Farnsworth Unit

Southwest Regional Partnership on Carbon Sequestration (SWP)

DE-FC26-05NT42591

Reid Grigg[1] - Robert Balch[1]

Brian McPherson[1,2]

[1]New Mexico Institute of Mining and Technology

[2]University of Utah

U.S. Department of Energy

National Energy Technology Laboratory

Carbon Storage R&D Project Review Meeting

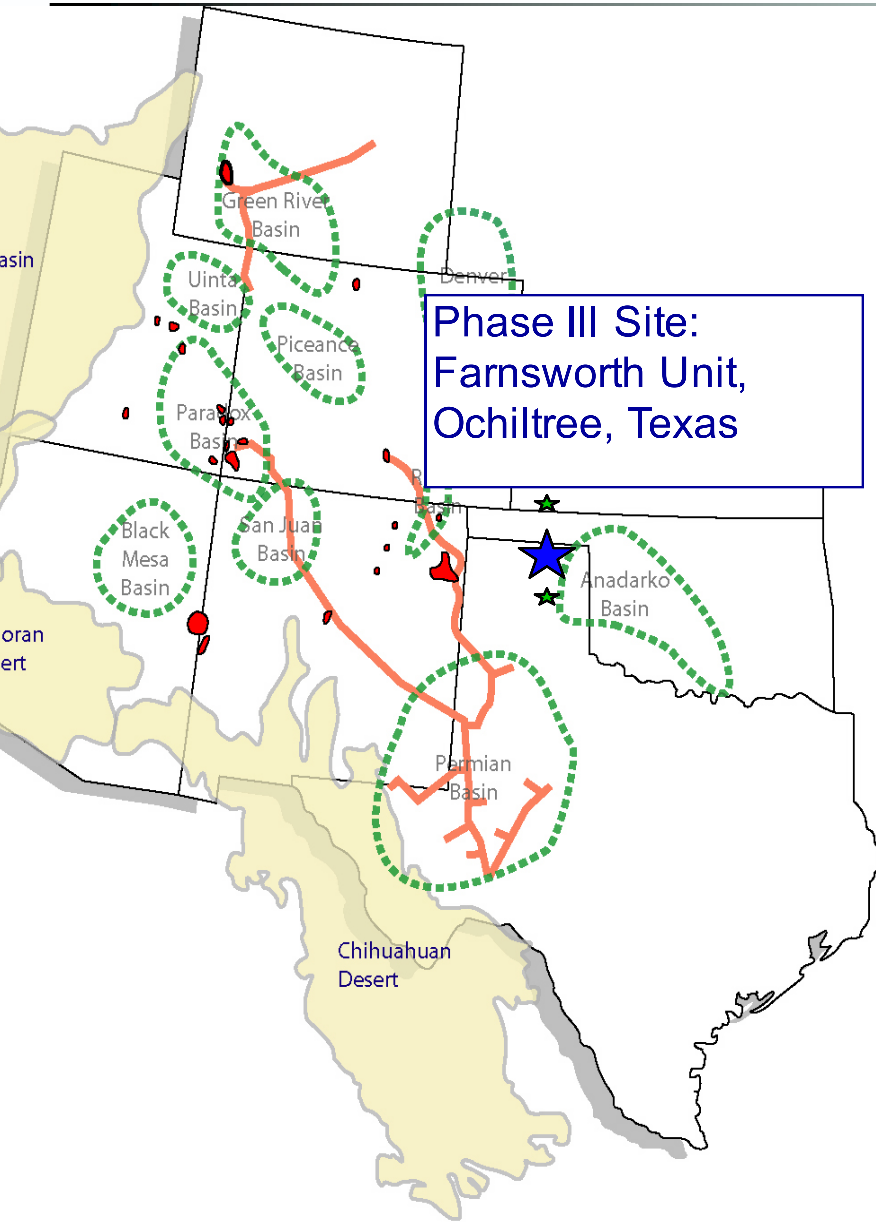
Transforming Technology through Integration and Collaboration

August 18-20, 2015

Presentation Outline

- **Introduction, Goals and Major Accomplishments (Reid Grigg)**
- Technical Status:
  - Characterization and MVA (Robert Balch)
  - Simulation and Risk (Brian McPherson)
- Summary, Questions and Answers

Brief Summary of Goals

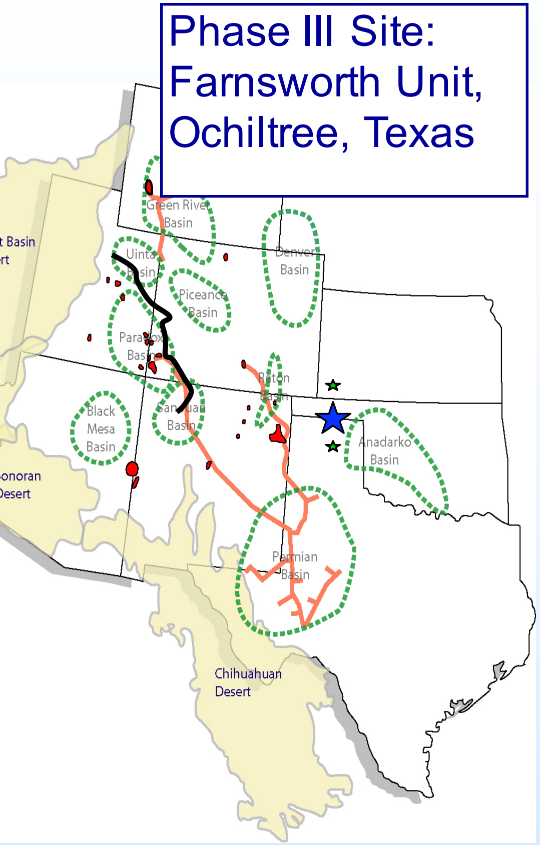


The SWP's Phase III is a Large-Scale EOR-CCUS Sequestration Test

General Goals:

- One million tons CO_2 injection
- Optimization of storage engineering
- Optimization of monitoring design
- Optimization of risk assessment
- "Blueprint" for CCUS in southwestern U.S.

Brief Summary of Accomplishments

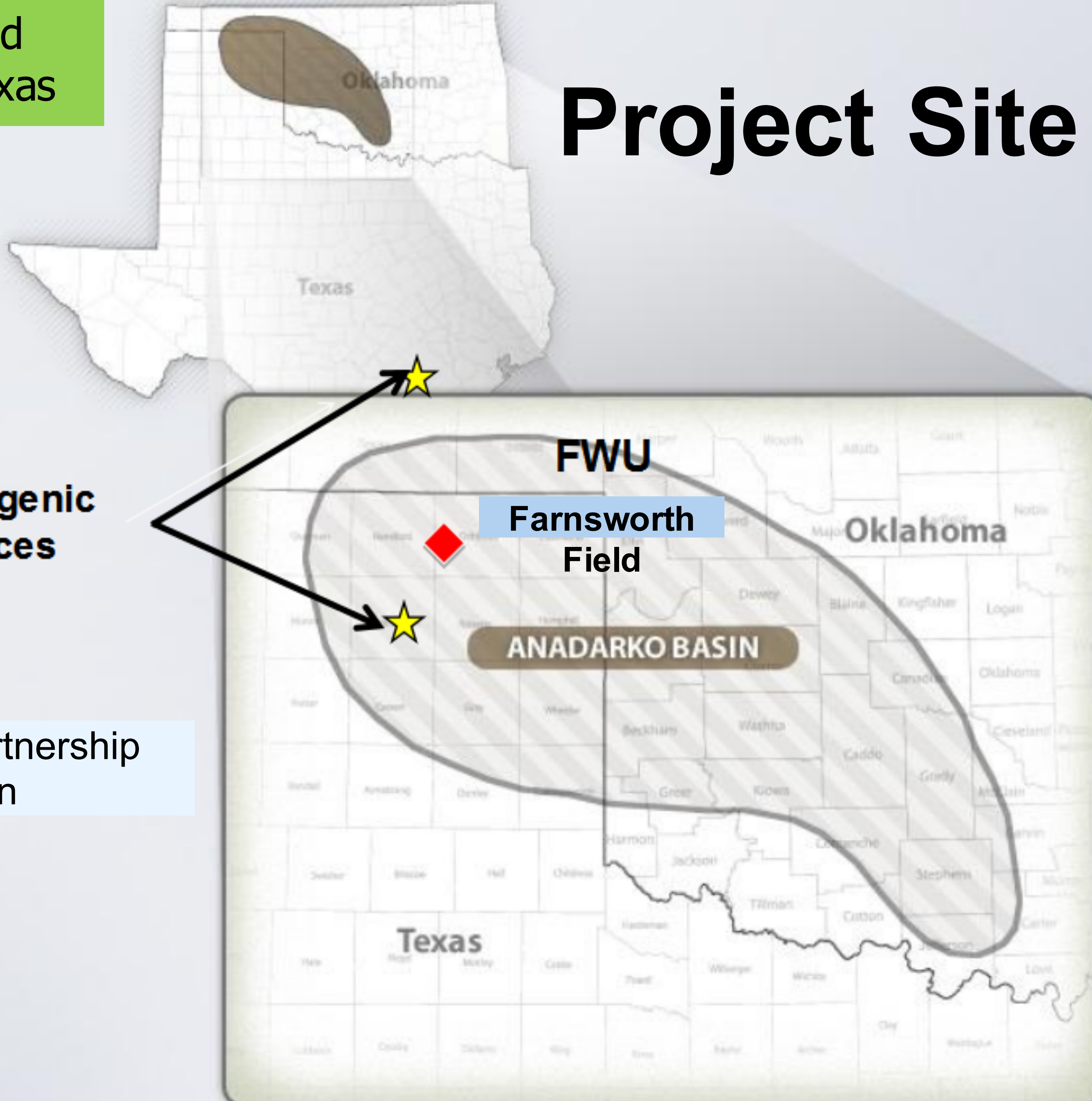


- Continuous geologic characterization;
- Annual updated geo-model;
- Continuous history match;
- Continuous monitoring (ongoing);
- New risk registry and assessment;
- Full FWU 3D surface seismic survey;
- 3 Characterization Wells drilled, cored, logged;
- 3 - 3D VSP and 4 - crosswell baselines
- ~540,000 (~1,070,000) tonnes CO_2 injected
- ~335,000 (~ 815,000) tonnes CO_2 purchased
- ~316,000 (~ 760,000) tonnes CO_2 stored

