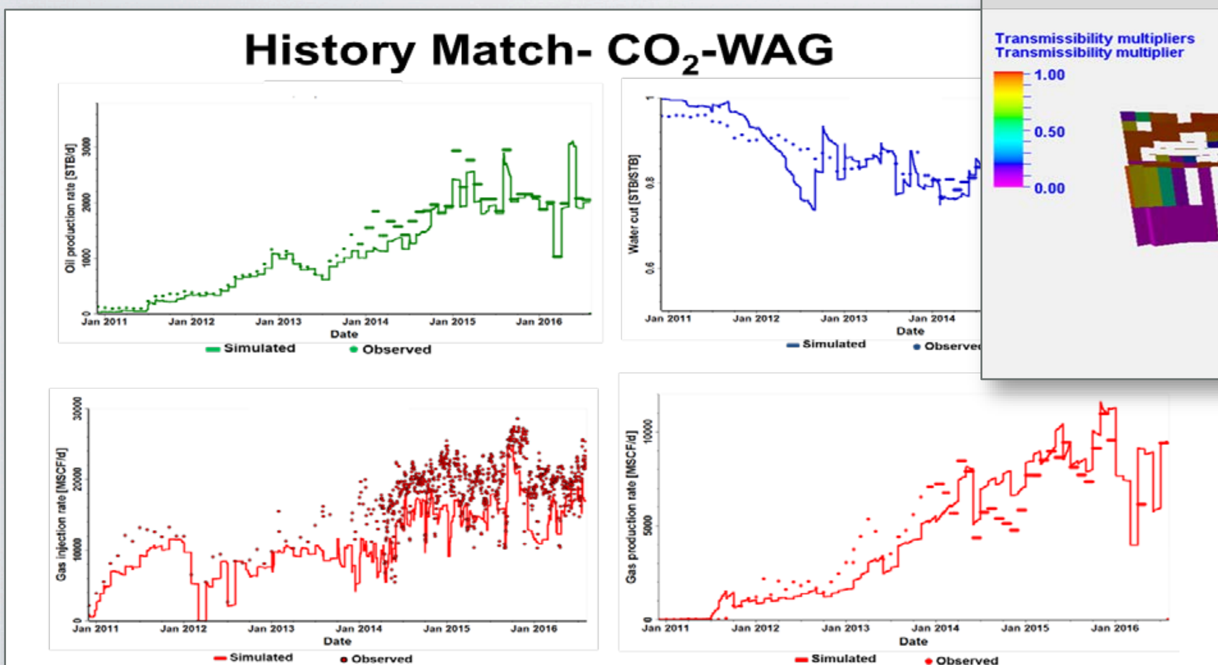
Simulation Working Group: Main Goals

- MVA Design
- Storage Forecasts
- Risk Assessment Basis
- Selection of on-going Simulation work
  - Porosity and Permeability distribution
  - Fault Permeability
  - History Matching
  - Production Forecasting







Simulation: Achievements

- Improved geological model with properties population based on eight distinct hydraulic flow units. **The current model has improved property distribution for caprock based on geomechanical and routine core analysis conducted by Characterization Working Group (esp NMT/SNL).**
- **Analysis of relative permeability and capillary pressure curves based on distinct hydraulic flow units to understand uncertainty associated with CO2 storage potential within Morrow B**
- Improved history matching efforts which encompasses the fault transmissibility modeling to better understand their effects on fluid flow within the Morrow B reservoir
- Pore-to log scale nuclear magnetic resonance log analysis, data processing, in house inversion and permeability calibration
- **Continuous improvement of history matching with tracer sampling results to increase our understand on potential CO2 migration paths and heterogeneity within Morrow B reservoir**
- Reactive transport simulations of water-CO2-rock interaction within Morrow B reservoir

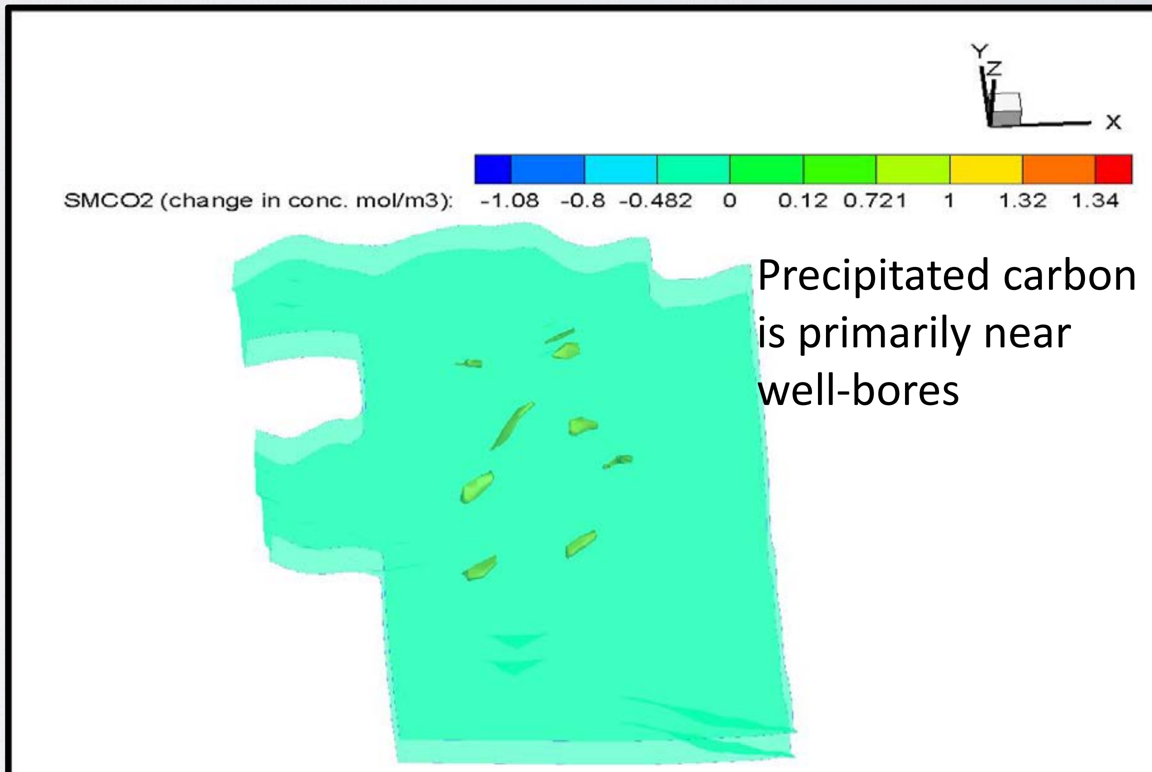
Simulation: Active Goals

- Simulation of production/storage history matching of primary, secondary, and tertiary recovery;
- Calibrated predictions of current and future carbon dioxide storage (capacity) in the reservoir (e.g., for Atlas updates);
- Interpretation of MVA tracer experiments;
- Newly-calibrated fully-coupled, full-scale simulations used to calibrate reduced order models for uncertainty quantification, risk assessment and storage optimization
- Continued forecasting of potential impacts (e.g., risk FEPs) via coupled thermal, geochemical and geomechanical processes

Simulation Result: Reactive Transport

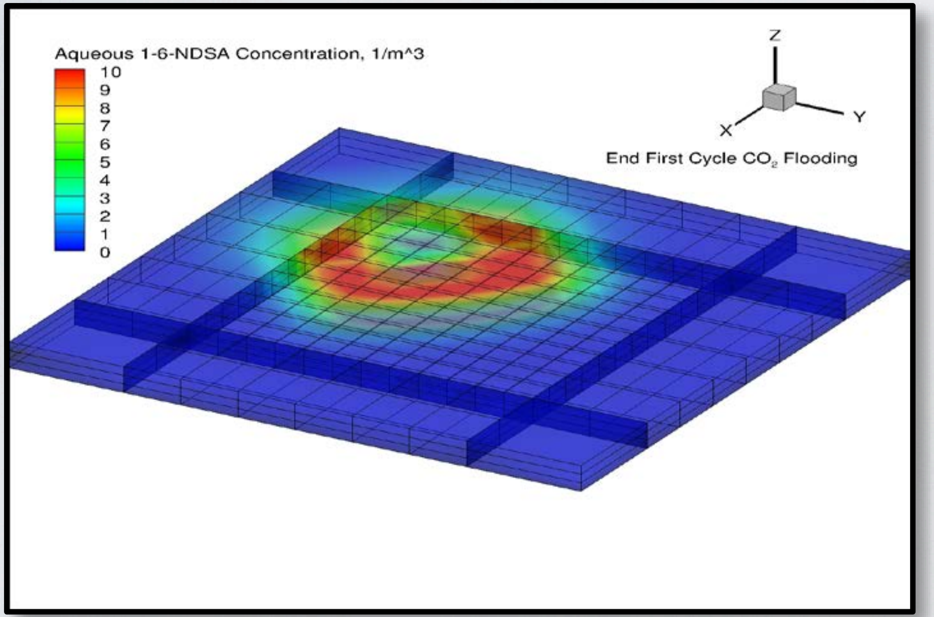
Reactive transport simulation of water-CO_2-mineral interactions in the Morrow B Sandstone in the Farnsworth Unit (TOUGHREACT and STOMP):

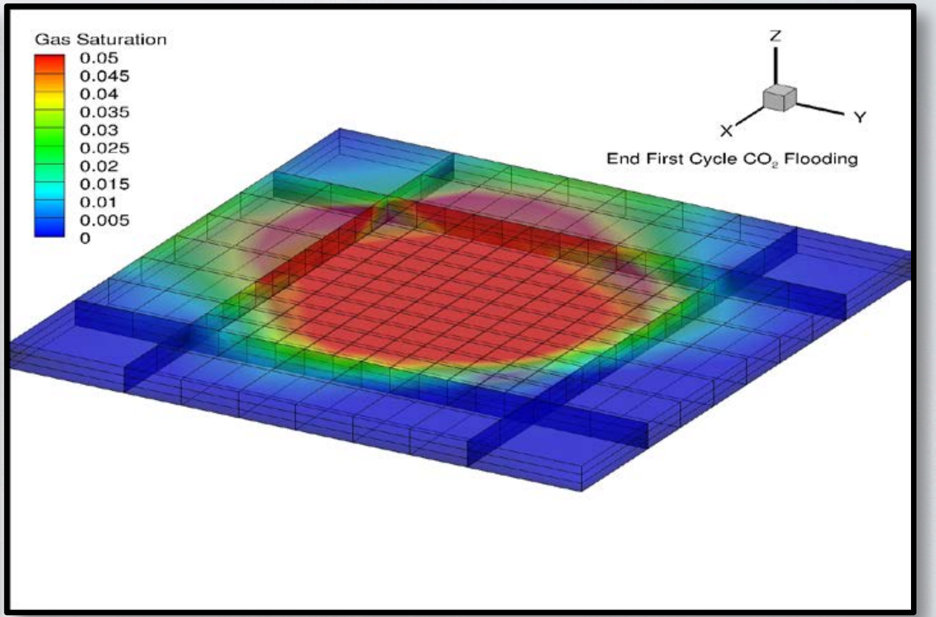
- Migration of CO_2 through the reservoir
- Partitioning of CO_2 between aqueous solution, an immiscible gas phase, and carbonate minerals
- Changes in formation water composition
- Mineral precipitation and dissolution
- Changes in reservoir hydraulic properties



Simulation Result: Reactive Transport

Simulation to interpret reactive and conservative tracers



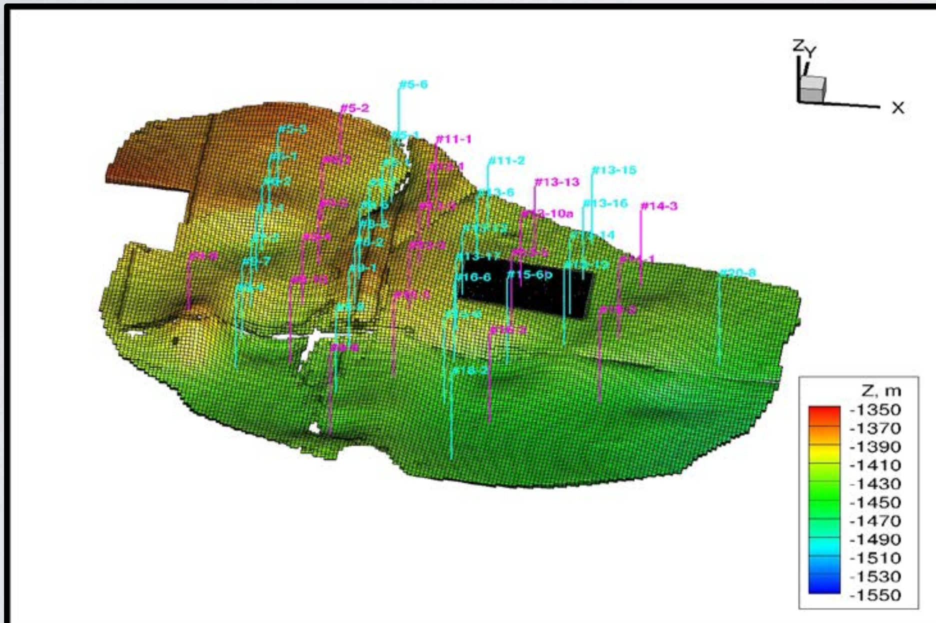


Normalized aqueous tracer concentration between first CO2-water flood transition.

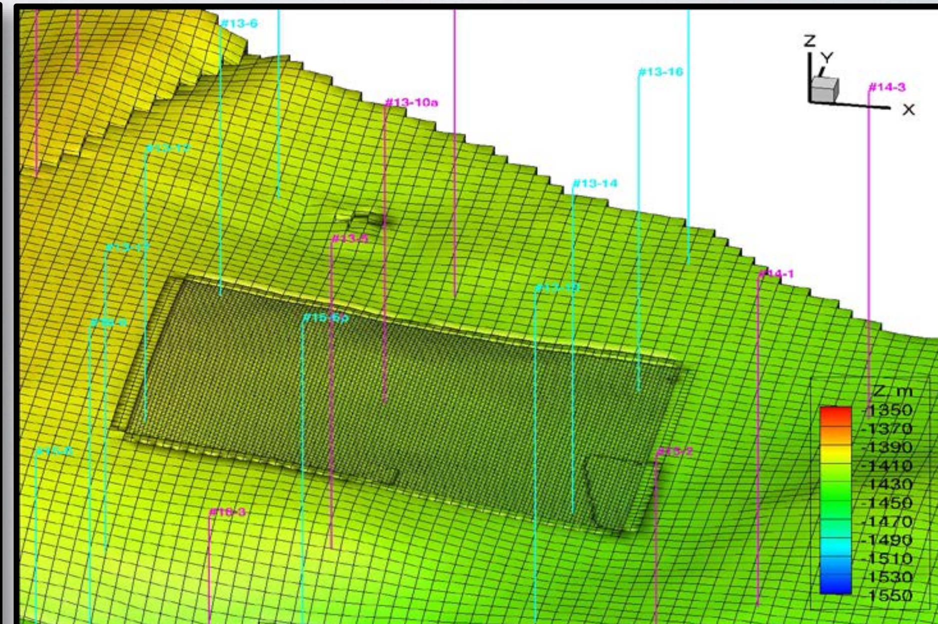
Gas saturation between first CO2-water flood transition.

Simulation Result: Reactive Transport

Simulation to interpret reactive and conservative tracers



2x refinement in x- and y-directions around #13-10a, #13-6, #13-12, #13-14, #13-16 for aqueous tracer experiment with injection



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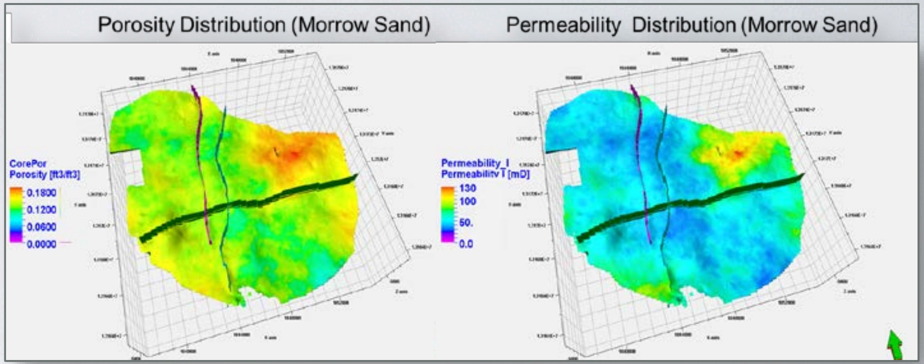

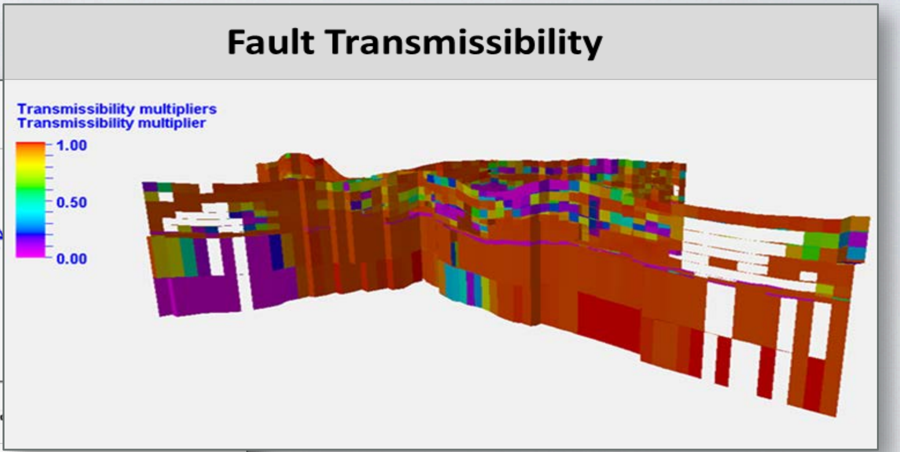

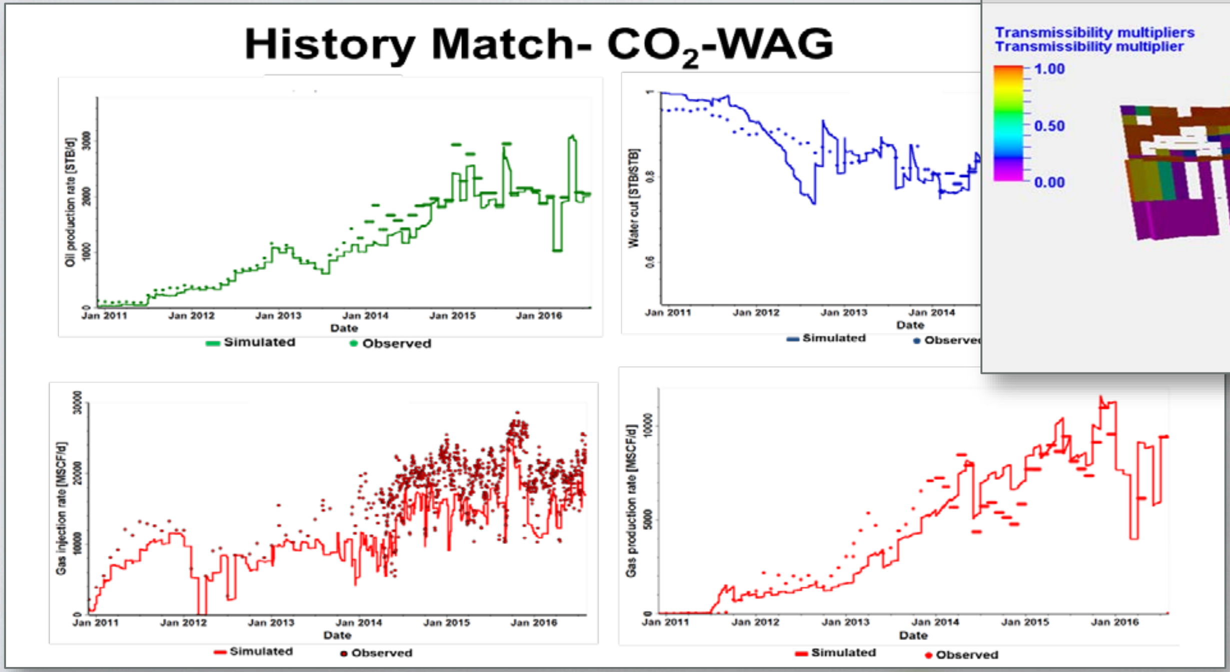

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Risk Working Group Goals

- Risk Management Planning
- Risk Identification (Risk Registry)
- Qualitative Risk Analysis
- Quantitative Risk Analysis
- Risk Response Planning
- Risk Monitoring and Control

Task 1

Overall risk management plan including

- Coordination with other working groups.