Farnsworth Oil Field
Ochiltree County, Texas

Project Site

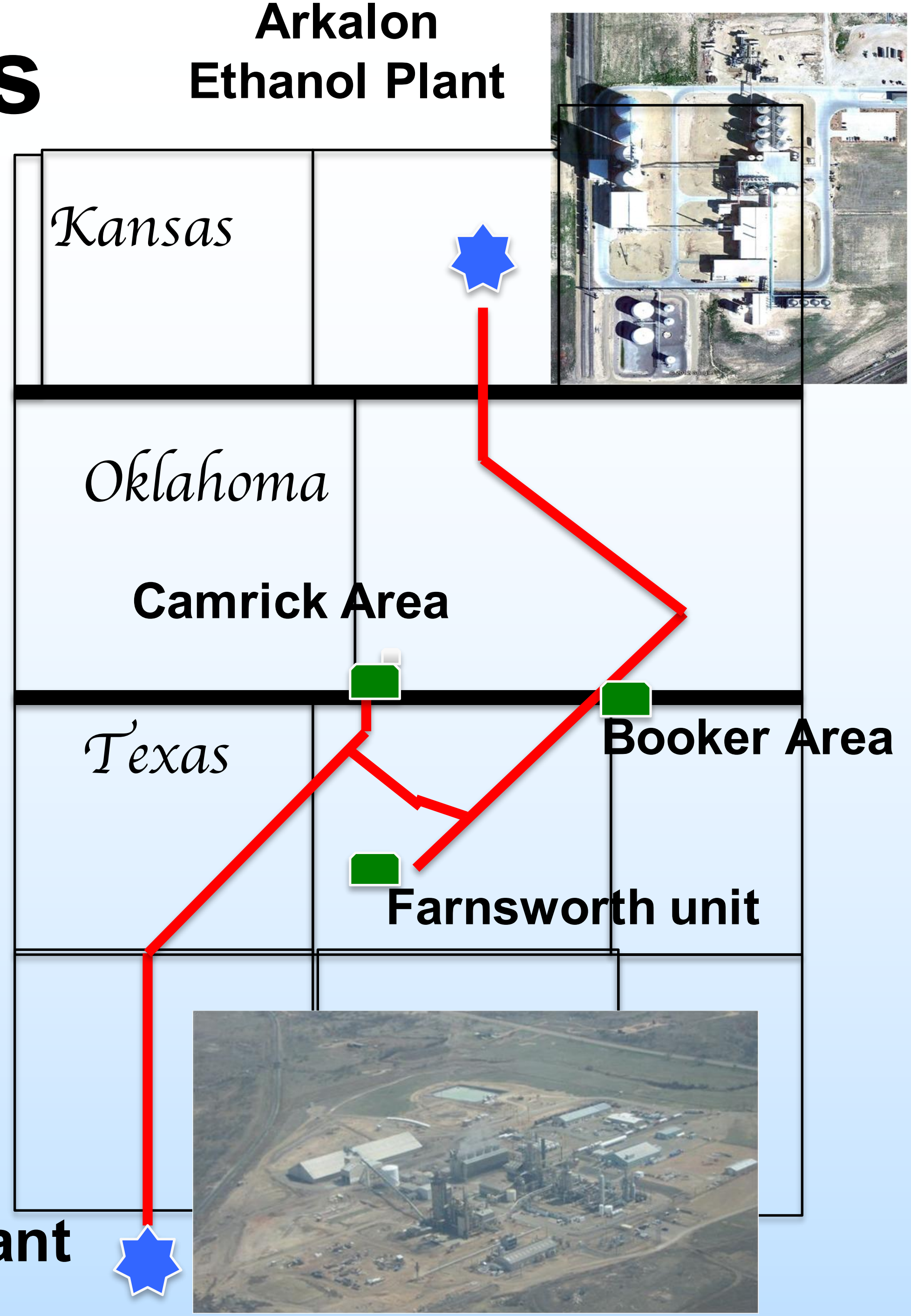
Anthropogenic CO_2 Sources



Southwest Regional Partnership on Carbon Sequestration

CO_2 Sources

Arkalon Ethanol Plant

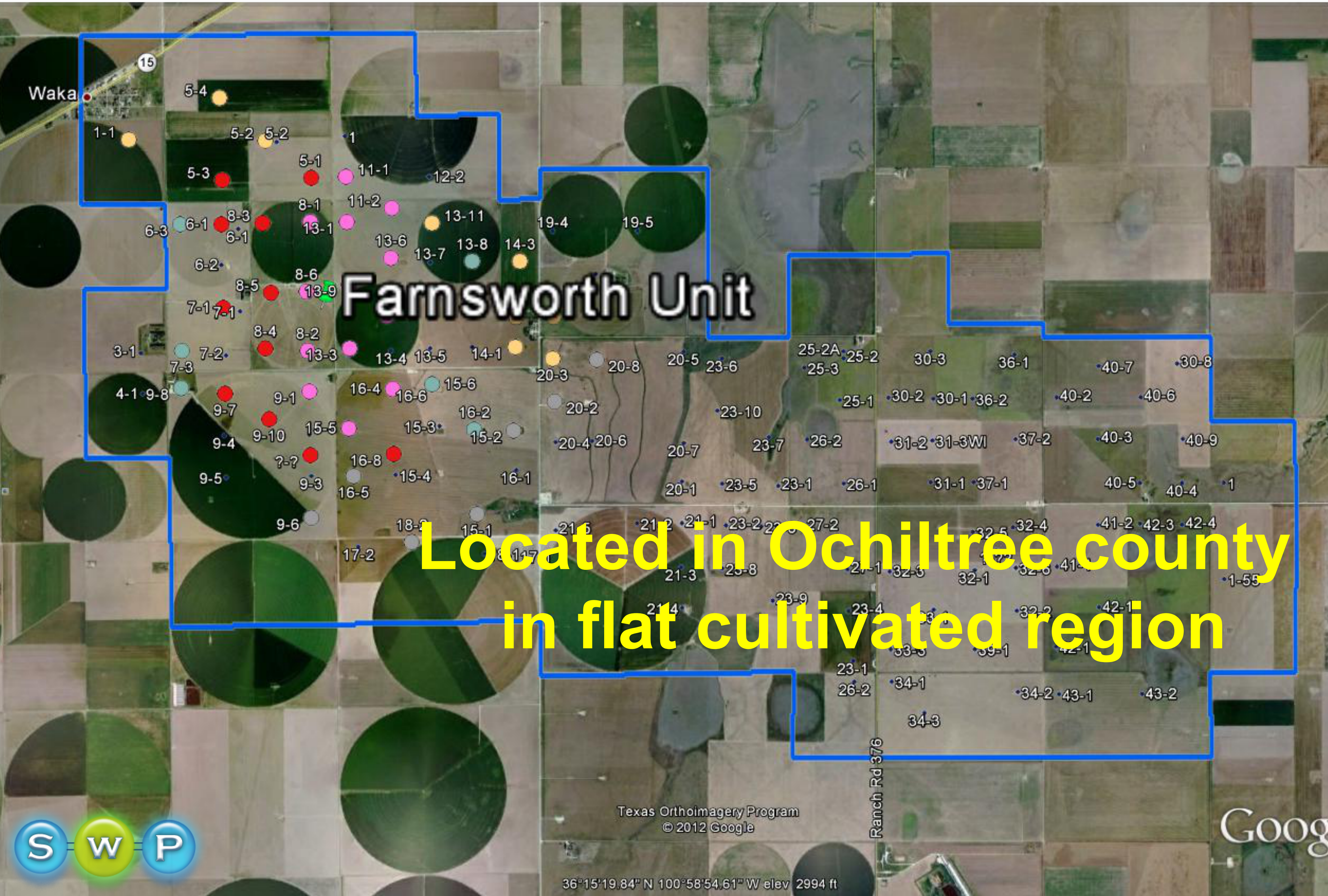


Agrium Fertilizer Plant

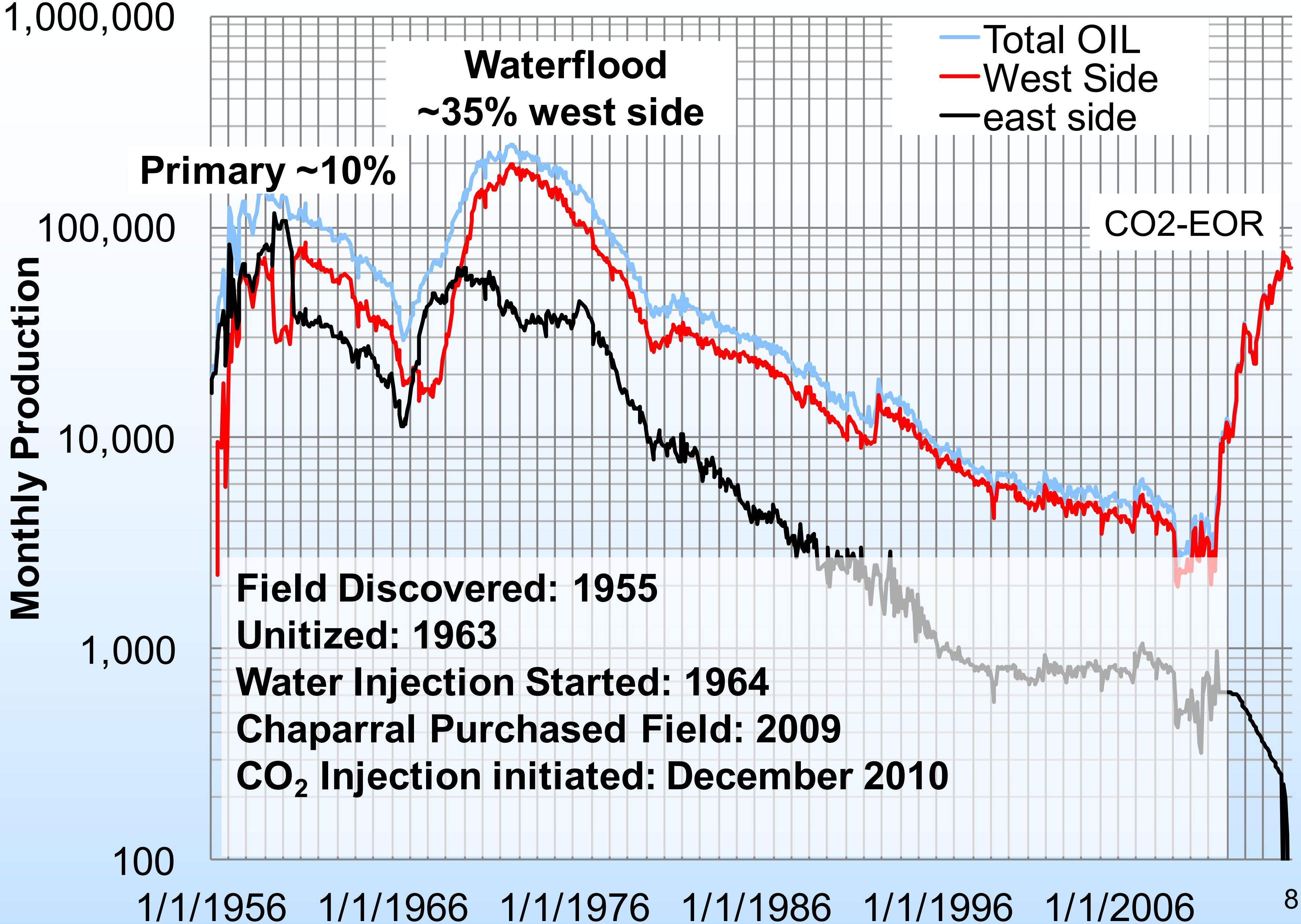
Carbon
- Capture
- Transportation
- Utilization & Storage

500-600,000 Metric tons CO_2/yr

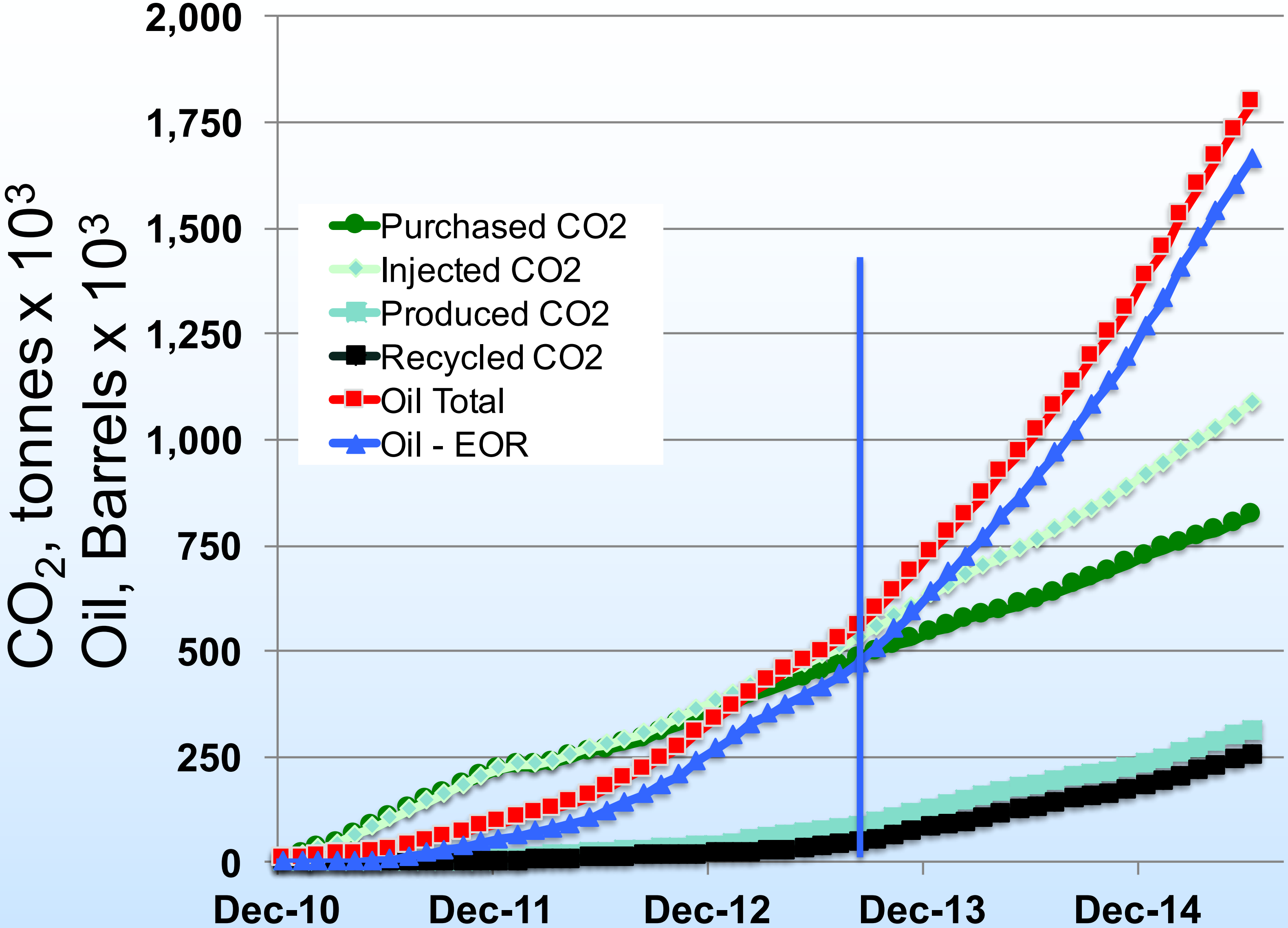
Project Site



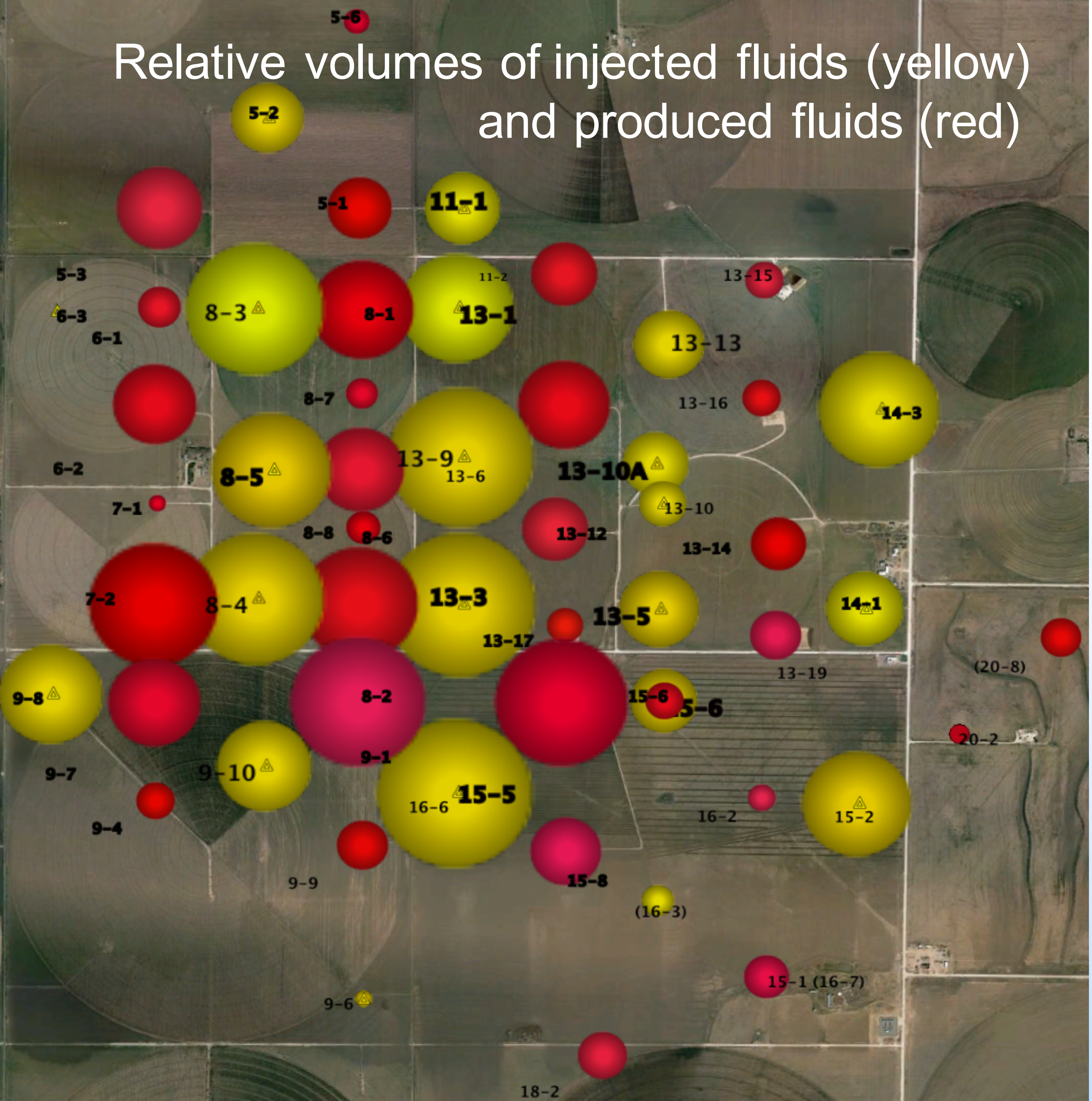
History Match Effort: Actual Data



CO_2 injection/production and oil production since 12/2010



Relative volumes of injected fluids (yellow) and produced fluids (red)