- Roles and responsibilities of each personnel

- Budget assignment

- Timing & frequency of risk assessment tasks

- New elements for the risk registry and its potential impacts

Task 2

- Identification of specific risk : features, events, and processes (FEPs)

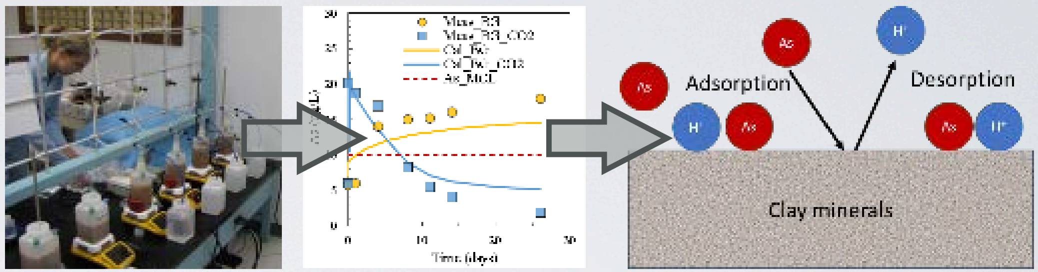
Risk Result - Risk Source Assessment (Task 2)

- Identification of specific risk : features, events, and processes (FEPs)
- 2014
  - Web-based online workshop (Jan. 13 and 16, 2014)
  - Total 405 FEPs identified
  - 23 project experts evaluated 79 initial FEPs, and generated & evaluated 24 new FEPs
- 2015
  - Email survey during (May ~ August 2015)
  - 15 project experts evaluated top 50 FEPs of 2014
- 2016
  - Web-based online risk workshop on Sep. 1, 2016
  - 15 project experts and 5 students participated to re-rank 69 FEPs (2 new in 2016, 46 from 2015, and 21 from 2014 black swans)
  - Likelihood for avg. S_{bg} was collected separately via email survey (September 2016)
  - Expertise of individual participants was identified in 7 FEP groups and used for ranking and analysis

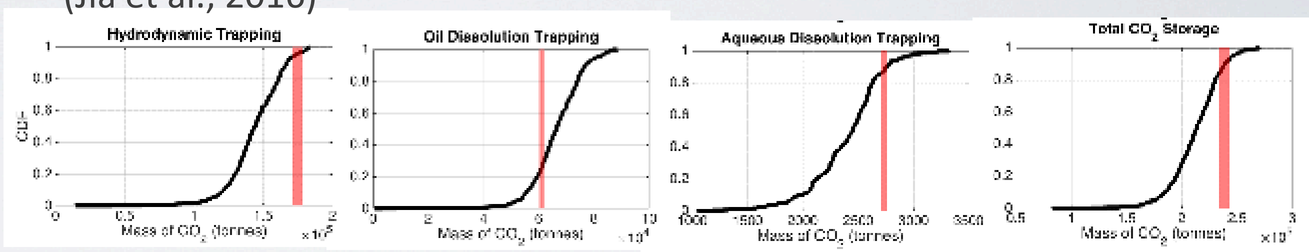
Risk Result – Qualitative Analysis (Task 3)

- Provide quantitative information on the risk
- Explicit treatment of uncertainties
- Perform probabilistic assessment due to the uncertainty
- Response Surface Method combined with Monte Carlo samplings
- Polynomial Chaos Expansion (PCE)

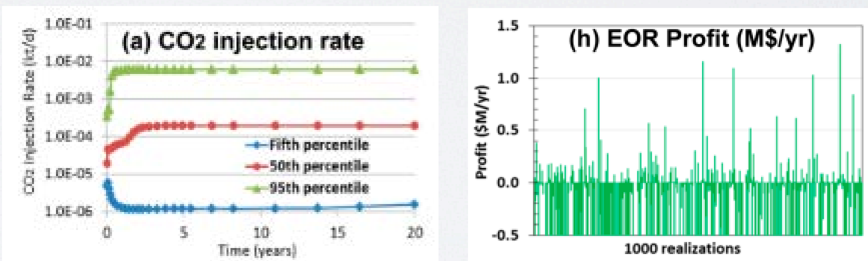
Arsenic Mobilization due to CO_2 Leakage (Xiao et al., 2017)



Uncertainty Analysis of Trapping Mechanism at FWU using ROMs (Jia et al., 2016)



Risk Analysis and Response-surface-based Economic Model



(Dai et al., 2016)

Xiao et al. (2017), Arsenic mobilization in shallow aquifers due to CO2 and brine intrusion from storage reservoirs. Sci. Rep. DOI:10.1038/s41598-017-02849-z

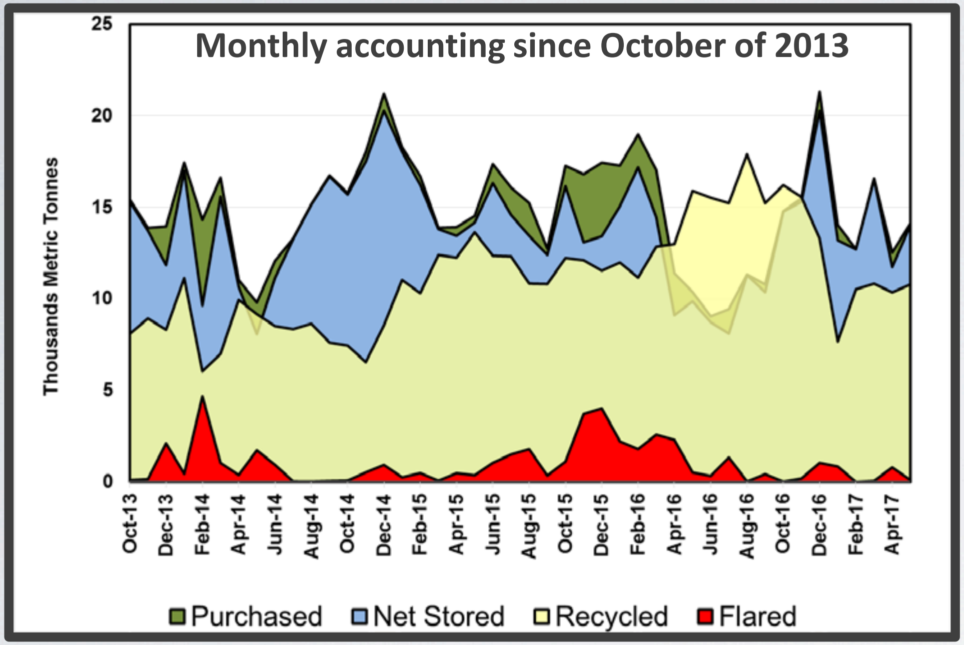
Jia et al. (2016), Probabilistic Risk Assessment of CO2 Trapping Mechanisms in a Sandstone CO2-EOR Field in Northern Texas, USA. GHGT-13. 2016 November 14-18, Lausanne, Switzerland

Dai et al. (2016), CO2 Accounting and Risk Analysis for CO2 Sequestration at Enhanced Oil Recovery Sites. ES&T

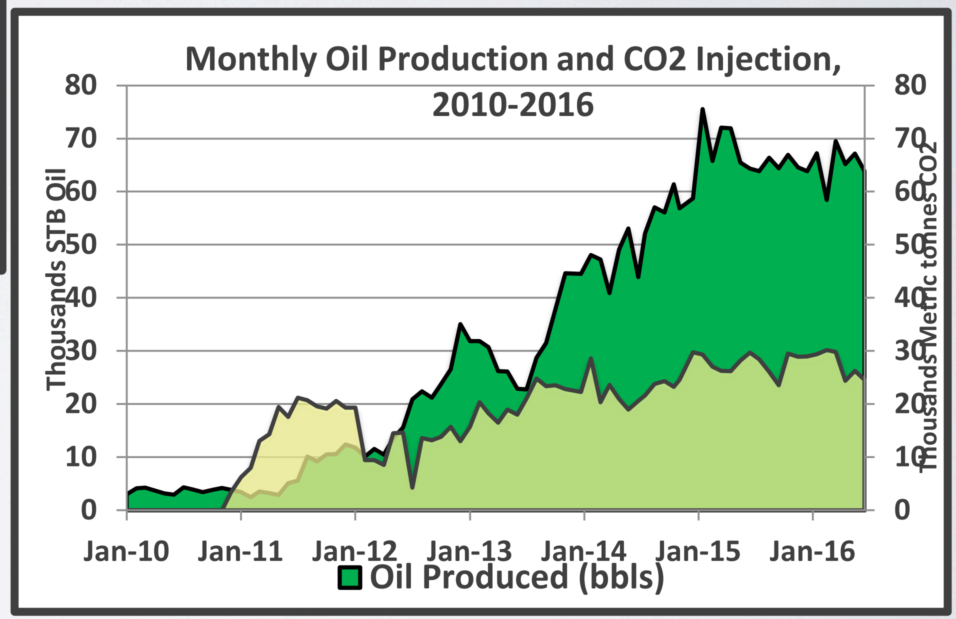
Risk Assessment: Accomplishments

- Annual Risk Identification (2014, 2015, 2016)
  - 2014: Identified total 405 FEPs
  - 2015: Evaluated top 50 FEPs
  - **2016: Re-ranked FEPs, evaluated likelihood for avg. S_{bg} (best guess severity)**
- Qualitative Risk Analysis
  - Updated the risk registry and identify interactions between FEPS
  - Identified the risk factors for the quantitative risk analysis
  - Constructed the process influence diagram for quantitative risk analysis
- Quantitative Risk Analysis
  - **Arsenic mobilization due to CO2 leakage**
  - **Uncertainty analysis of trapping mechanism at FWU using reduced order models**
  - **Risk analysis and response-surface-based economic model**

Conclusions and Ongoing Work



- 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



- 620,000 tonnes stored since October 2013
- 1,050,000 tonnes stored since November 2010
- **92.2% of purchased CO_2 still in the system**

Conclusions and Ongoing Work

- 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);
- New risk registry and quantitative assessment of PDFs and CDFs for top FEPs;
- 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***

Characterization Working Group

Milestones

Remaining Milestones:

Two remaining geomodel updates to include

- ❖ refined characterization of faults from tracer studies and associated simulations
- ❖ Correlation of geologic facies to acoustic impedance inversion results of the baseline 3D surface seismic survey
- ❖ Results from fluid-rock interaction data from lab studies at NMT and Sandia

Characterization

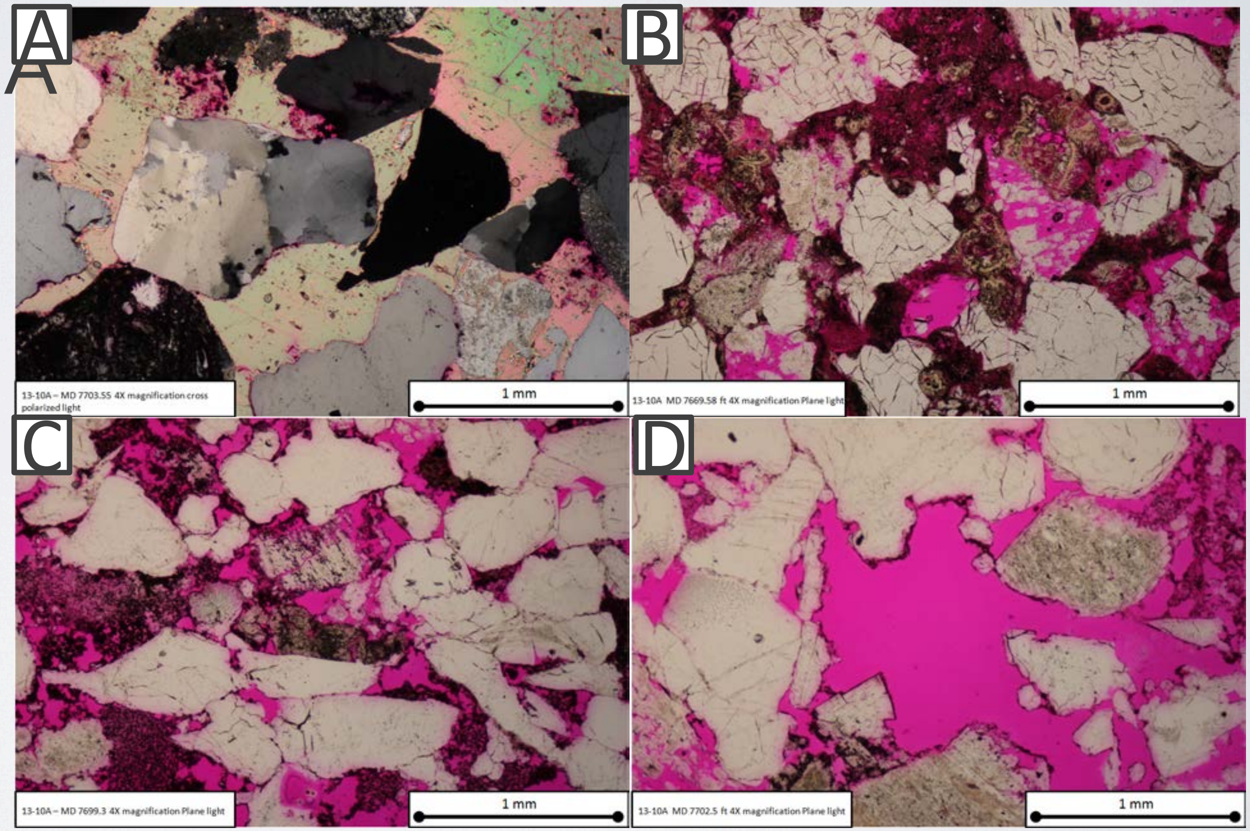
Geologic controls on Hydraulic Flow Units

[A] HU1
Porosity occluded by calcite cement

[B] HU3
Intra-granular porosity dominant, lacks interconnected pore networks

[C] HU5
Lack of inter grain cementation enables better flow paths

[D] HU8
abundant macroposity creates great flow paths

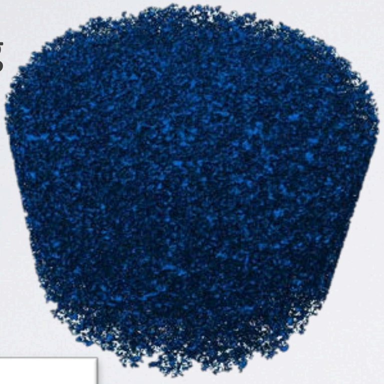


Characterization – Hydraulic Flow Units

HFU 8 – best single phase Φ, K

- Porosity spaces are fairly unimodal in size and moderately well-sorted
- Pore networks are fairly well connected.

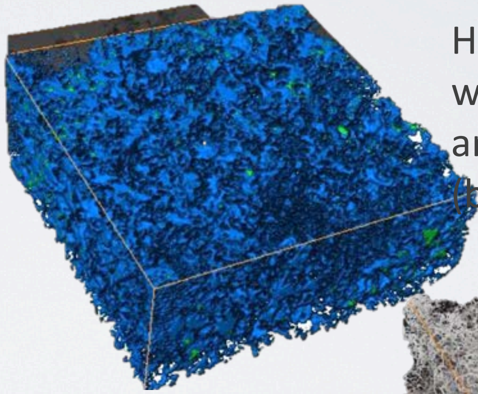
HFU 8 rendering from micro-CT scan



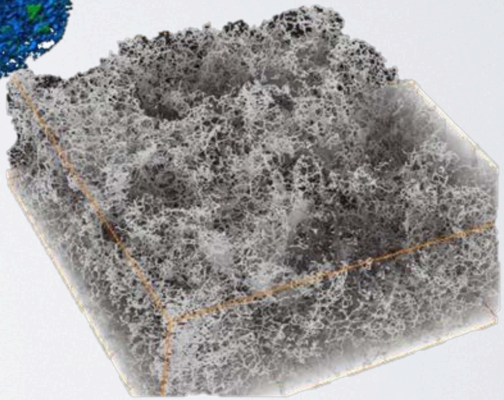
Skeletonized pore network – lines are through medial axis of pores.

HFU 1 – lowest single phase Φ, K

- Porosity spaces are generally bimodal, with some large pores and much clay-filled microporosity
- Pore networks are poorly connected



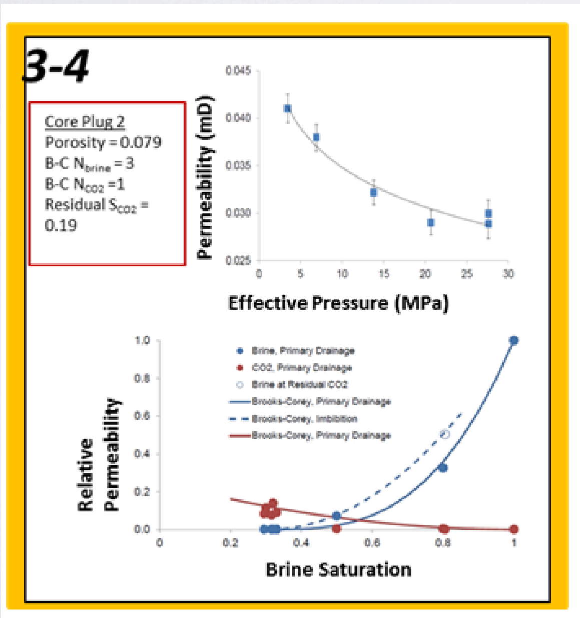
HFU 1 volume rendering, with macropores (green) and clay-filled pores (blue)

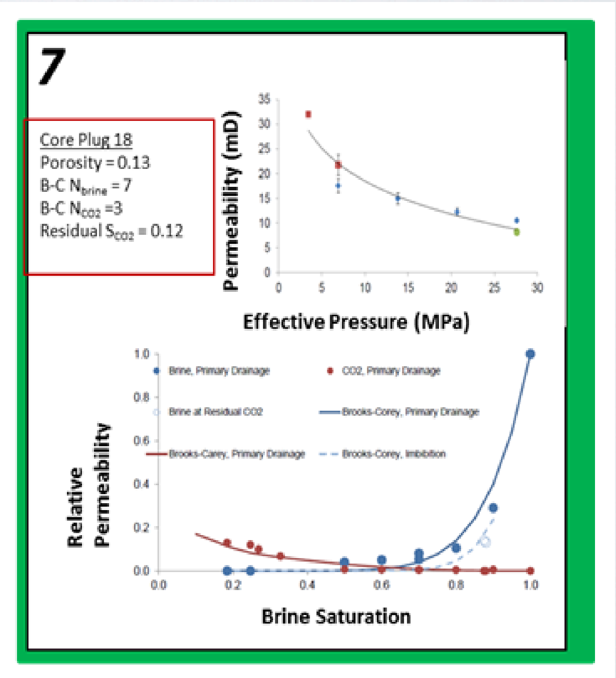


Pore image skeletonized along medial axes showing macropores and clay-filled micropores

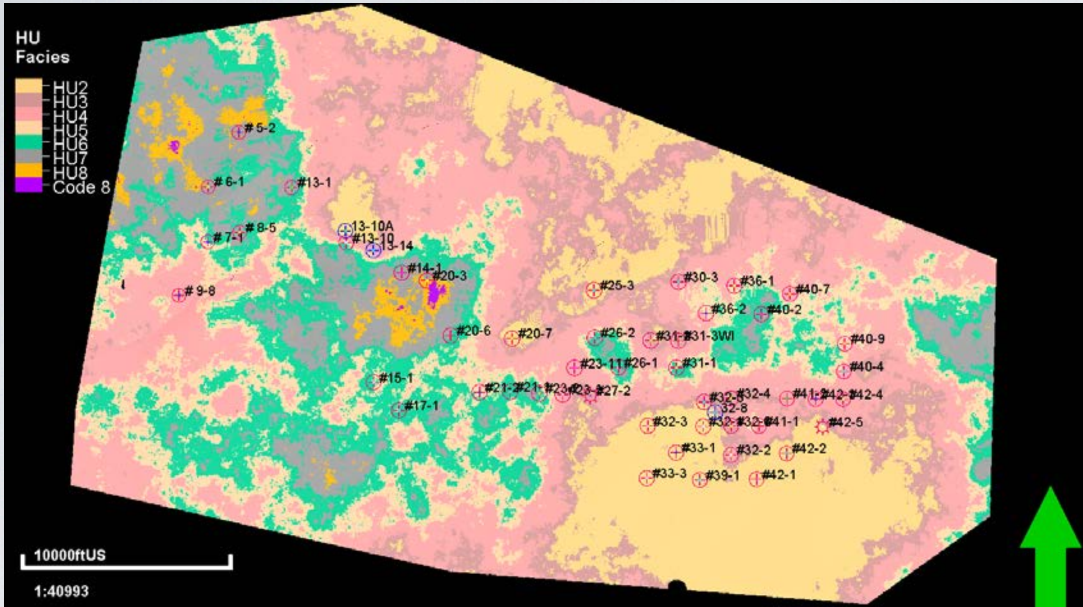
Characterization – HFUs ➔Relative permeability