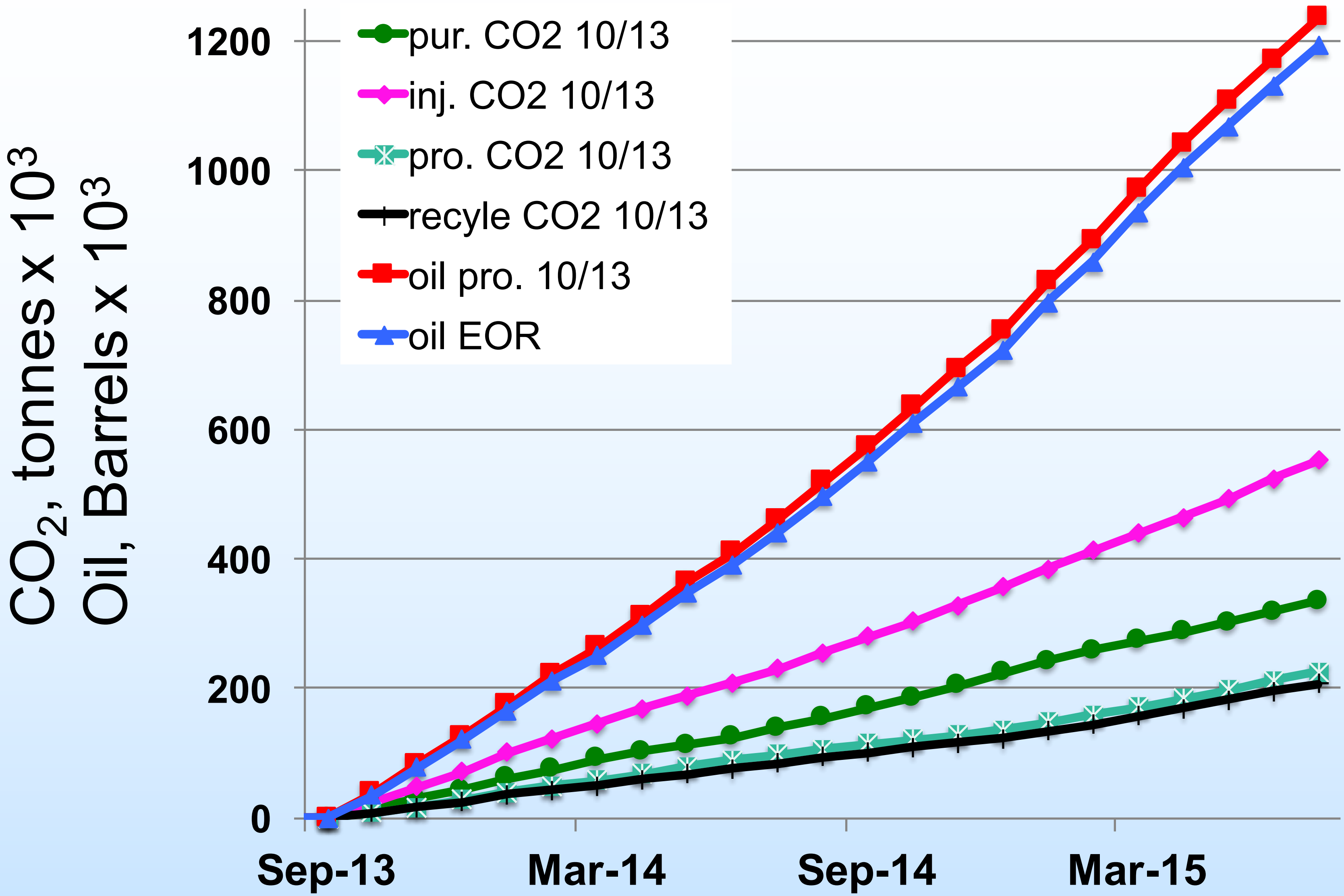


Bubble Map
Western Half FWU.

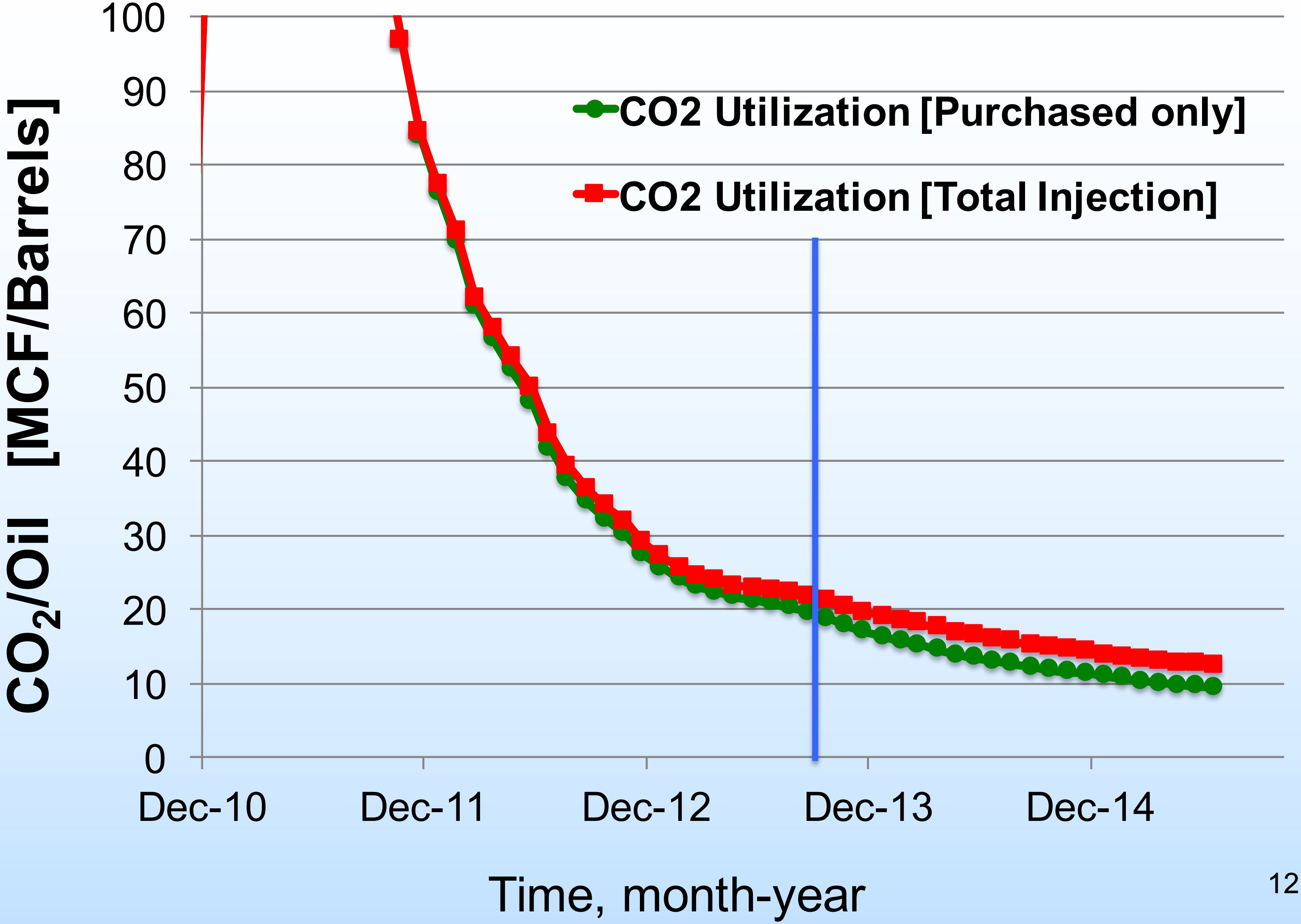
Injection:
14,794,360 res. bbls

Production
14,033,352 res. bbls.

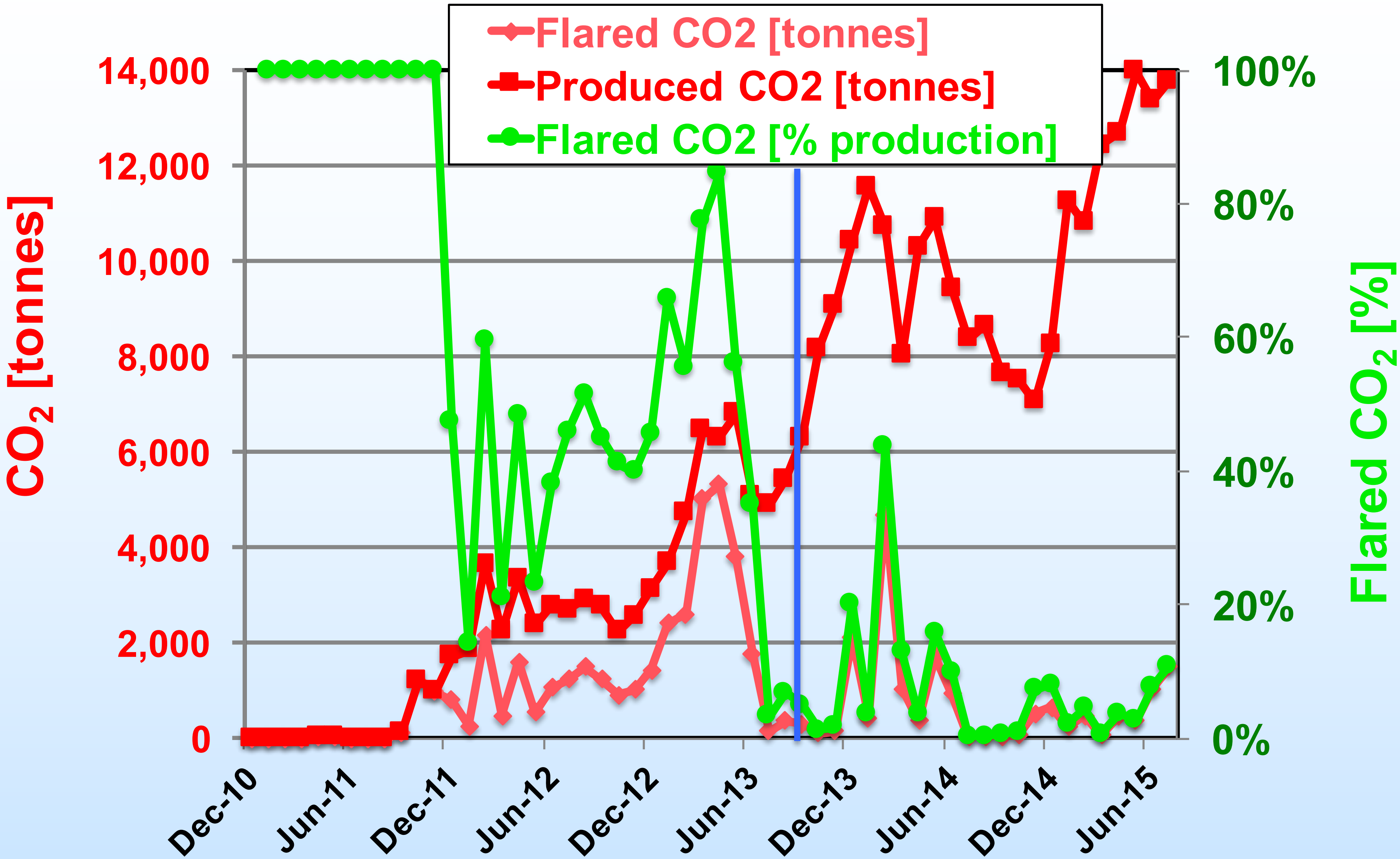
CO_2 injection/production and Oil production Since 10/2013



CO_2 Utilization



CO_2 lost to the system during recycle




Found another risk to add to the registry!


Above Normal Rain Fall: Standing water and weeds.

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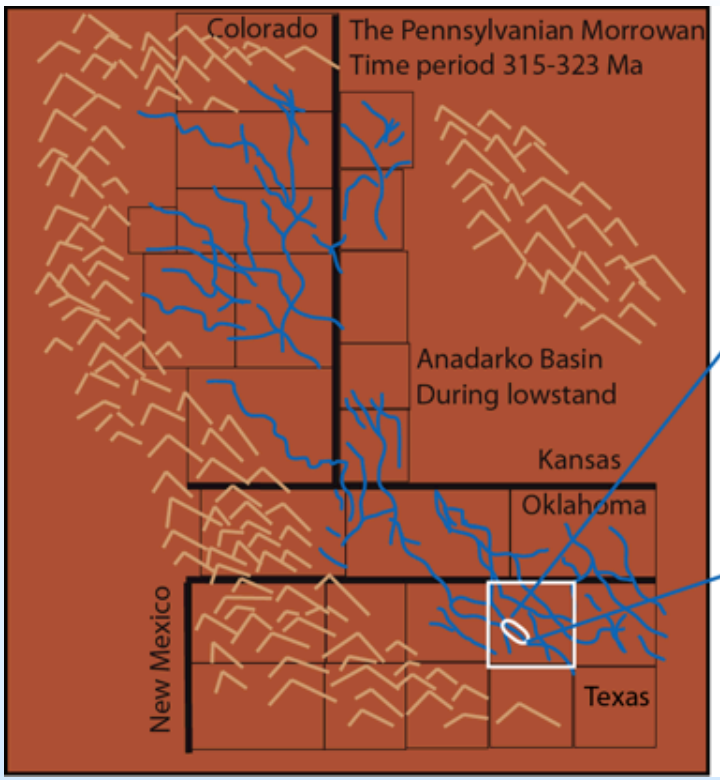
Characterization Efforts

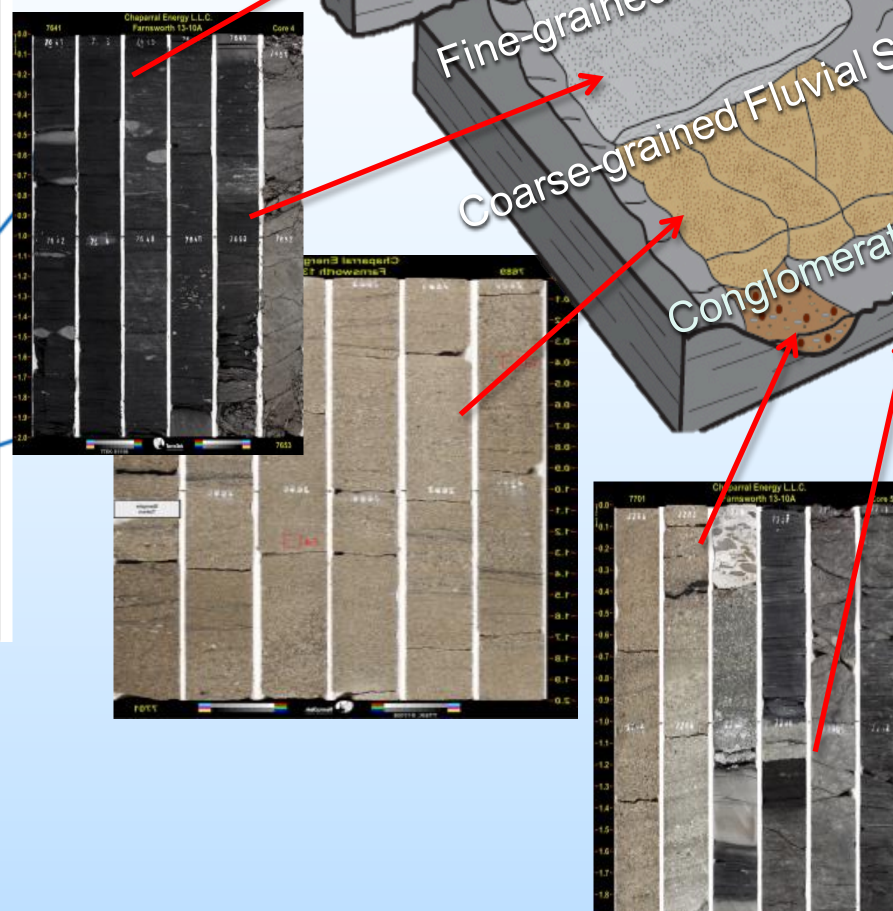
Goal – Improve Geologic Understanding

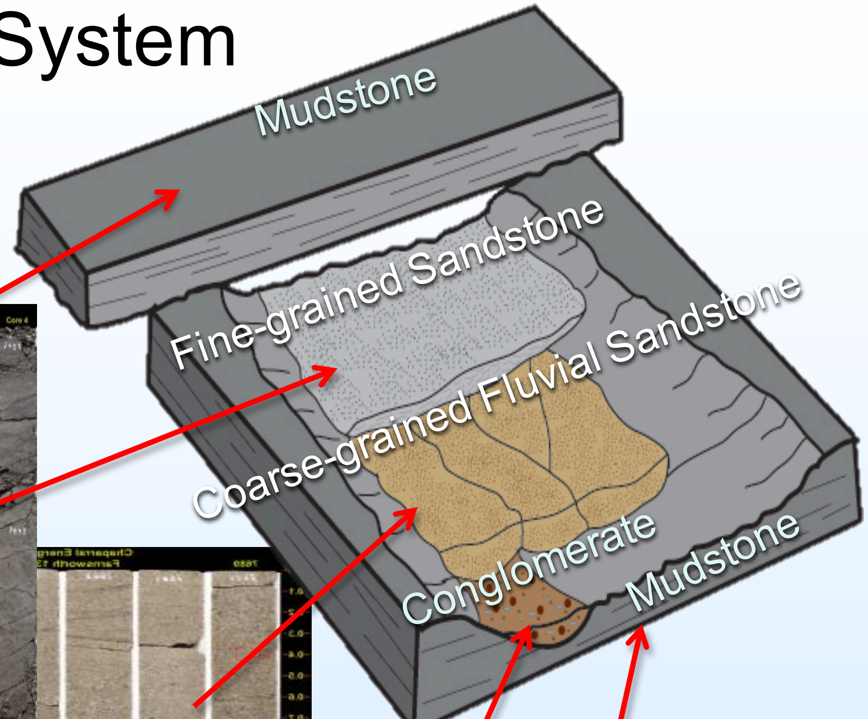
- Focuses on describing and defining the geology and depositional system for the Morrow B, secondary reservoirs, and cap-rock layers
  – Geologic Characterization - Utilizes 750ft of acquired core, modern logs in 3 wells, and legacy logs in 145 existing wells
  – Seismic Characterization, utilizes acquired baseline and legacy data to define structure and stratigraphy, and to distribute reservoir properties for models.
- Data and interpretations support modeling efforts, MVA program, Simulation and Risk Assessment

Conceptual Geologic Model

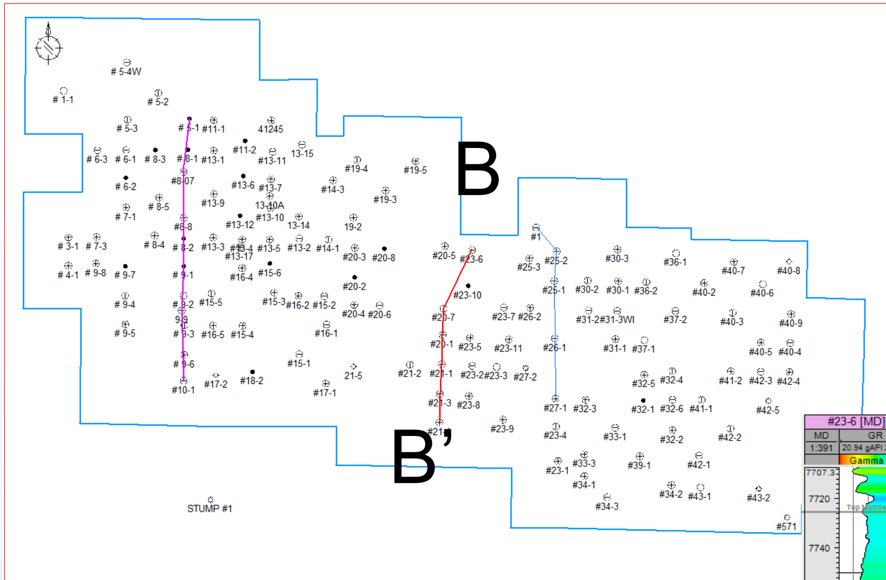
Incised Valley Depositional System

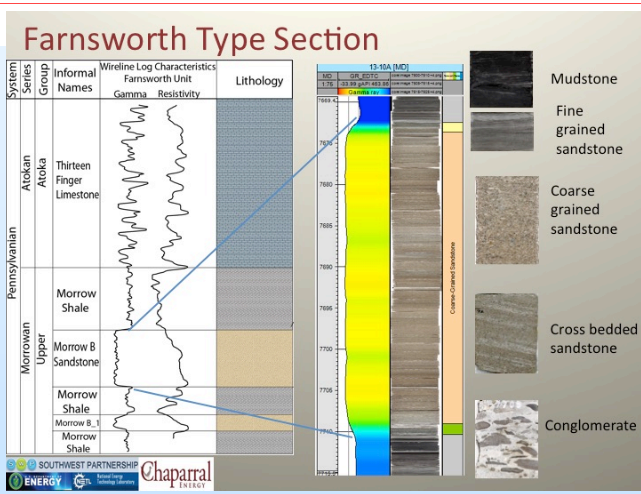






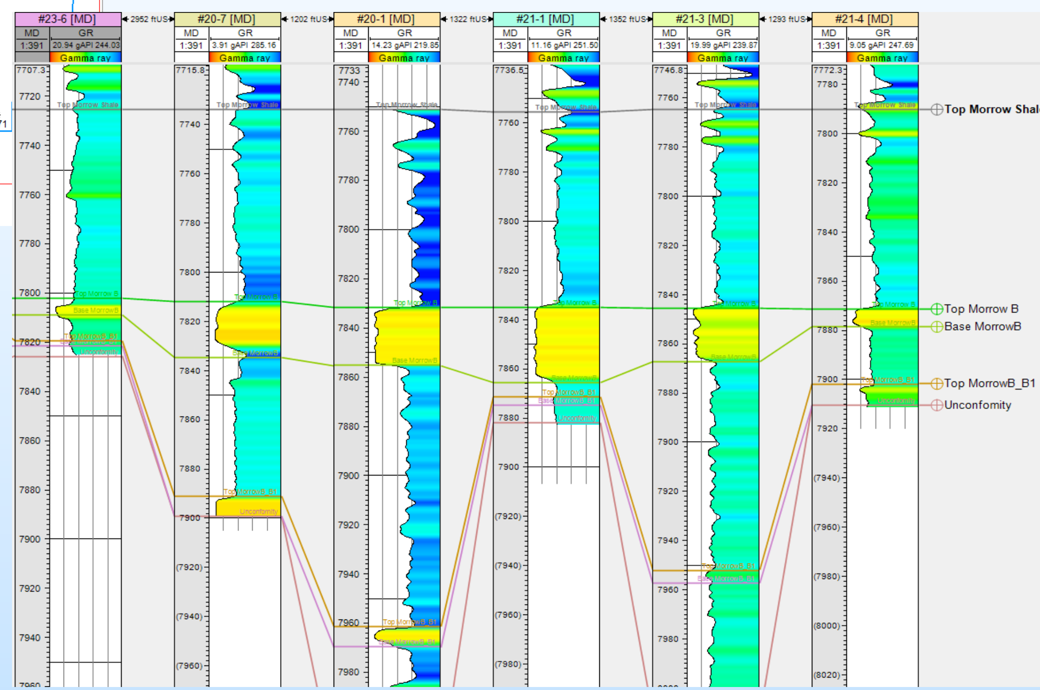
Conceptual Geologic Model

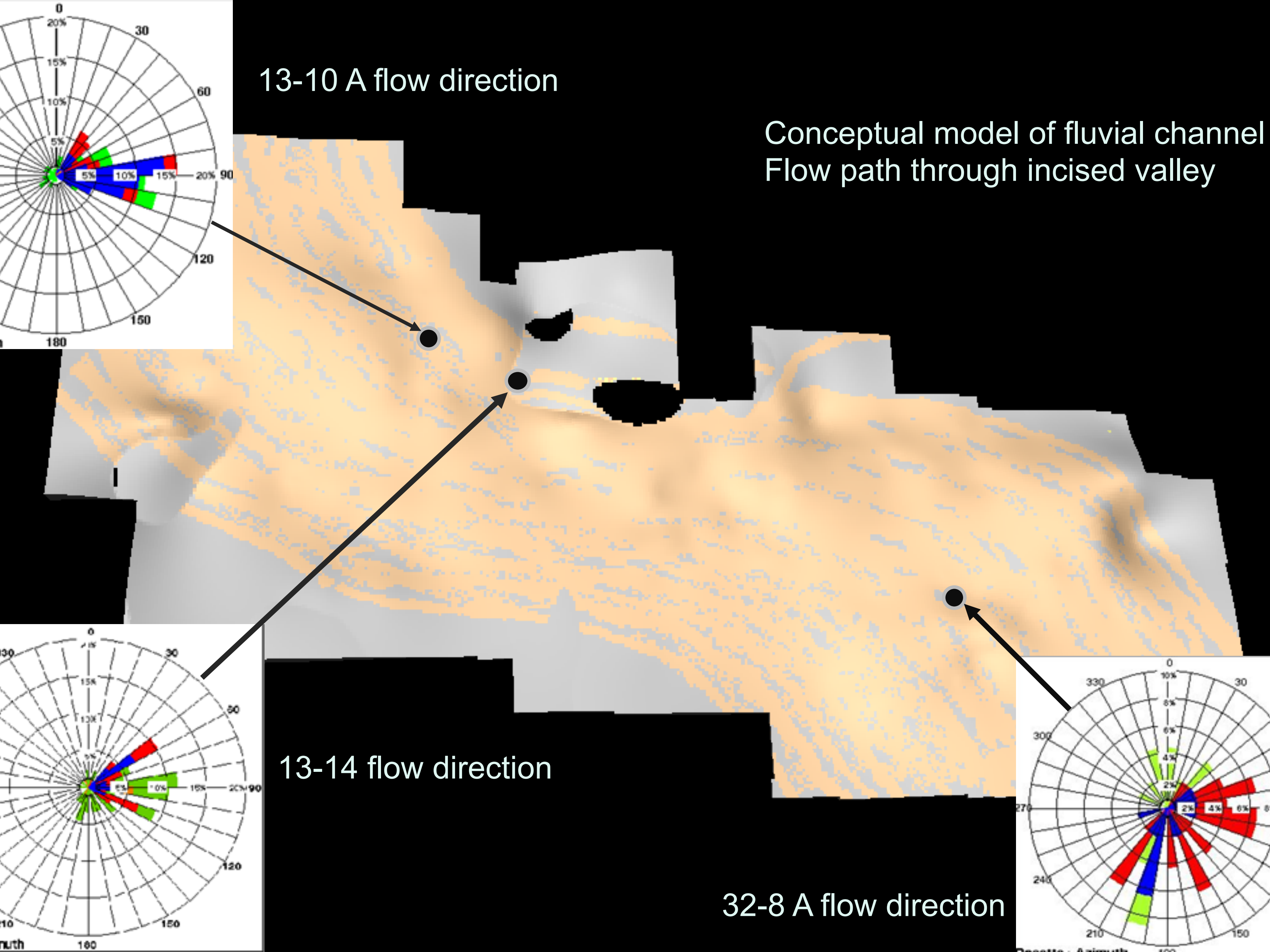




Incised Valley

- Hung on Morrow shale
- Nice channel shapes across reservoir



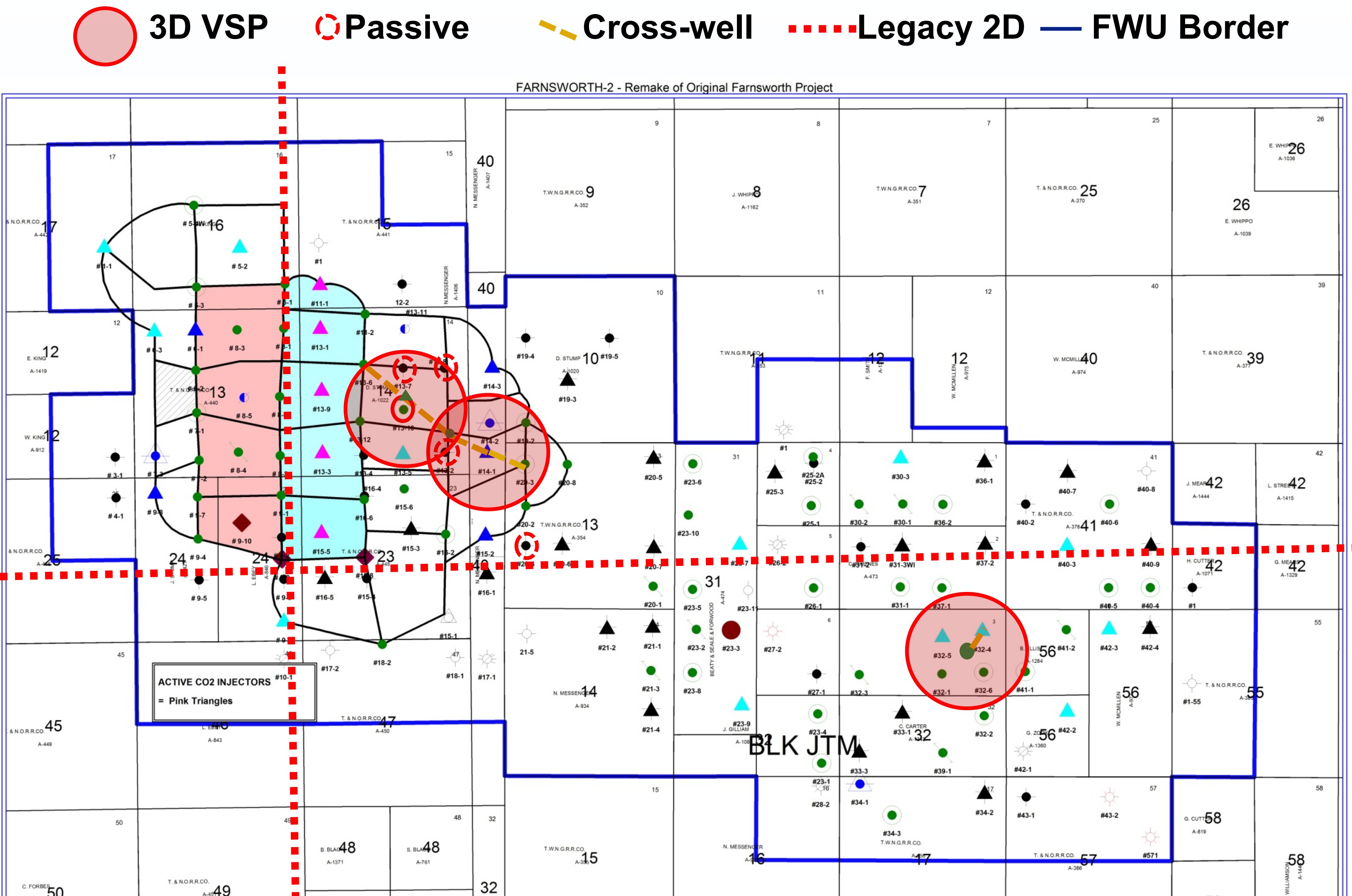


13-10 A flow direction
Conceptual model of fluvial channel
Flow path through incised valley
13-14 flow direction
32-8 A flow direction