- Low apparent endpoint perm for the lower HFUs is likely due to change in capillary number. Viscous forces dominate under experimental conditions for higher HFUs; capillary forces for lower
- Higher degrees of heterogeneity lead to higher amounts of residual trapped $scCO_2$. Residual CO_2 amounts range in saturation values from 10-15% in the tested HFUs
- HFUs exhibit mixed-wettability and lower value HFUs contain most of the residual oil. Higher HFUs represent fast paths that may thwart efforts at broad sweep efficiency of EOR

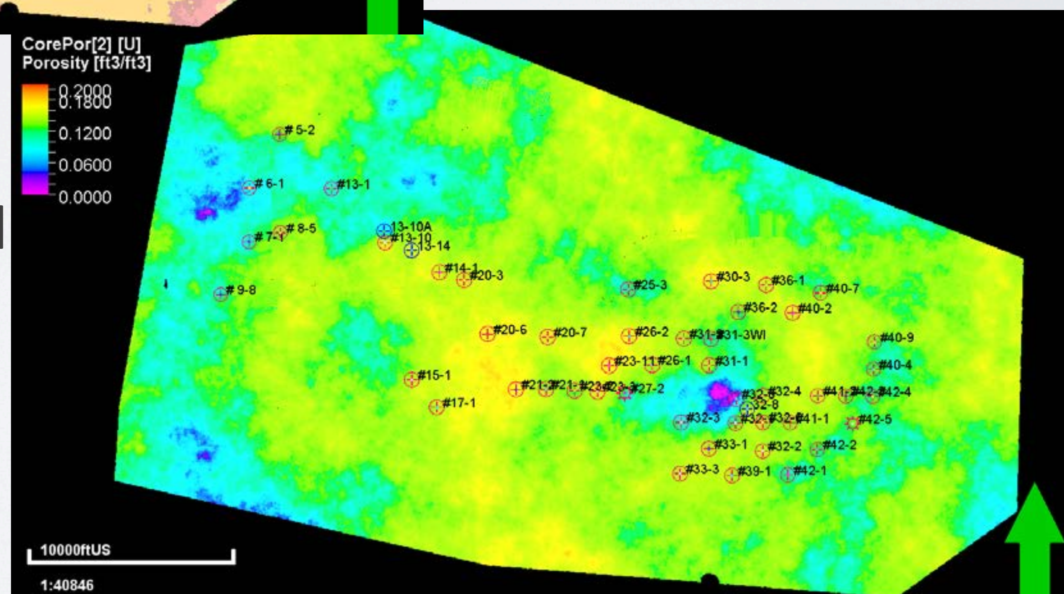




Characterization – Reservoir Modeling



Upper surface of the Morrow B zone showing distribution of hydraulic flow units binned using R35 values



Up-scaled porosity values extrapolated and modeled as a function of hydraulic flow units

Characterization – Fluid-Rock Interactions

Relative permeability experiments

Conducting experiments on cores from the eight different hydraulic flow units of the Morrow B Formation using brine-CO_2, oil-brine, and oil-CO_2 fluid pairs Sandia National Laboratories is using synthetic fluids, and New Mexico Tech is using formation fluids = 71°C, 4200-4800 psi pore fluid pressure, ~7500 psi confinement pressure

Fluid-rock experiments

Flow-through experiments at New Mexico Tech – CO_2-rich brine injected into Morrow B Formation cores with different carbonate cement compositions at 71°C, 4200 psi pore fluid pressure, and 5000 psi confinement pressure Mechanical tests (ultrasonic and Brazilian tests) at Sandia National Laboratories are used to identify impact of fluid-rock interaction on core mechanical properties

Simulation: Design, Forecasts, Risk

- Simulation of production/storage history matching of primary, secondary, and tertiary recovery provides some calibration
- Calibrated simulation used for predictions of future and CO_2 storage in the reservoir;
- Uncertainty estimates are critical for forecast context and risk assessment; relative permeability is paramount
- Forecasting potential impacts (risk FEPs) via coupled thermal, geochemical and geomechanical processes;
- Fully-coupled, full-scale simulations used to calibrate reduced order models for uncertainty quantification, risk assessment and optimization for ongoing forecasts.

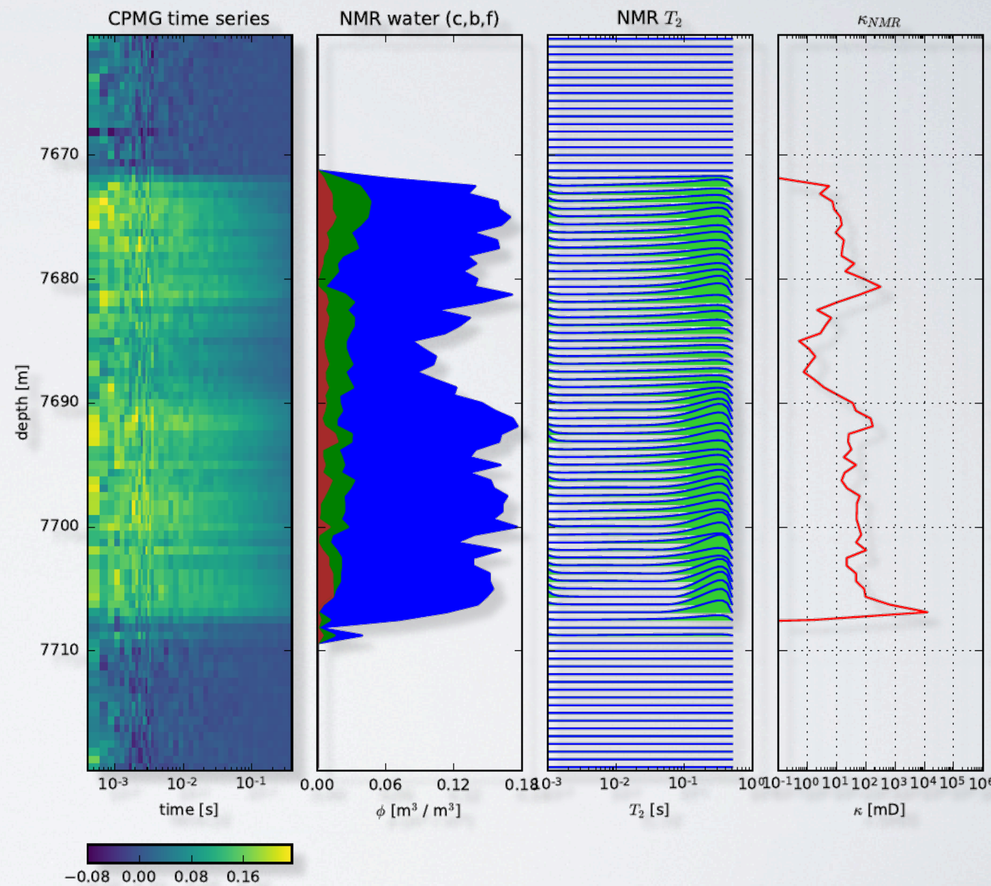
Focus Area: Relative Permeability

- CMR inversion
  - Data processing
  - Bootstrapped error metric
  - Adaptive noise T_2 inversion

- CMR interpretation
  - Calibration for permeability
  - Pore-scale modelling using µCT
  - Multi-phase interpretation tool

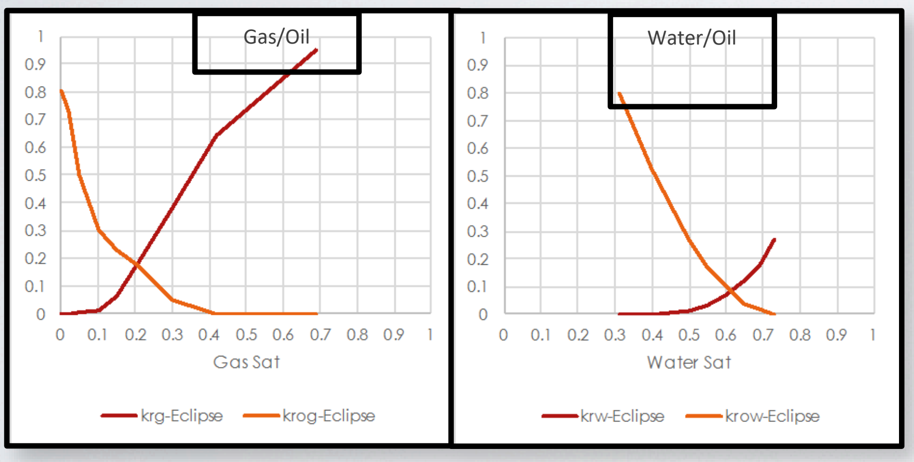
- Relative permeability
  - Stress-dependent in triaxial instrument
  - Small plugs →small fluid volume
  - Effluent analysis using benchtop NMR

CMR log analysis

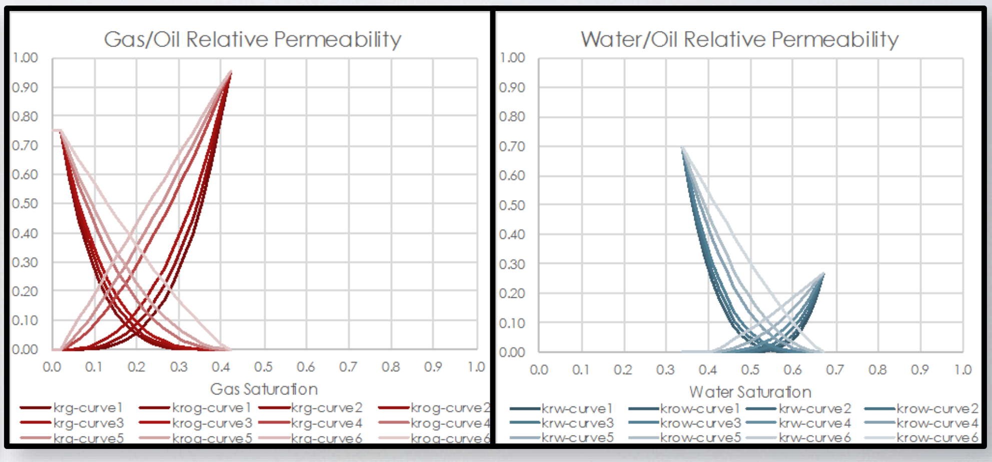


Focus Area: Relative Permeability

Uncertainty Estimation: Impact of choice of three-phase relative permeability model on storage forecasts



Morrow Sandstone relative permeability curve from the Unocal 1988 reservoir simulation study.