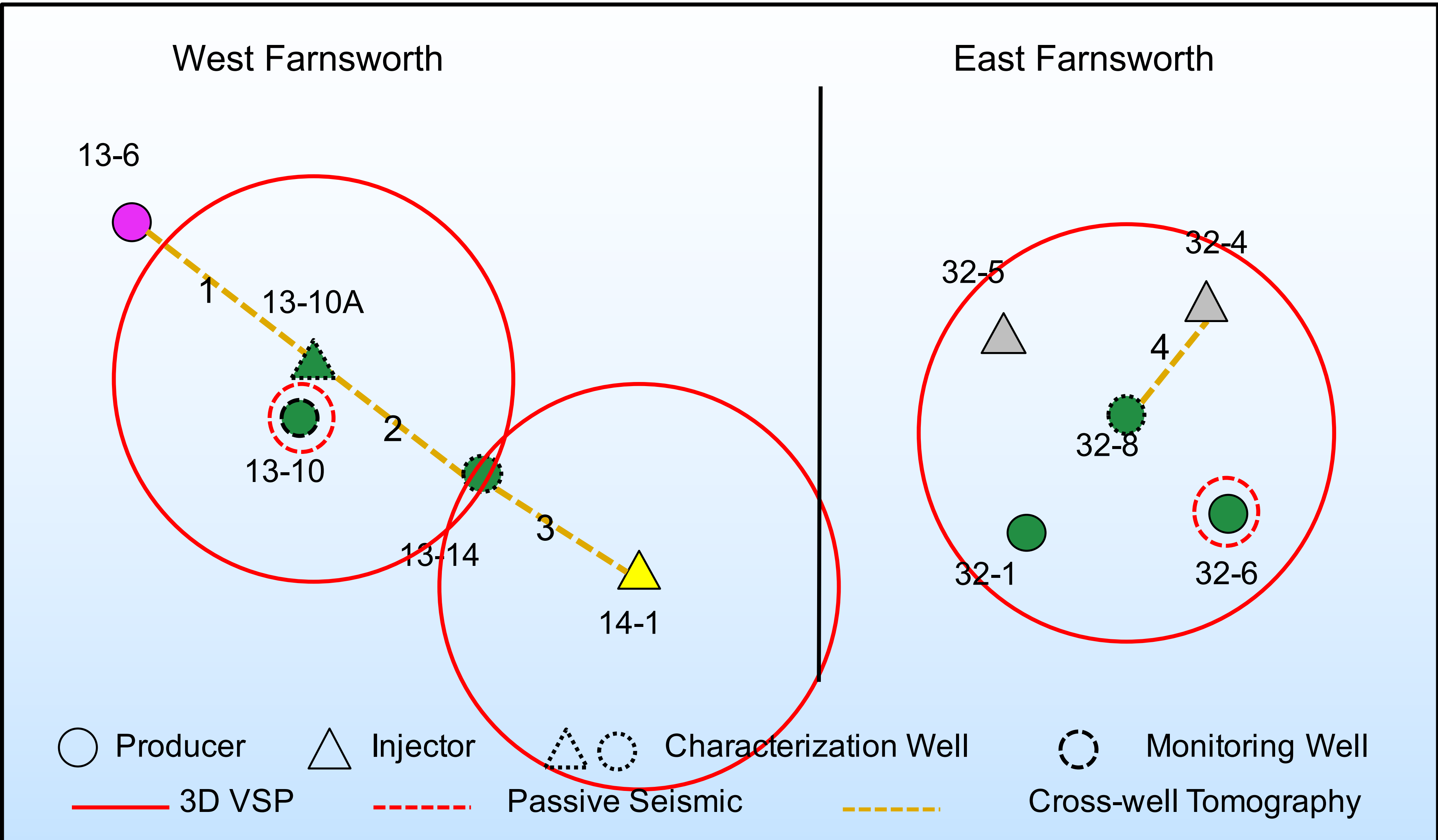
Seismic Characterization

- 3D, VSP, cross-well, and passive seismic when combined with acquired well logs, core, and other physical data provide a framework for a detailed facies-based geomodel.
  - Surface Seismic survey provides framework and structural/stratigraphic framework to construct geologic models for the entire field
  - Allows for interpretations of faults and other potential features that could impact flow
  - 3D VSP and cross-well data allow for more detailed interpretations around injection wells.
- Interpretations improve geologic understanding and ultimately improve MVA, simulation, and risk studies.
- Most recent model delivered in June 2015

Existing and Planned Seismic



Existing and Planned Seismic



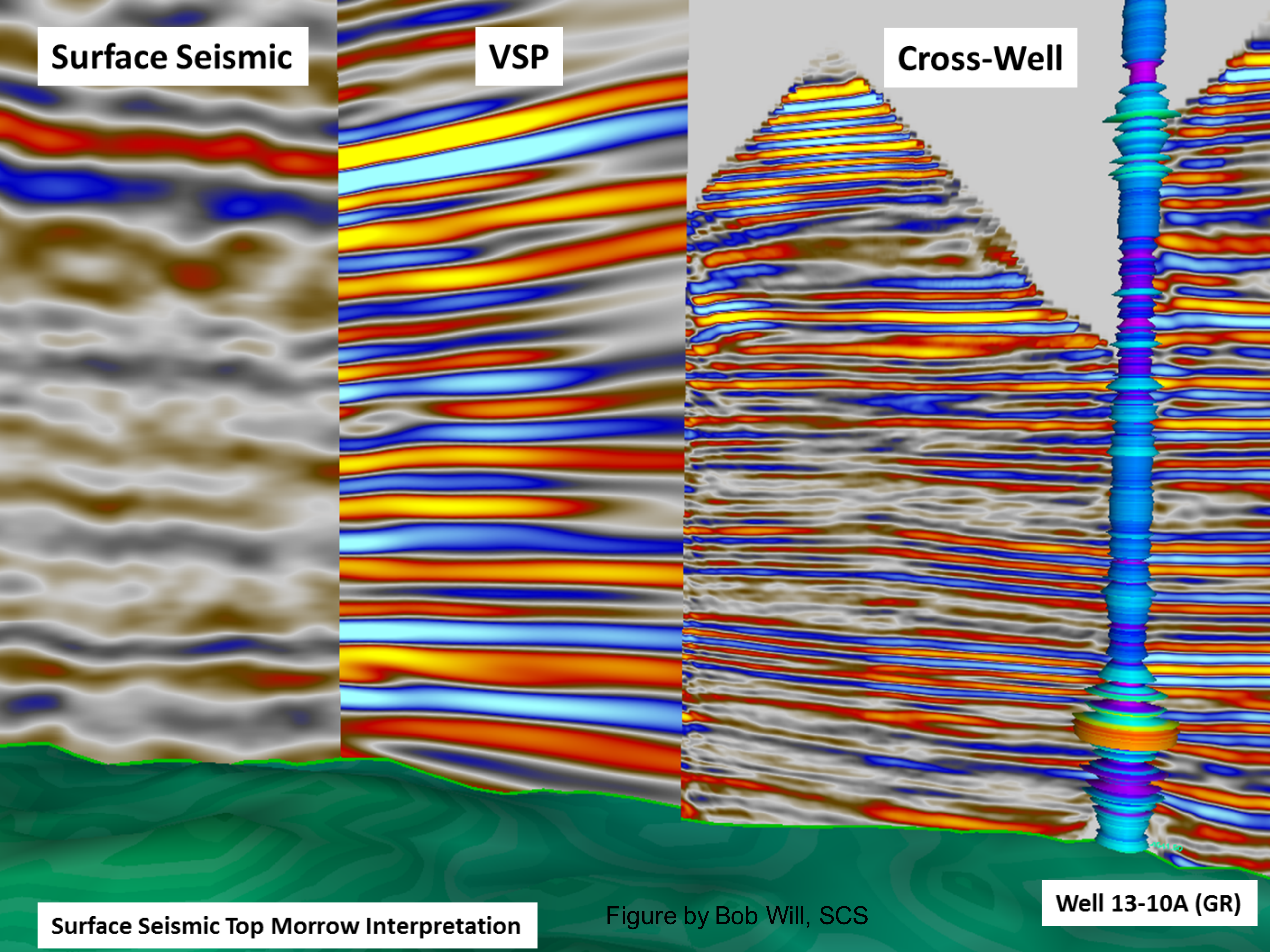
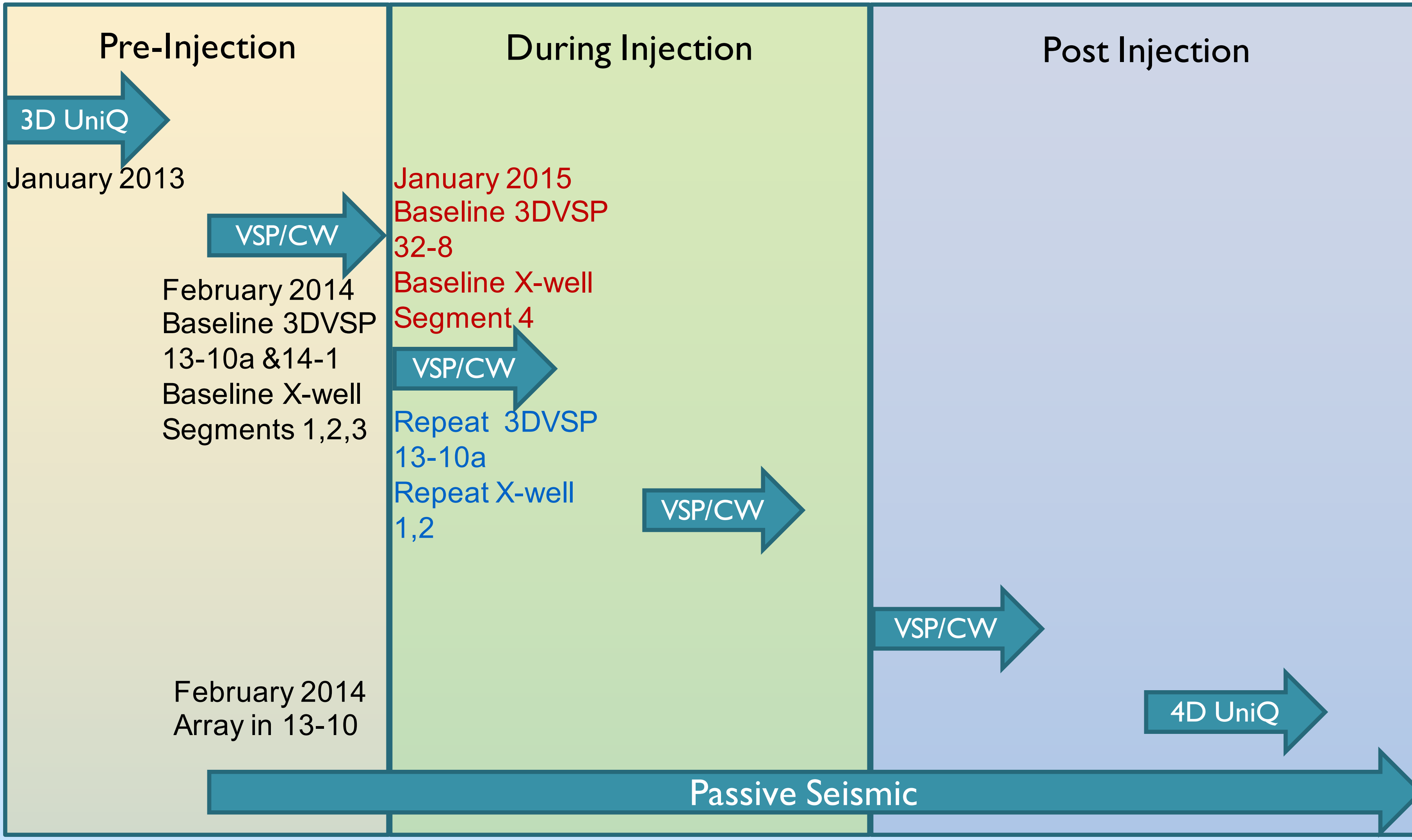
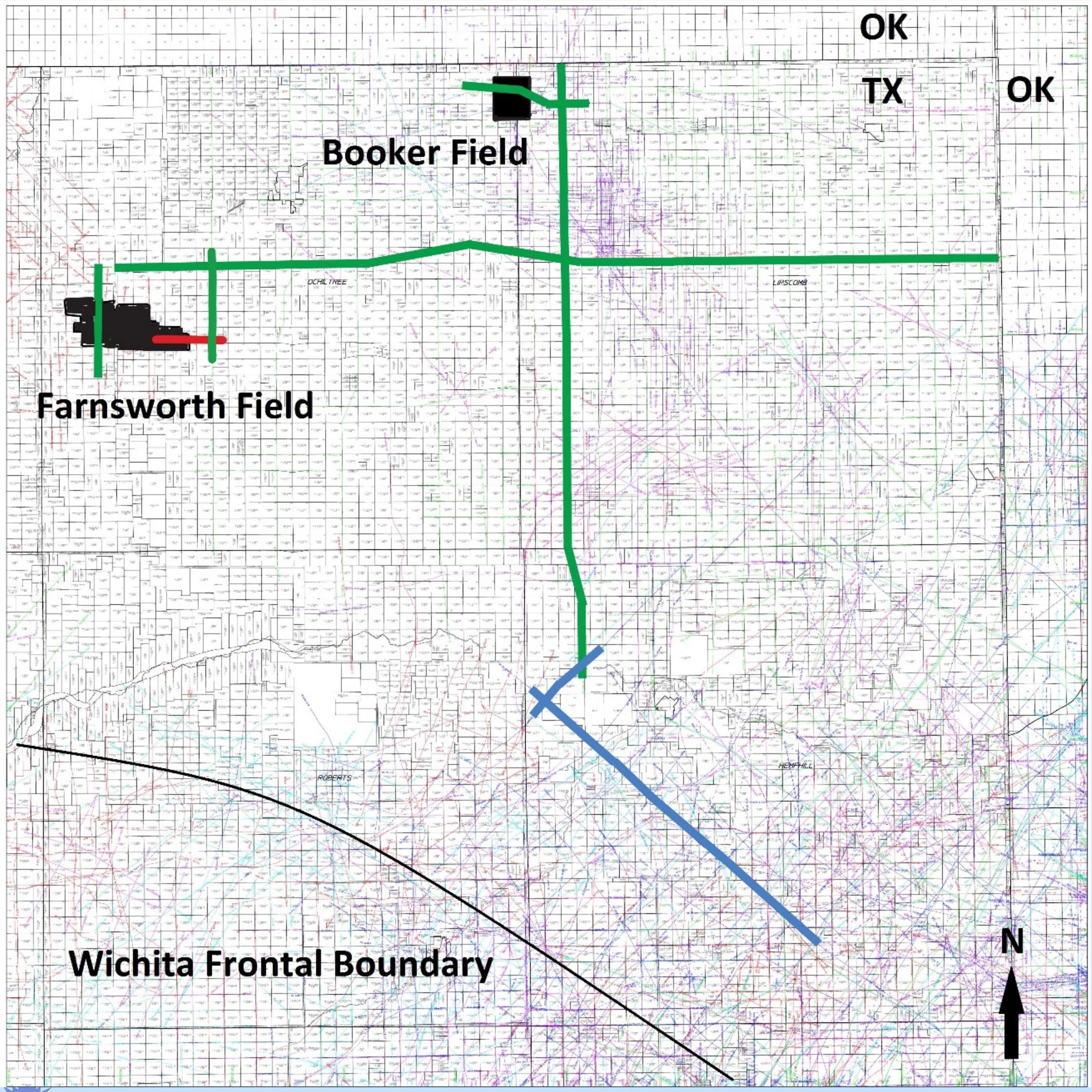