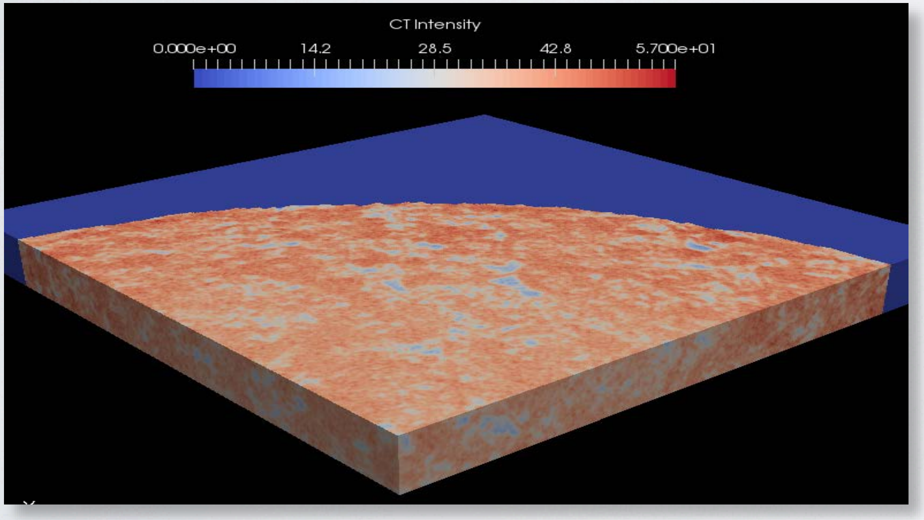
Six targeted synthetic relative permeability curves each assigned to hydraulic flow units

Focus Area: Relative Permeability

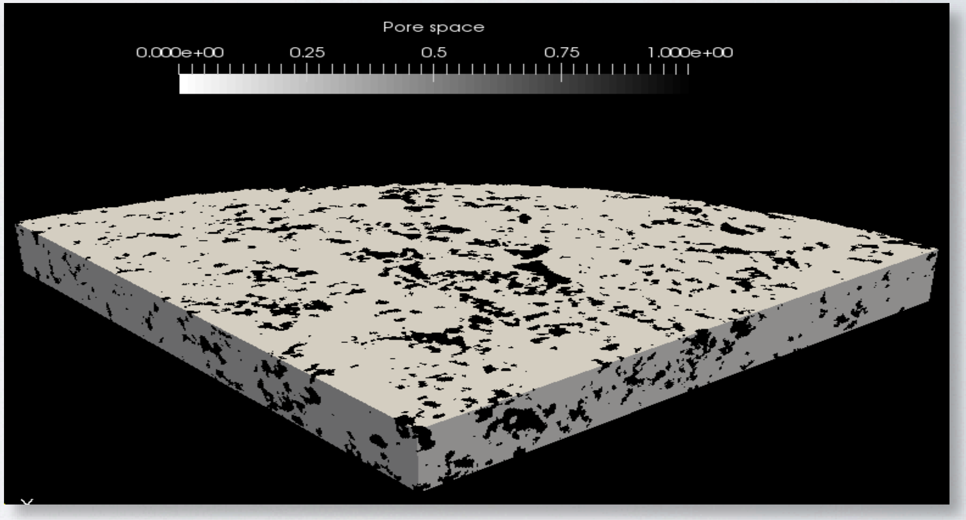
Example Result: Synthetic Relative Permeability Models

Pore-scale modeling
- Relative permeability information
- Inputs for reservoir simulation
- Compliment laboratory studies
- Flexible for statistical analysis

Micro CT imaging as input
- Extract pore matrix
- Cost-effective
- Multi-thresholding for pore matrix
- Alternative to network approximation



Raw CT image



Pore matrix threshold

Simulation: Design, Forecasts, Risk

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- Fully-coupled, full-scale simulations used to calibrate reduced order models for uncertainty quantification, risk assessment and optimization for ongoing forecasts.

Example Risk Identification - Risk Source Assessment (Task 2)

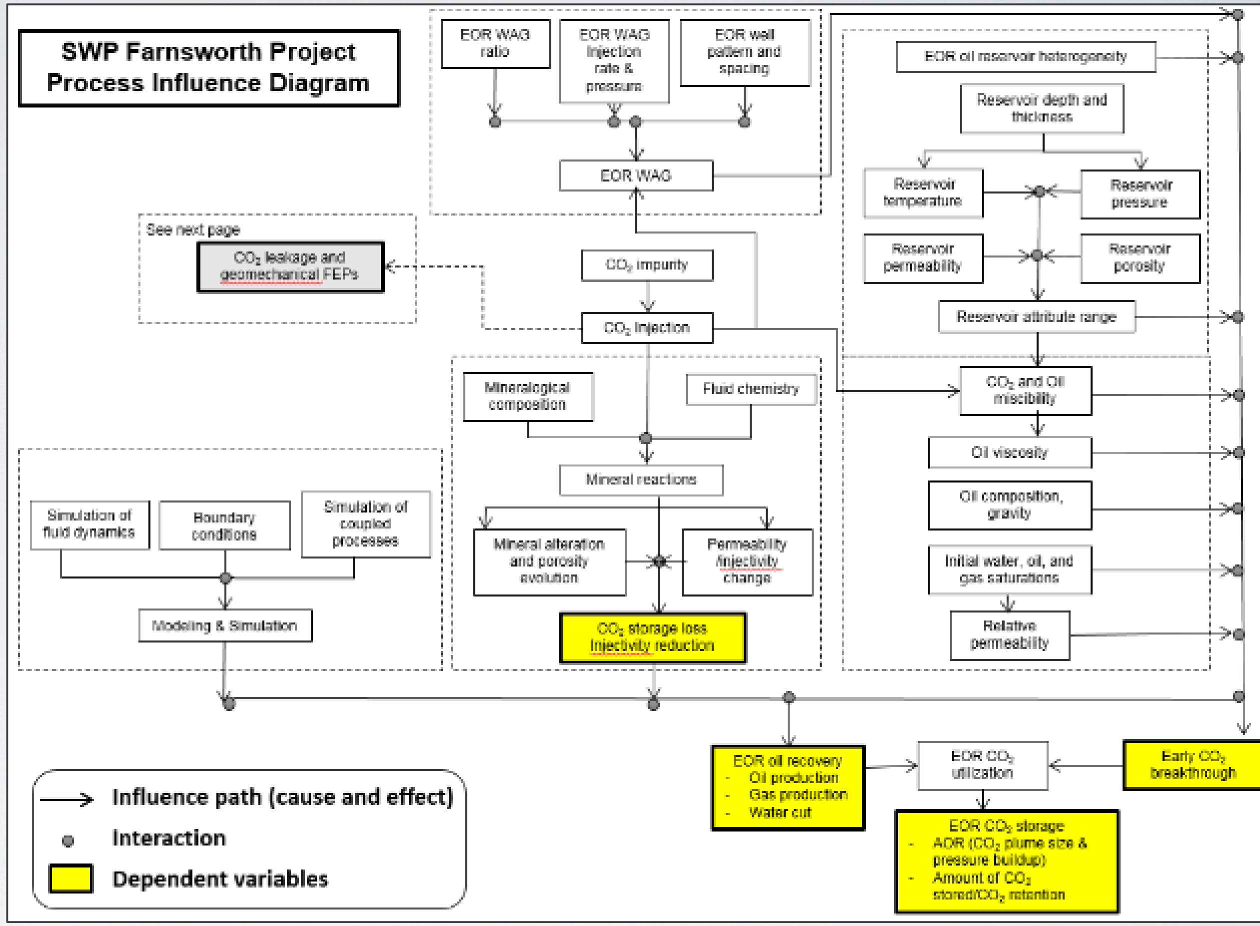
Risk Rankings 2014, 2015, and 2016

FEP No.	FEP	Rank 2016 3wt	Rank 2015 3xWt	Rank 2014 wKSY2b
F22	Price of oil (or other related commodities)	1	1	6
F63	CO2 legislation	2	18	29
F66	Accidents and unplanned events	3	8	18
F19	CO2 supply adequacy	4	7	2
F24	Operating and maintenance costs	5	3	7
F38	Simulation of fluid dynamics	6	17	15
F23	EOR oil recovery	7	2	37
F34	EOR injection and production well pattern and spacing	8	4	45
F46	Blowouts	9	26	8
F41	Severe weather	10	#N/A	84
F12	EOR oil reservoir heterogeneity	11	11	19
F43	Ignition of flammable gases or liquids	12	#N/A	72
F01	Caprock lateral extent and continuity	13	#N/A	80
F18	Data acquisition conflicts	14	#N/A	51
F10	Reservoir exploitation	15	#N/A	97
F65	On-road driving	16	28	35
F20	Competing project objectives	17	42	46
F35	EOR early CO2 breakthrough	18	5	25
F64	Release of compressed gases or liquids	19	13	3
F47	Operator error in pipeline operation	20	49	31
F44	Seal failure	21	14	22
F37	Simulation of coupled processes	22	19	5
F40	Modeling and simulation - parameters	23	36	1
F53	Defective equipment	24	16	48
F36	Simulation of geomechanics	25	6	9
F48	Injection well components	26	41	33
F49	CO2 containing H2S	27	21	13
F61	Leaks and spills (related to oil and chemicals other than CO2)	28	23	44
F13	Reservoir heterogeneity	29	15	16
F31	Fault valving and reactivation	30	#N/A	57
F26	Execution strategy	31	9	21
F54	Well lining and completion	32	31	38
F29	Competition	33	12	49
F05	Fractures and faults (CO2 leakage through new or existing fractures or faults)	34	#N/A	90
F04	Seismicity (natural earthquakes)	35	#N/A	101
F14	Geomechanical characterization	36	32	4
F28	Operator training	37	#N/A	62
F59	Permit modifications	38	24	40
F16	Seismic method	39	25	12

- Triple-weighted expert ranking
- Most FEPs have maintained roughly consistent positions in multiple years.
- Top ranked FEPs are mostly programmatic/non-technical risks related to project management, permitting/safety, and site.
- Re-included FEPs (unlikely but high severity) from 2014 survey.
  - ✓ Some of them shows high risk in 2016 (#10, #12 ~15)
  - ✓ Project operations, progress, and experience over time

Example Risk Result – Qualitative Risk Analysis (Task 3)

- Risk Management Planning
- Risk Identification (Risk Registry)
- Qualitative Risk Analysis
- Quantitative Risk Analysis
- Risk Response Planning
- Risk Monitoring and Control



- Update the risk registry and identify interactions between FEPS
- Identify the risk factors for the quantitative risk analysis
- Construct the process influence diagram (PID) used to develop scenarios for quantitative risk analysis

Risk - Previous Work and Ongoing Studies

	Independent Variables (Uncertain Parameters) FP, ZD, WJ	Dependent Variables	Comments /Suggestions
CO_2 Storage	Reservoir properties (porosity & permeability, Kv/Kh ratio) Relative permeability (e.g. irreducible water saturation) WAG (including well pattern and spacing, and injection rate) FP, ZD CO_2 miscibility (e.g. minimum miscibility pressure) Boundary conditions Model uncertainty (e.g. simulation of coupled processes, simulation of fluid dynamics) CO_2 impurity Reservoir depth and thickness ZD Initial water, oil and gas saturations FP, ZD Mineralogical composition TX	Amount of CO_2 stored (or CO_2 recovered or Net CO_2 stored) FP, ZD Early CO_2 Breakthrough time ZD CO_2 Retention (or residence) WJ CO_2 Injectivity reduction (Net CO_2 injection amount) WJ CO_2 storage capacity loss - Amount of CO_2 mineral trapping - Mineral alteration and porosity evolution AOR (CO_2 plume size & pressure buildup)	
Oil Recovery	Reservoir temperature Reservoir pressure Oil composition, gravity Oil visicosity Ongoing Study	Oil production FP, ZD Water cut (or net water injection) FP Gas (CH4) production ZD	
Geomechanics	Fault density and distributions Stress and mechanical properties Coefficient of friction (fault properties) Caprock geomechanical properties Mechanical processes and conditions	Pressure Buildup FP SL Induced seismicity (seismic magnitude) Injection-induced faults reactivation	e.g. Probability of inducing an earth quake of magnitude 2
CO_2 Leakage	Caprock geometry (discontinuity) & heterogeneity Caprock capillary entry pressure Initial water chemistry TX CO_2 migration (point & non-pont source) Distributions of leaky wells	pH change in the overlying aquifer TX CO_2 concentration or total carbon concentration Heavy metal concentration TX TDS change in the overlying aquifer TX Trace metal mobilization TX TX CO_2 migration through caprock Caprock sealing quality evolution (porosity change)	FP: Feng Pan SL: Si-Yong Lee TX: Ting Xiao WJ: Wei Jia ZD: Zhenxue Dai

Risk - Risk Response Planning (Task 5)

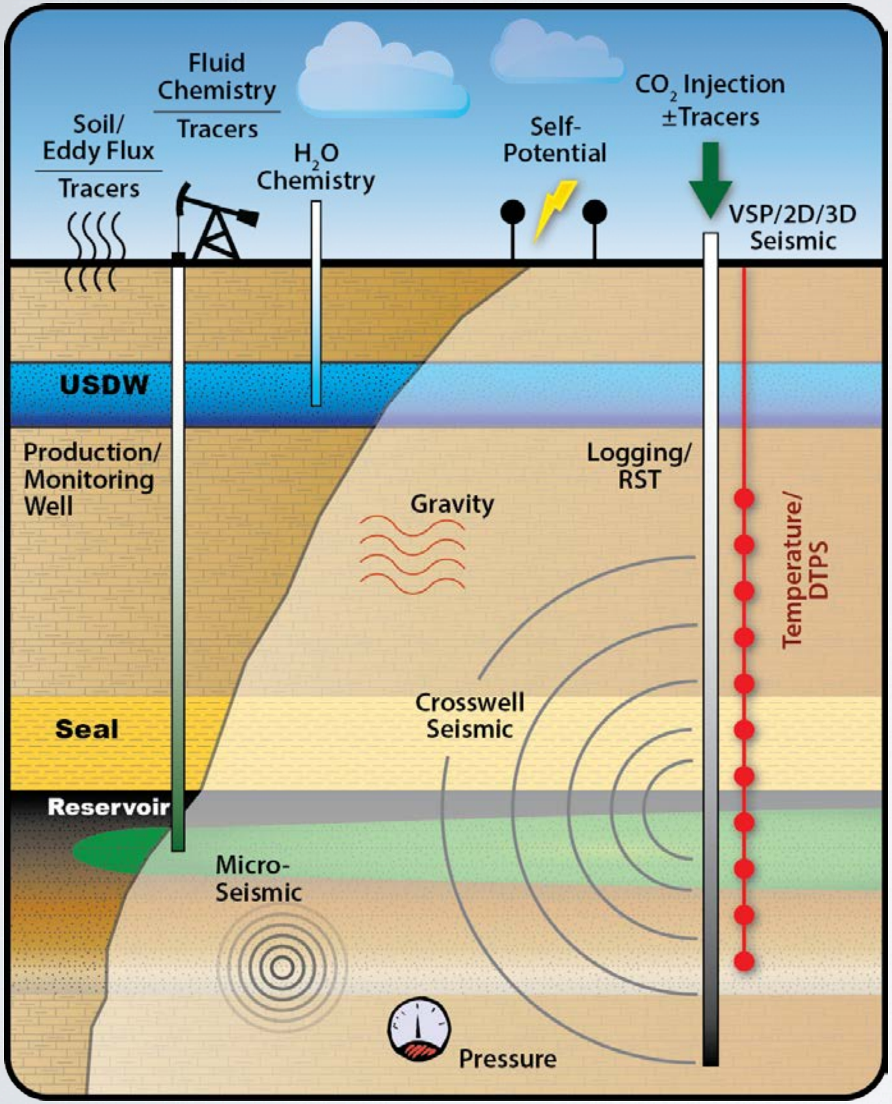
- Keep tracking of existing and new risks
- Review of mitigation activities (response plan) and their effectiveness
- Iterative process

- Risk prevention plan
- Risk mitigation plan
- Update PMP

Established risk prevention and mitigation treatments for 69 FEPs

FEP	2016 Ranking	2015 Ranking	2014 ranking	Risk Prevention	Risk Mitigation
Price of oil (or other related commodities)	1	1	6	Analyze trends in commodity prices. Plan for worst case scenarios. Hedge oil prices. Establish a CO2-EOR economical model to predict the possible proft and lost and to evaluate the economical risk	Control costs. Shut in wells until prices recover. Shift to backup CO2 supplier.
CO2 legislation	2	18	29	Tie investment in CCS projects to passage of appropriate CO2 legislation. Implement public outreach program to educate stakeholders on the legislative needs of the project. Shift from DSA to EOR or ECBM if CO2 legislation does not get passed, is insufficient or too onerous for DSA.	Monitor CO2 legislation and analyze the impact of CO2 legislation on the project. Continue public outreach program. Comply with CO2 legislation.

MVA – Methods

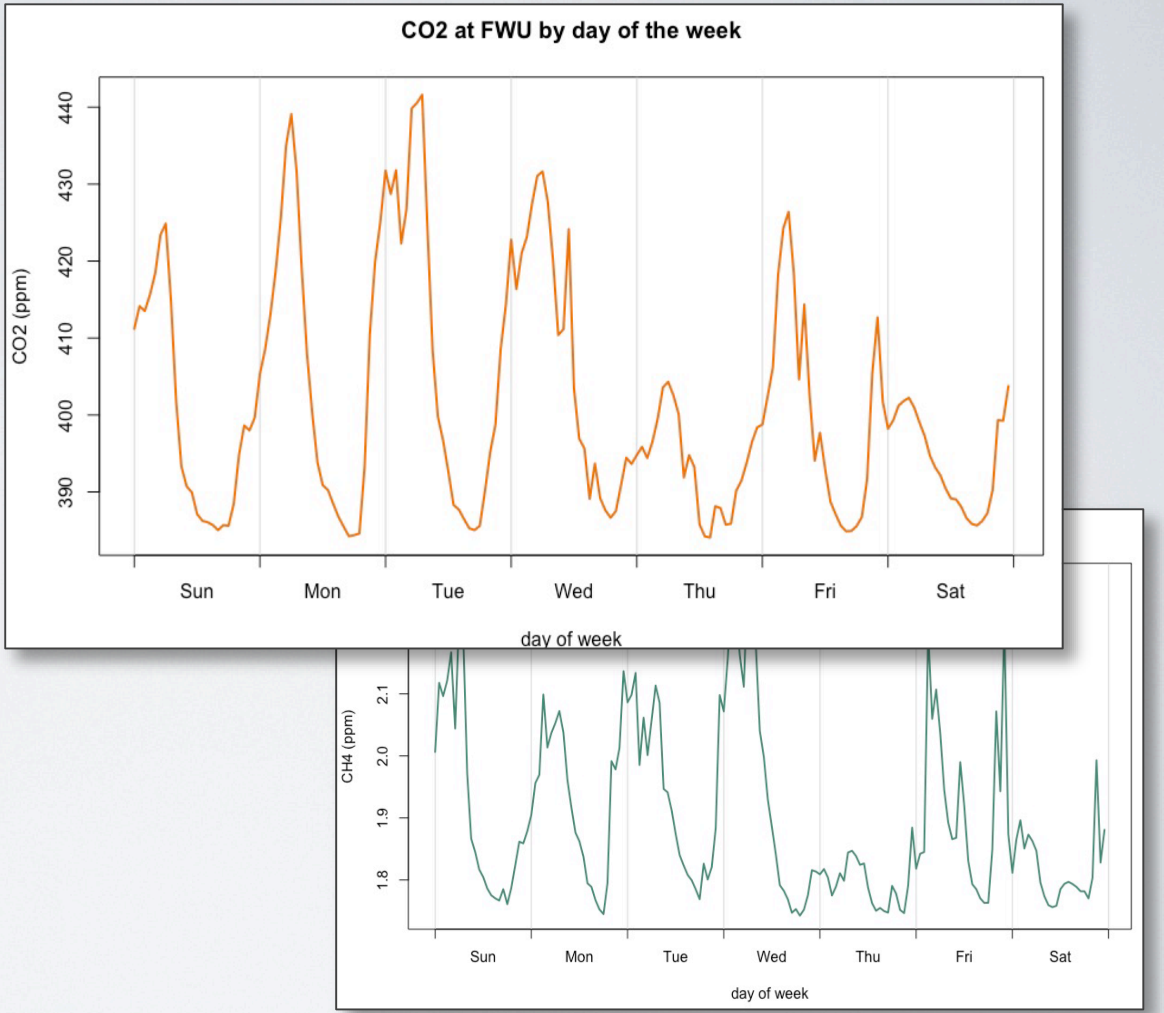


<u>Detecting CO_2 and/or brine outside Reservoir:</u>
- Groundwater chemistry (USDW)
- Soil CO_2 flux
- CO_2 & CH_4 Eddy Covariance
- Aqueous- & Vapor-Phase Tracers
- Self-potential (AIST)
- Distributed Sensor Network (OK State)