Figure by Bob Will, SCS

Seismic Acquisition Scheduling



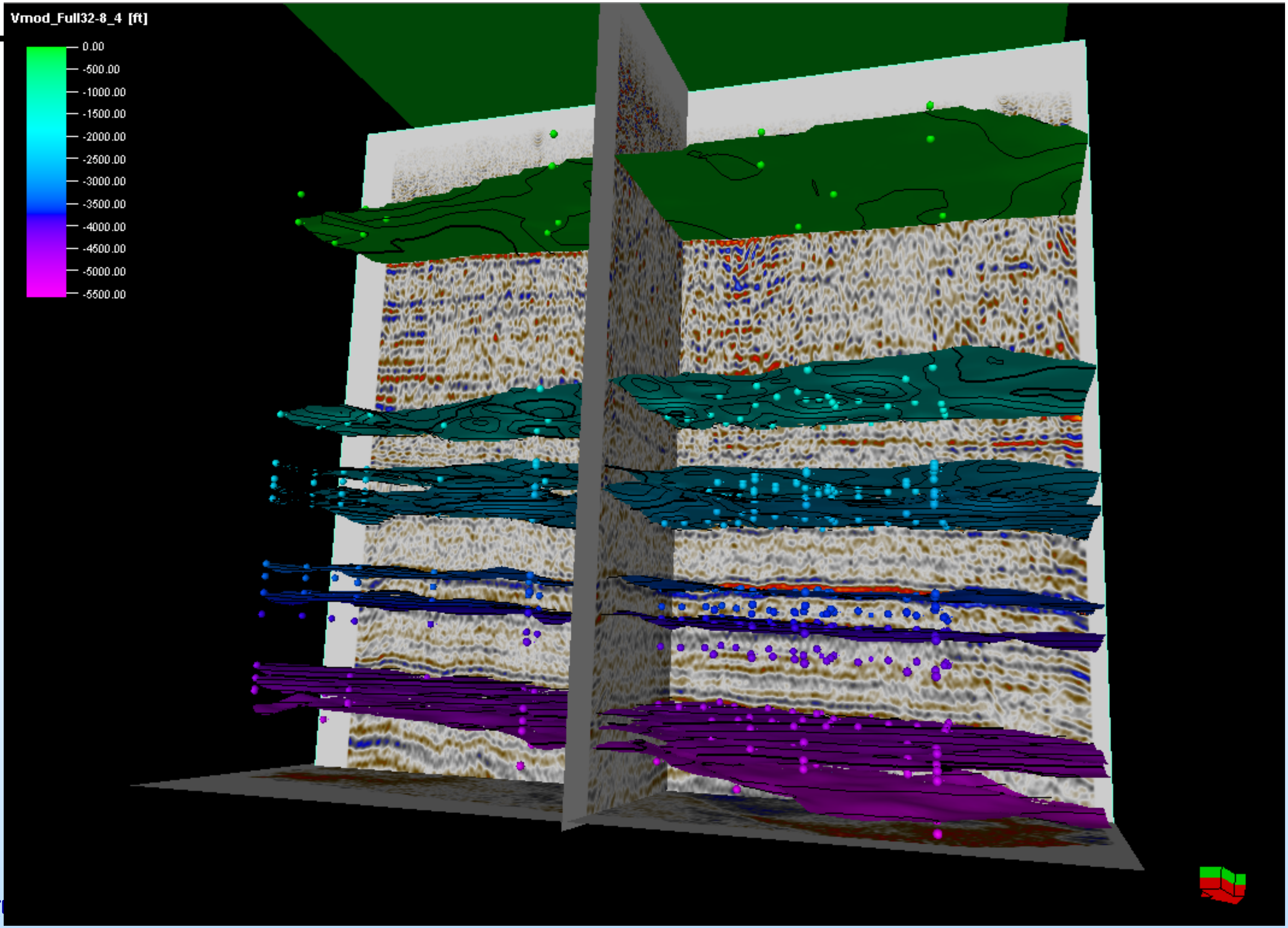
Existing 2D Data – Basin Modeling



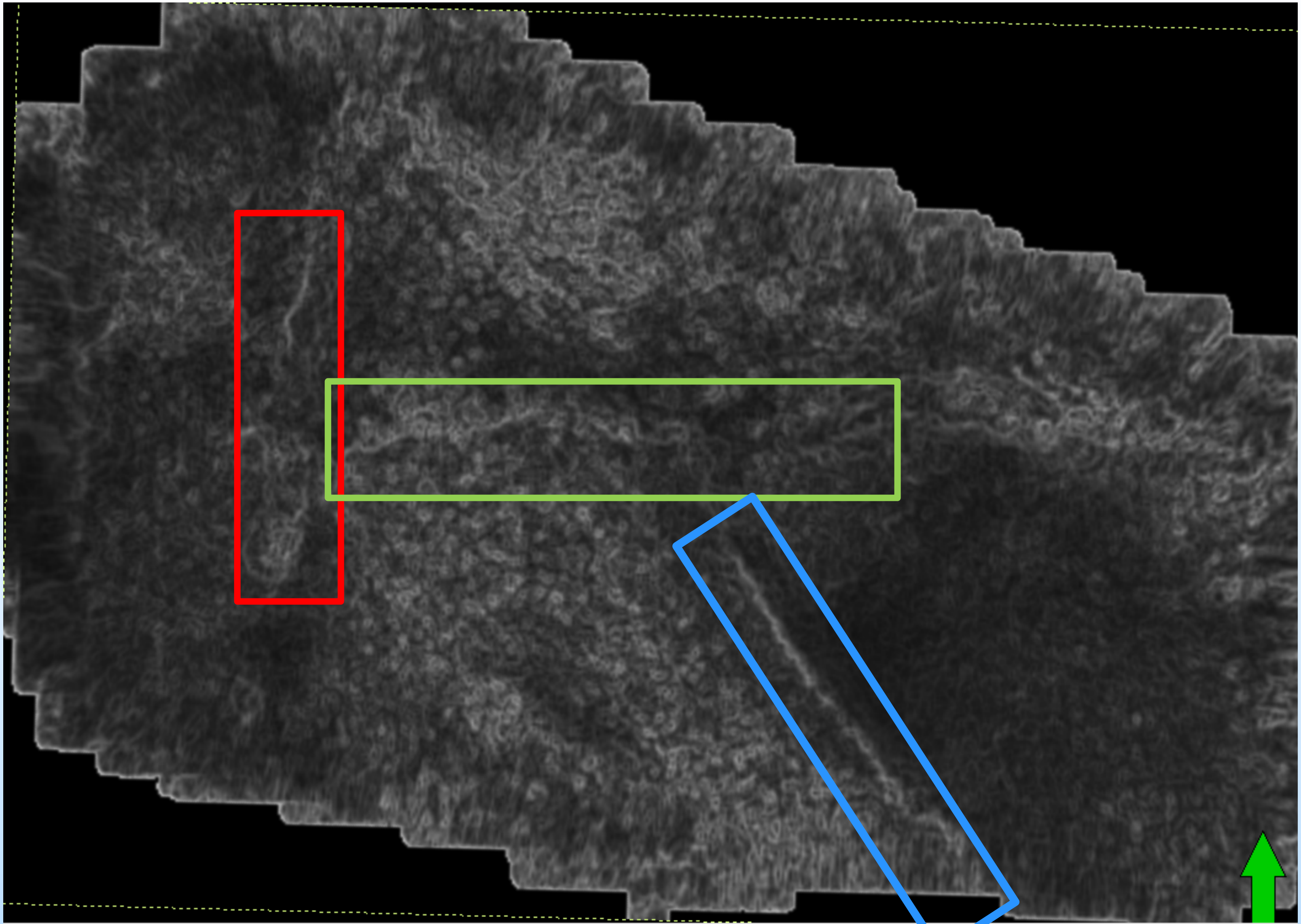
- Existing 2D data is mostly Mid 1980's vintage and 15-64 fold

- Important geologic considerations:
  - thermal history,
  - burial history,
  - tectonic history,
  - vitrinite reflectance,
  - TOC,
  - heat conductivity/ thermal gradients/
  - stratigraphy,
  - Structure,
  - porosity &permeability,
  - unconformities,
  - fluid flow regimes, etc.

Major Structural Tops with Well Ties

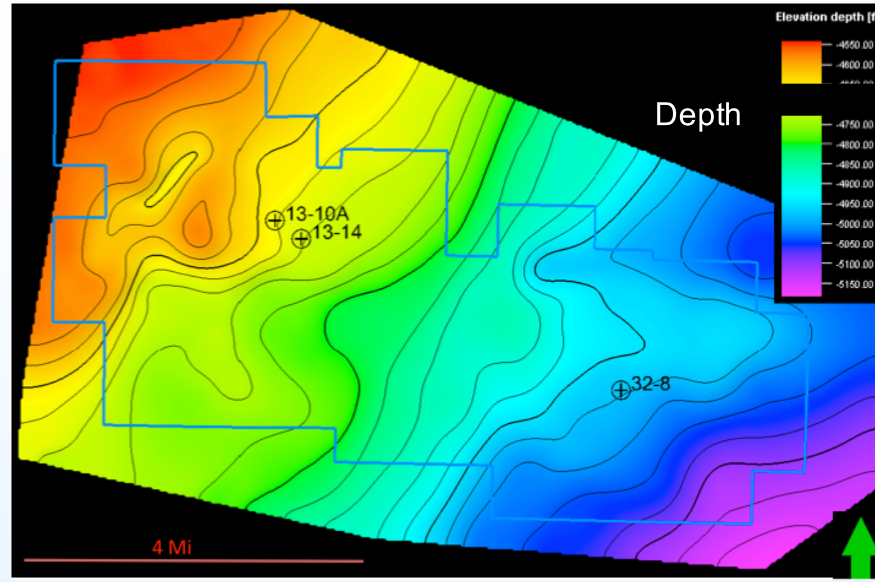


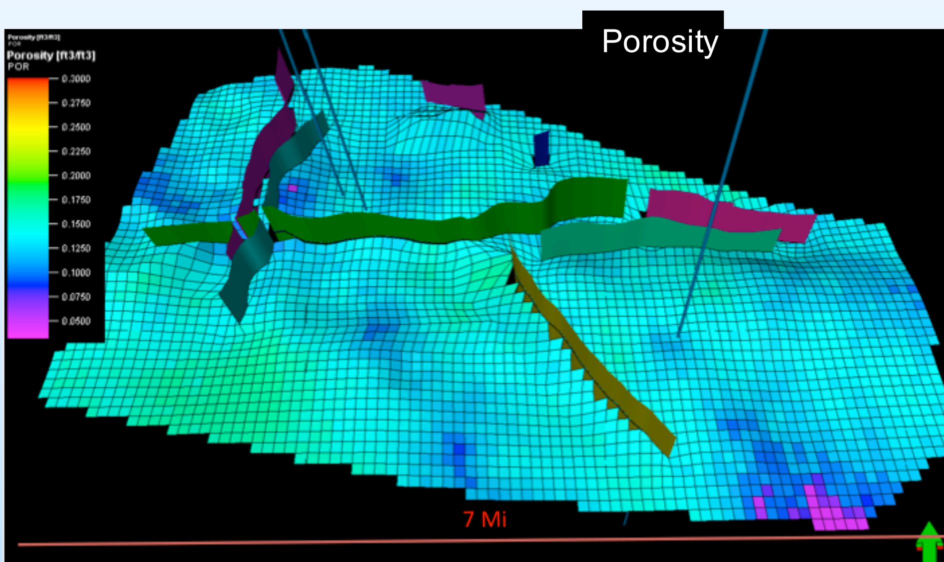
Large Scale Faults and Channels

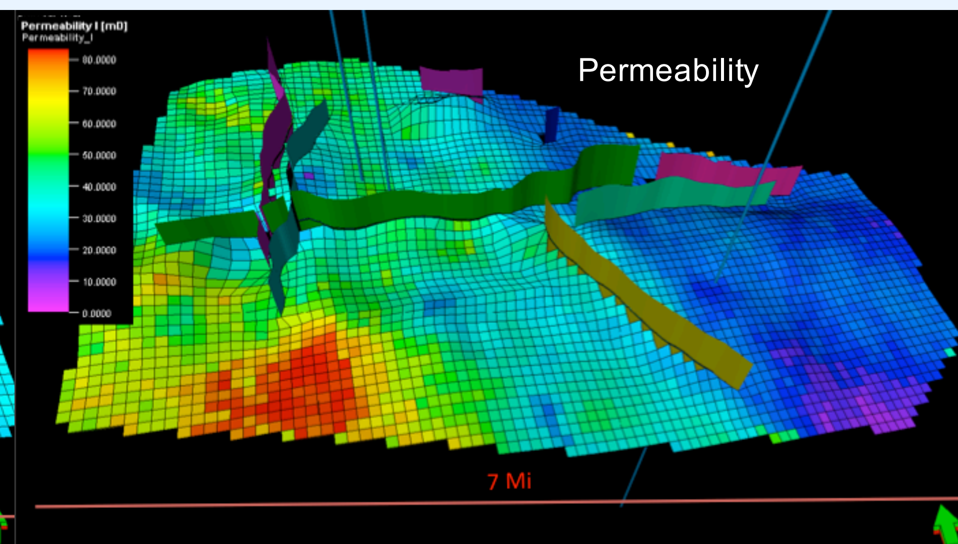


Geologic Model - Current State

- Integrates seismic and well data and honors both
- Channel features can be correlated across reservoir
- Includes fault planes as picked from seismic interpretation.







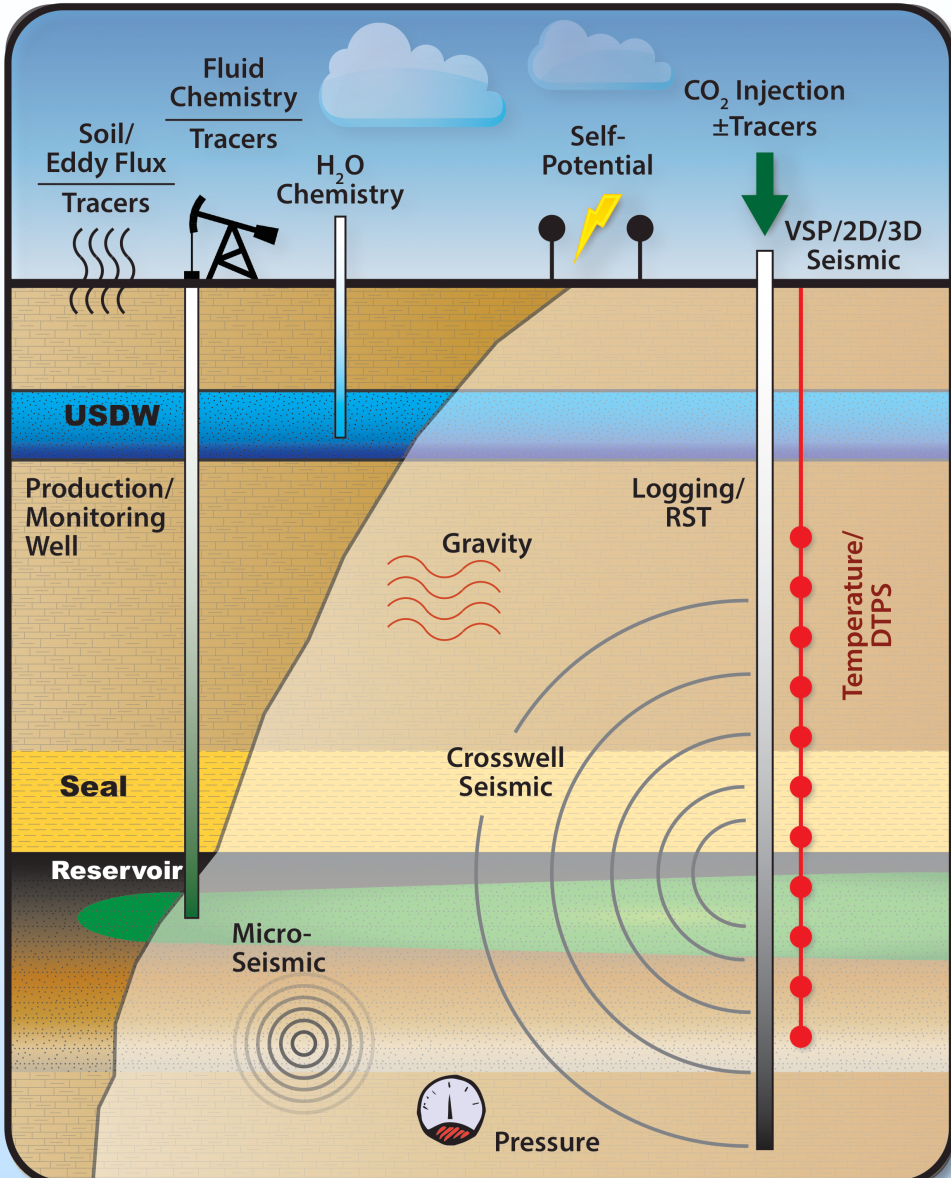
Next Steps

- Geologic Characterization
  - Reservoir Analysis - integrate Macro and micro scales
  - Study fluid rock interactions, and implications for sweep and storage efficiency
  - Caprock Analysis
- Seismic Characterization
  - Detailed geologic model centered on two injection wells based off of 3D VSP data
  - Basin-scale petroleum system modeling