<u>Tracking CO_2 Migration and Fate:</u>
- *In situ* pressure & temperature
  - Distributed temperature array
- 2D/3D seismic surveys
- VSP
- Cross-well seismic
- Passive seismic
- Fluid chemistry (target reservoir)
- Aqueous- & Vapor-Phase Tracers
- Gravity surveys (AIST)
- MagnetoTelluric (AIST)

Example MVA Result – Flux Tower

- CO_2 & CH_4 Eddy Tower
  - Continuous, wide-area coverage and point-source leak detection.
  - FWU Eddy Tower deployed at 13-10A data shed in May 2015 (for ~1 month).
  - Continuous acquisition of CO_2 and CH_4 and wind data.
  - Exploratory statistics and data filtering methods.
  - Examination of diurnal and daily trends.
  - Probability estimates of leak source(s).

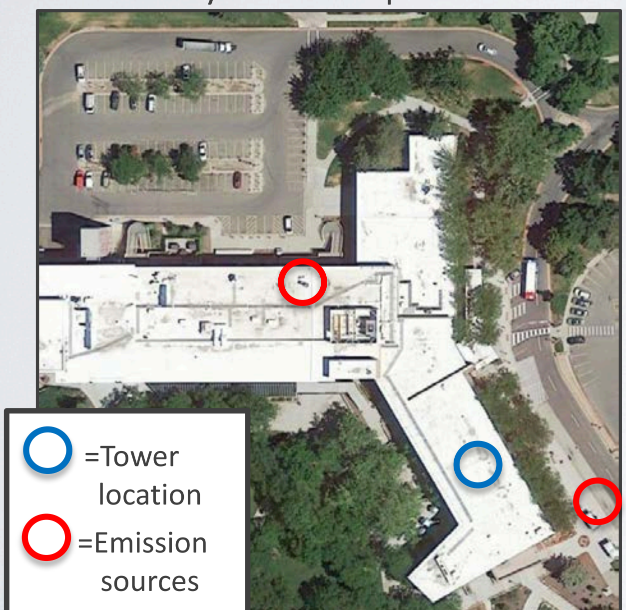


Daily trends (aggregate hourly averages) of CO_2 (top) and CH_4 (bottom)

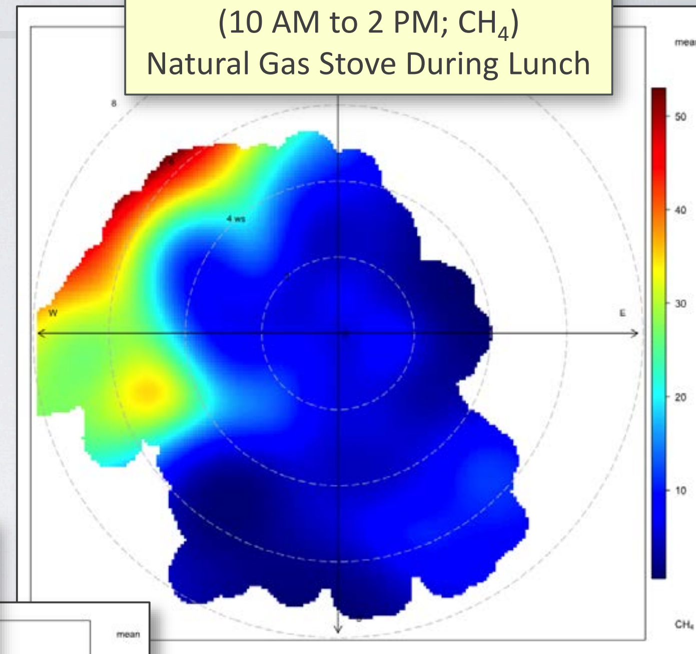
Example MVA Result – Flux Tower

- CO_2 & CH_4 Eddy Tower
  - Eddy covariance methods undergoing pre-deployment testing at Univ. of Utah.
  - Point source detection of CO_2 and CH_4.
  - Release from natural gas cooking vent (lunch) and methane-powered buses (evening).

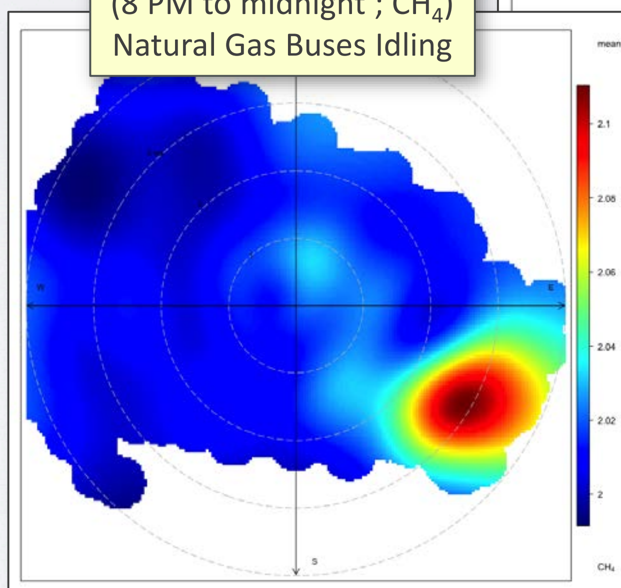
University of Utah Experiment Site



Jan 24, 2017
(10 AM to 2 PM; CH_4)
Natural Gas Stove During Lunch



Jan 26, 2017
(8 PM to midnight ; CH_4)
Natural Gas Buses Idling



Conditional Bivariate Probability Functions (CBPF):

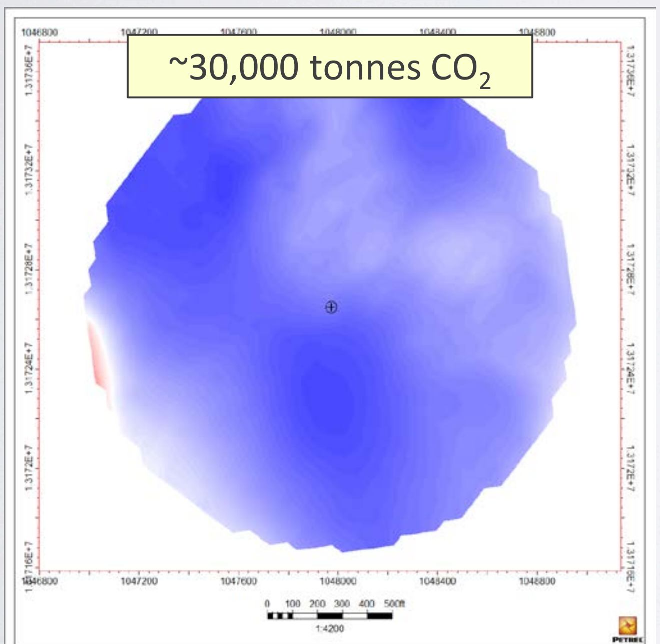
- 99th percentile concentration.
- Plots probability that high concentrations occurred in a specific direction or “bin” of degrees at different wind speeds.

SWP MVA – VSP

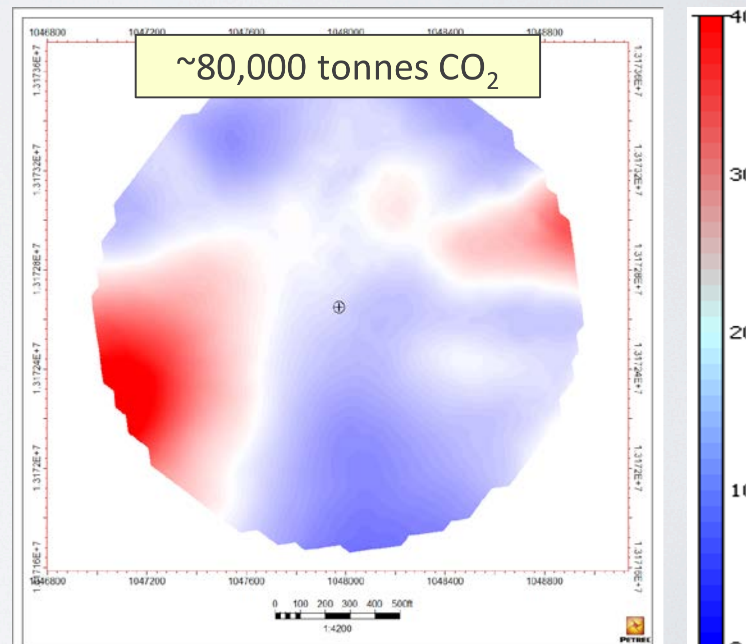
- 3D VSP conducted in 2014 (baseline), 2015 (repeat 1), 2016 (repeat 2)
  - Detailed Characterization near injectors
  - Monitor the evolution and image CO_2 plume.
  - Contribute to model verification.

Processed VSP: NRMS amplitude attribute (7600 - 8100 ft)

Baseline VSP to **2015** VSP



Baseline VSP to **2016** VSP



SWP MVA – CO_2 Accounting

- FWU storing approximately 10,000-20,000 metric tons per month
  - Over 90% of purchased CO_2 has been stored (balance due to upsets and flaring)