MVA Work

- Focuses on establishing baseline data, then comparing repeat data to ensure successful long term storage of CO_2
  - 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
- MVA also uses geologic models and simulation to make predictions of storage security

Direct Monitoring Strategy



Detecting CO_2 at Surface:

- Surface soil CO_2 flux
- Atmospheric CO_2/CH_4 eddy flux
- Gas phase tracers

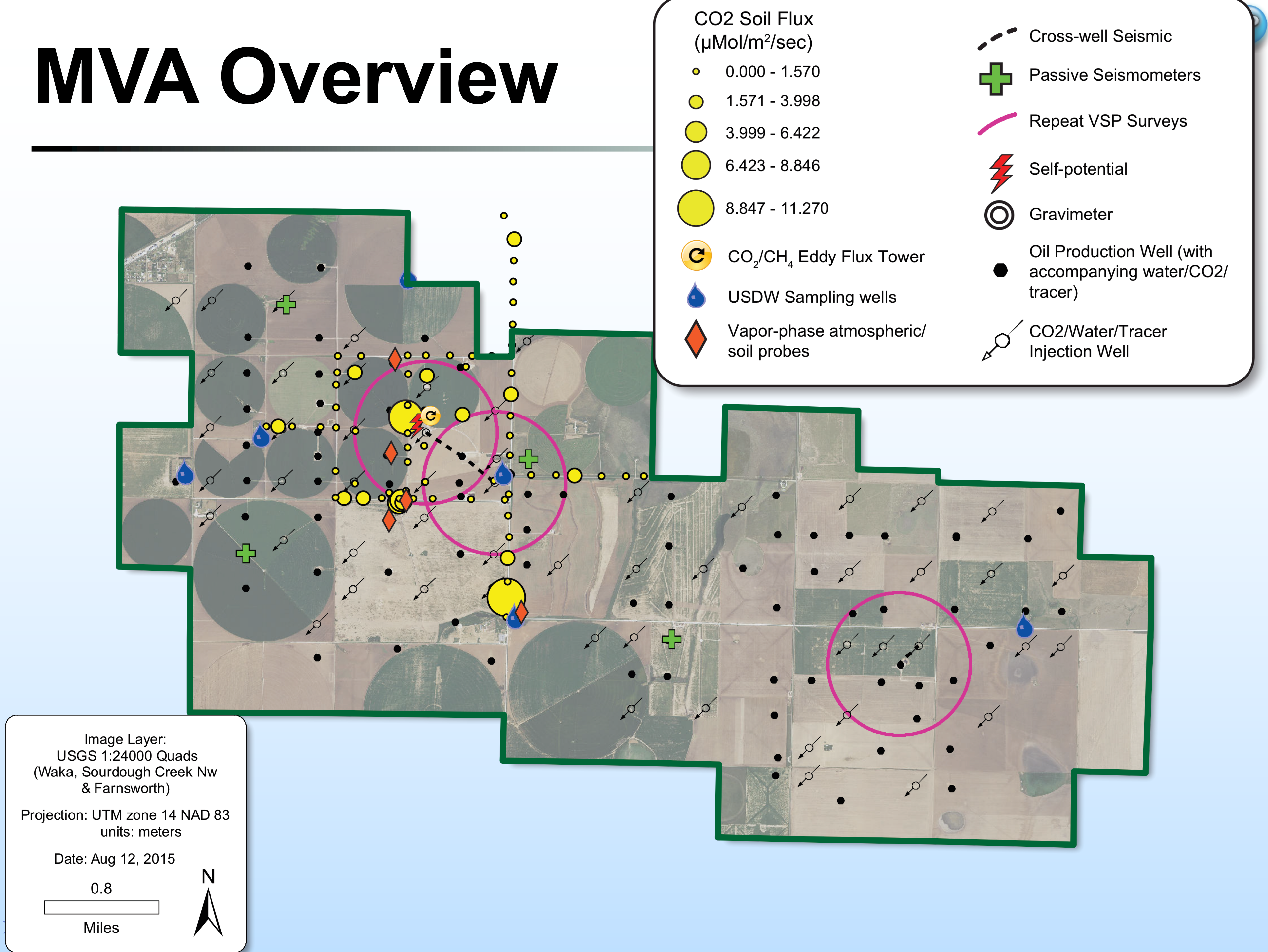
Detecting CO_2 and/or other fluid migration in Target/Non-Target Reservoirs:

- Groundwater chemistry (USDWs)
- Water/gas phase tracers
- Self-potential

Tracking CO_2 Migration and Fate:

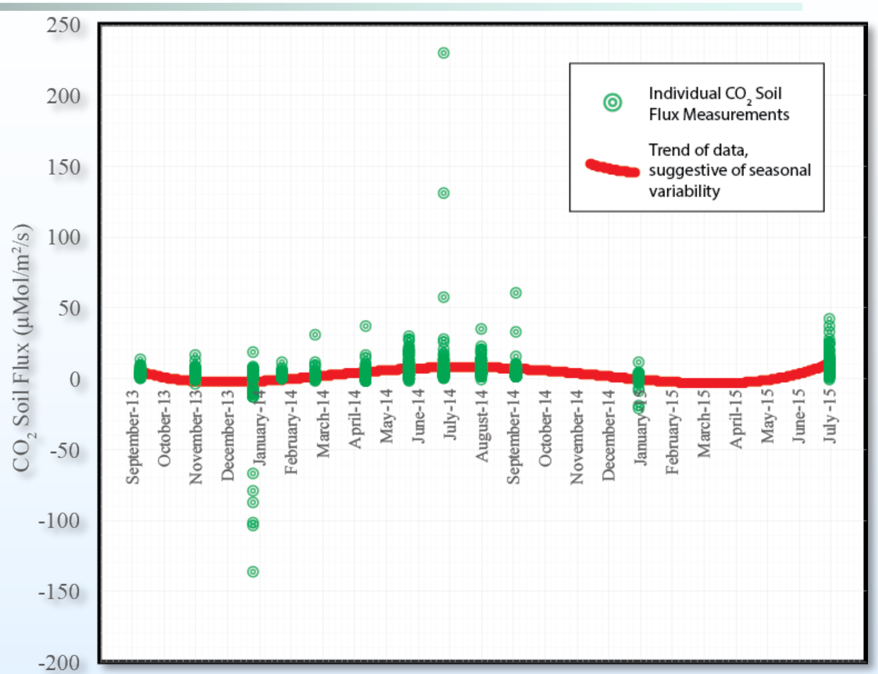
- *In situ* pressure & temperature
- 2D/3D seismic reflection surveys
- VSP and Cross-well seismic
- Passive seismic
- Fluid chemistry (target reservoir)
- Water/gas phase tracers
- Microgravity surveys
- Water/gas isotopes

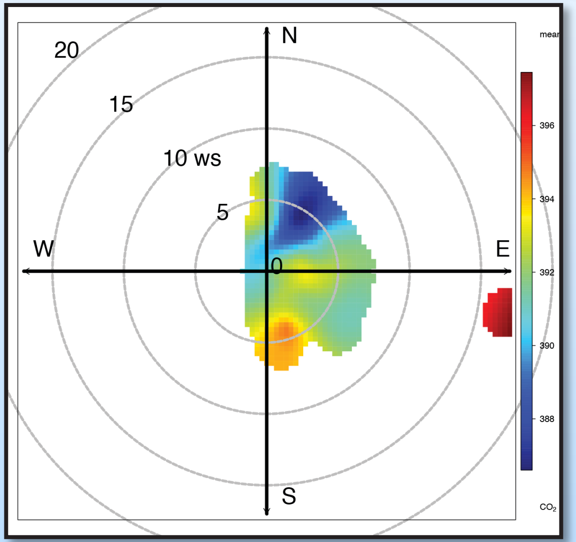
MVA Overview



MVA – Results to Date

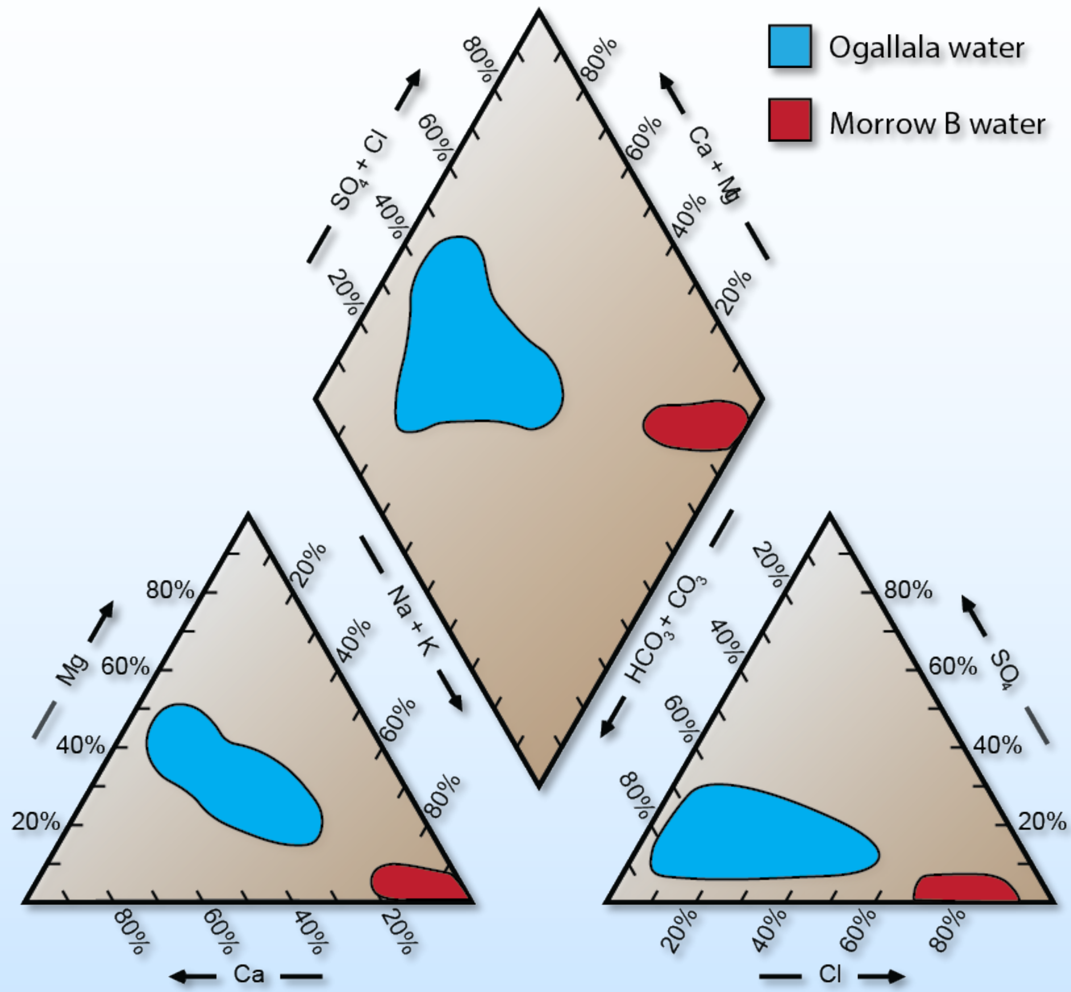
- **Surface and Atmospheric CO_2/CH_4 flux**
  - Soil flux measured quarterly
    - Very sensitive
  - Eddy flux measured continuously
    - Wide area
    - Multiple stations can "triangulate" point sources





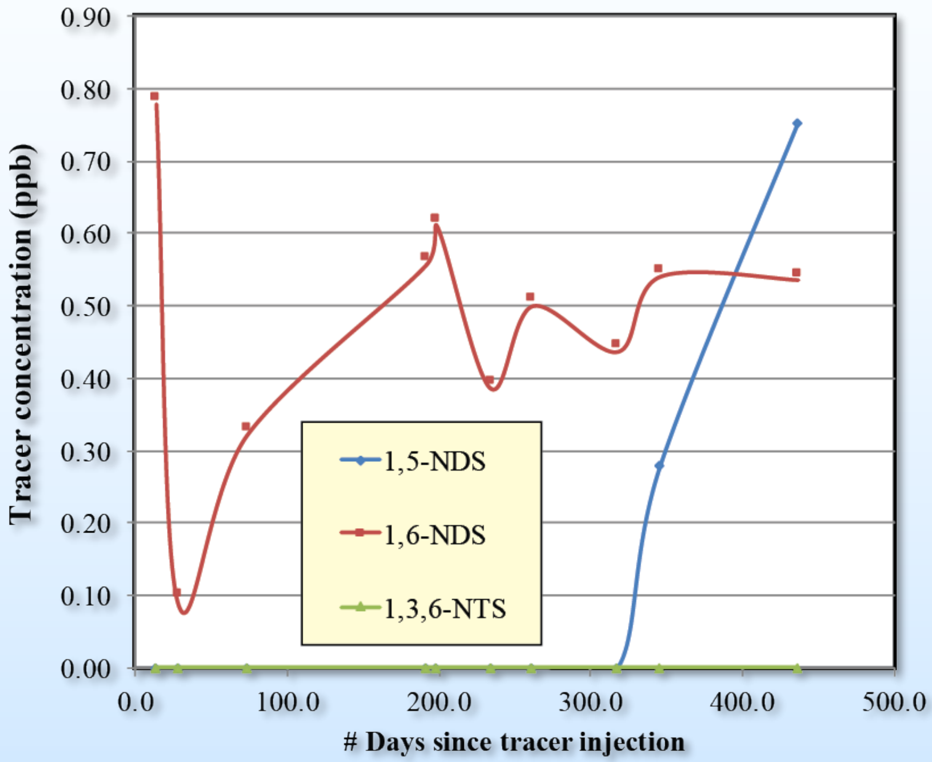
MVA – Results to Date

- **Fluid Chemistry**
  - USDW and reservoir chemistry analyzed quarterly
    - Monitored for brine and/or CO_2 leakage from reservoir to USDW
    - Monitored for CO_2 breakthrough & migration



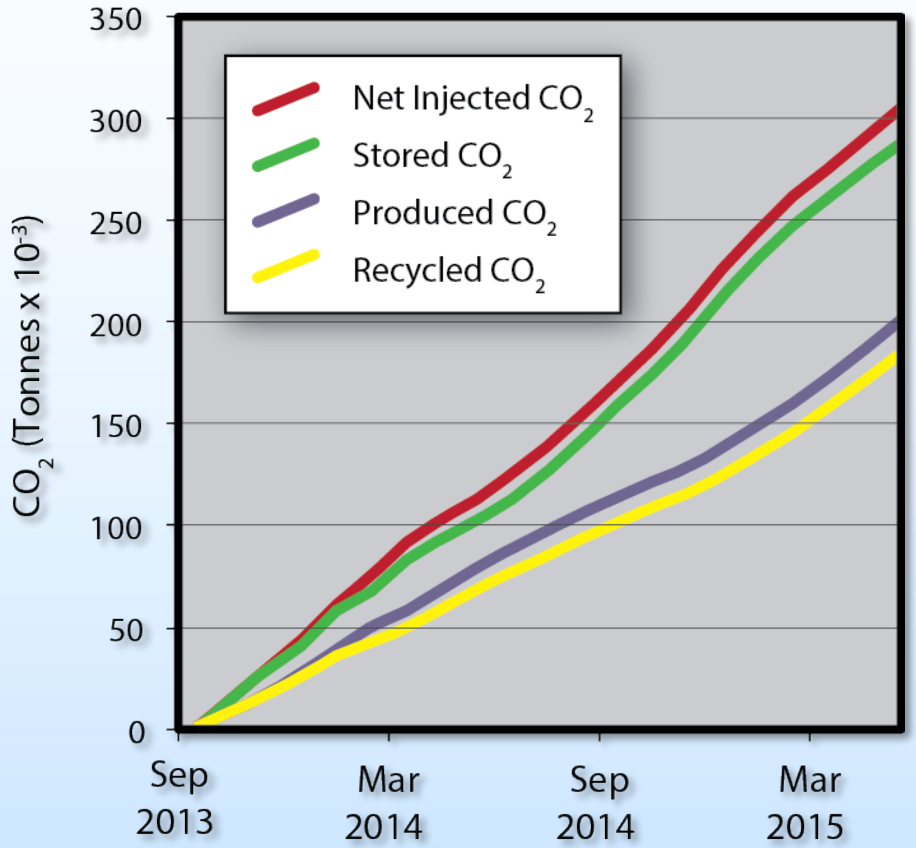
MVA – Results to Date

- **Tracers**
  - Aqueous-phase tracers injected with water; Vapor-phase tracers injected with CO_2
    - Determine reservoir fluid-flow patterns
    - Detection and quantify CO_2/brine leakage to subsurface/atmosphere
    - Evaluate CO_2 saturation levels and storage capacity
    - Evaluate sweep efficiency
    - Confirm other verification methods



MVA – Results to Date

- CO_2 Accounting
  - CO_2, water and oil are accurately metered to/from each injection/production well, and reported daily
    - Allows for near real-time evaluation of CO_2 accounting
    - Currently assessment: >300,000 tonnes of 100% anthropogenic CO_2 stored in subsurface.

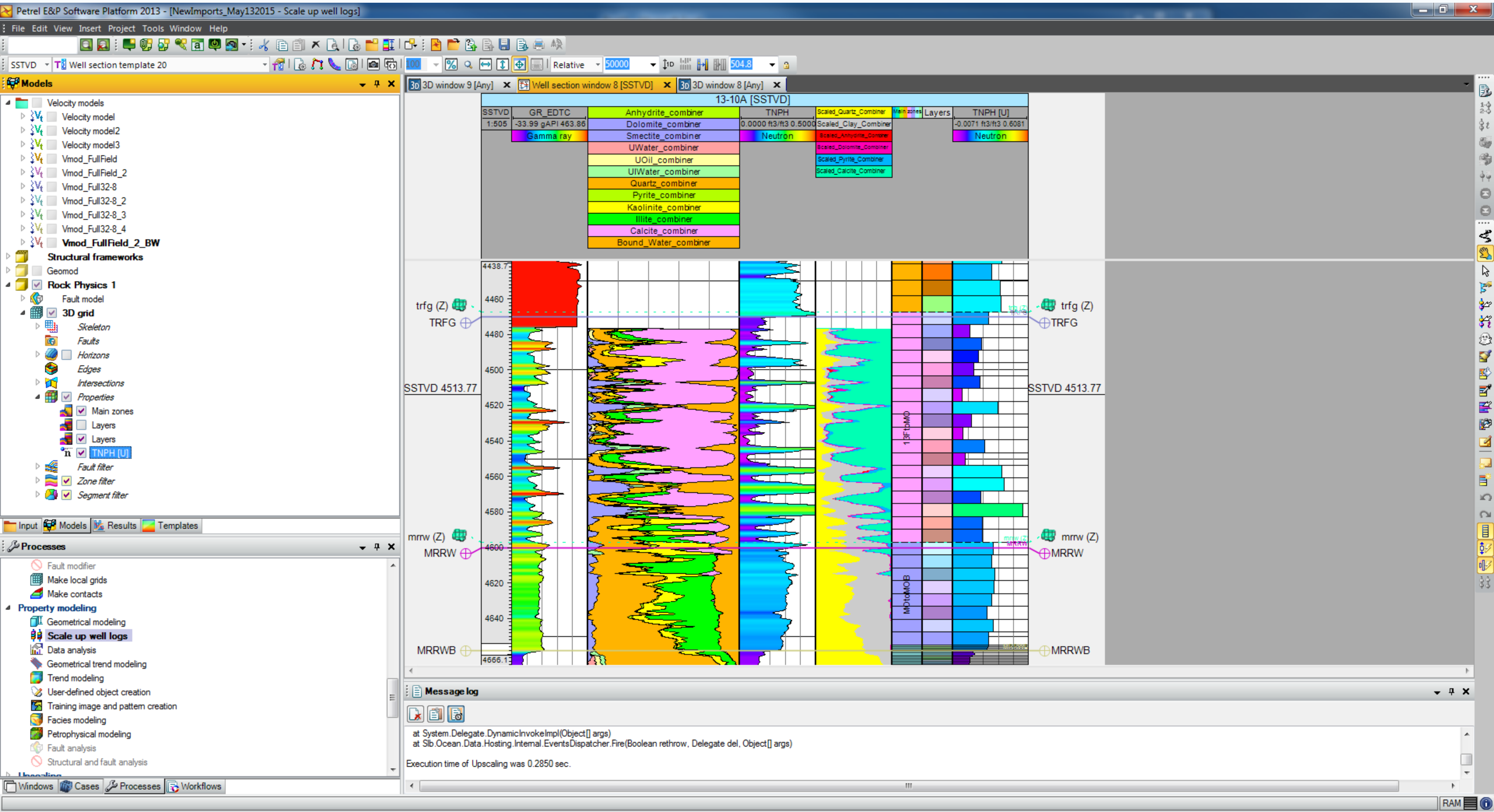


Seismic Monitoring

- First repeat 3D VSP and cross-well data acquired.
  - Direct differencing of the volumes is inconclusive, but only 28,000 tonnes had been injected into the imaged pattern
- Surface and subsurface passive seismic recording to check for induced seismicity
  - Currently archiving well-bore seismic data
- Performing Fluid substitution modeling to understand sensitivity of the system to CO_2

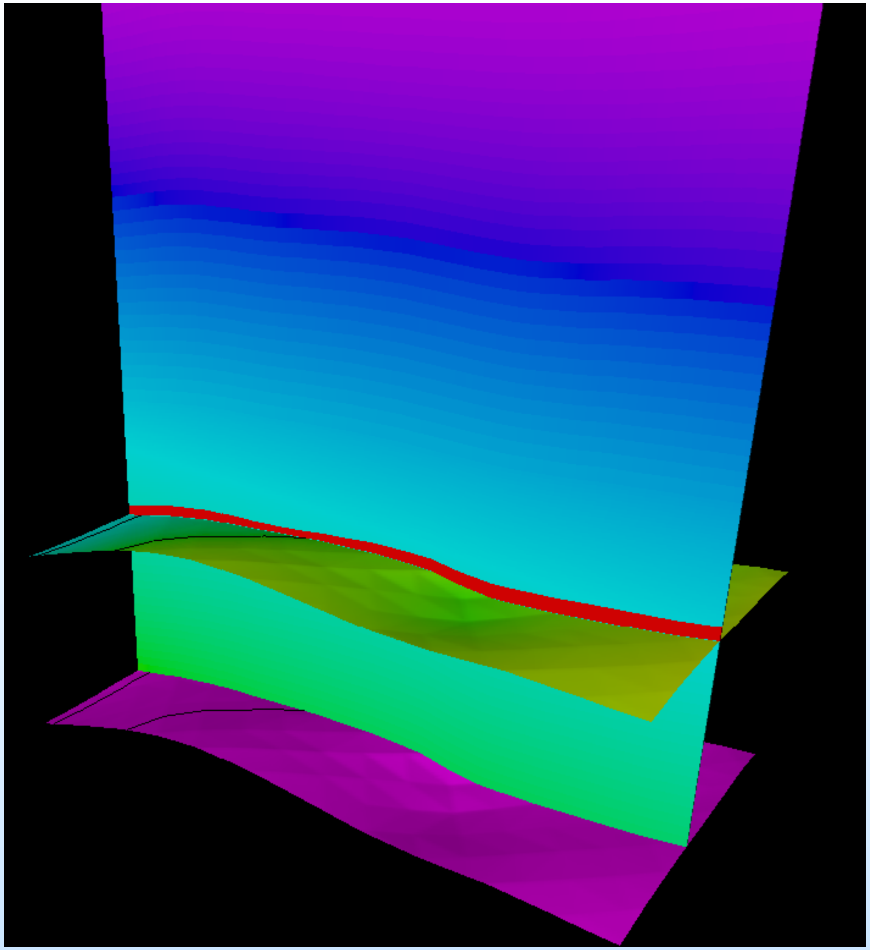
Property Modeling

- Property modeling > Scale up well logs, select wells, and logs, and method ex shown is TNPH



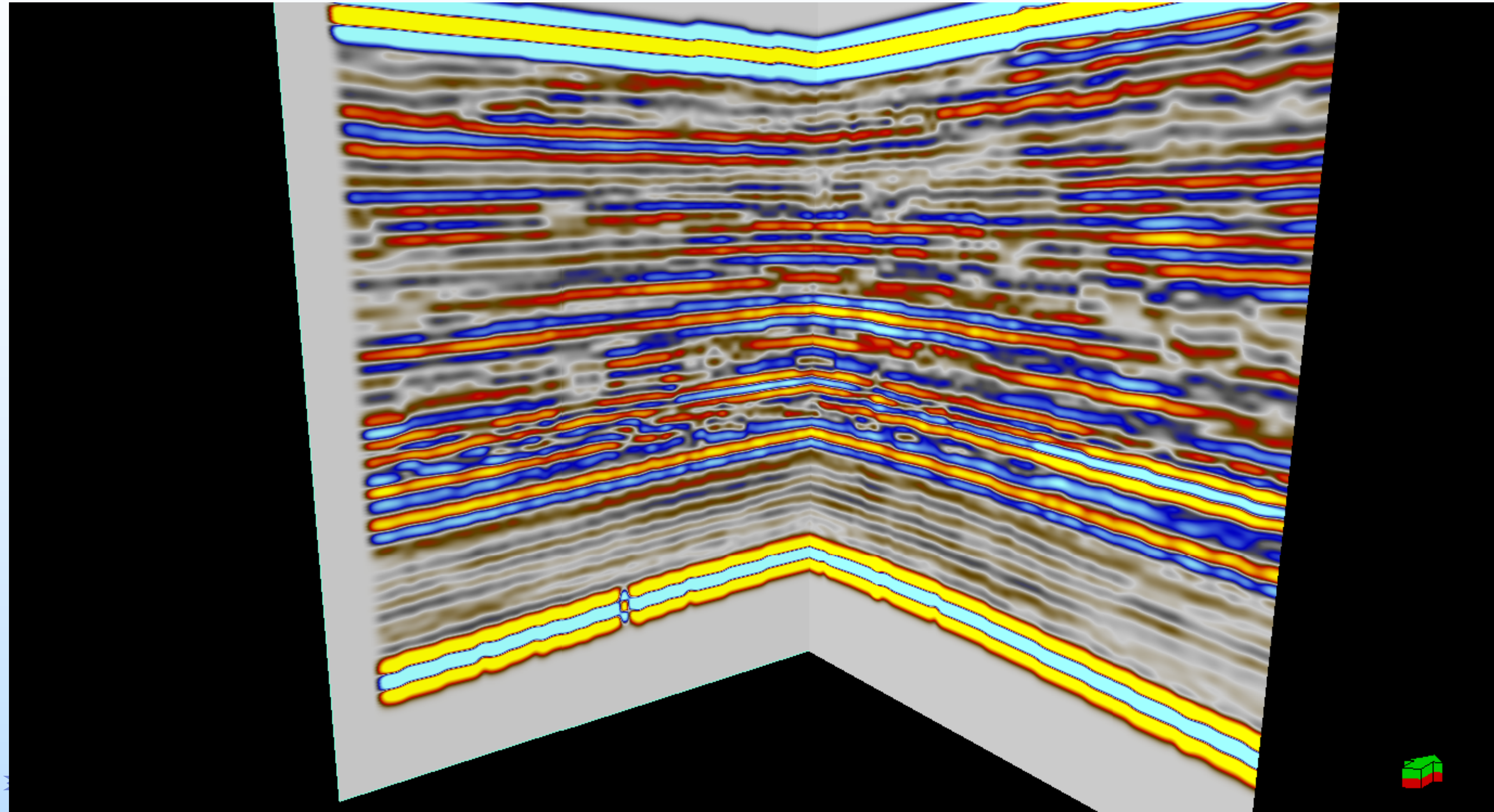
Petrophysical Modeling

- **Petrophysical modeling**, Can take results straight from simulation models or can use geostatistics to calculate from elan logs.
- Define a static state for before CO_2, and a second one for after.



Example of Pressure distribution showing Overpressure at Morrow B Level

Seismic Calculated: 60 hz Ricker Wavelet



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SWP Simulation Analyses

Objective

- Contribute to the understanding of carbon dioxide utilization and storage in petroleum reservoirs via the iterative application of numerical simulation and comparison with field observations.

Research Thrust Areas

- Carbon dioxide interactions with reservoir minerals and fluids.
- Aqueous, nonaqueous liquid, and gas relative permeability models.
- Mixed wettability capillary pressure models.
- Reservoir production history matching through primary, secondary, and tertiary recovery.
- Predictions of future production and carbon dioxide storage in the reservoir.
- Scientific high performance computing numerical simulator for enhanced oil recovery and carbon dioxide storage with coupled geochemistry and geomechanics.
- Reduced order models for risk assessment analyses.

Connections with other SWP Workgroups

Simulation WG – Risk Assessment WG

- Risk Assessment response surfaces of reservoir behavior for guiding historical matching and field process interpretation.
- Simulation provides HPC numerical simulators, three-phase relative permeability models, and historically matched geologic conceptual models.

Simulation WG – Characterization WG

- Characterization provides scheduled updates to a series of standardized geologic conceptual models and computational domains.
- Simulation identifies data needs and visualization of reservoir thermal and hydrological processes.

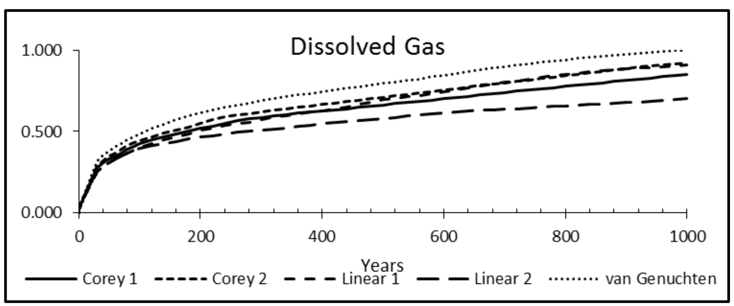
Simulation WG – Monitoring, Verification and Accounting WG

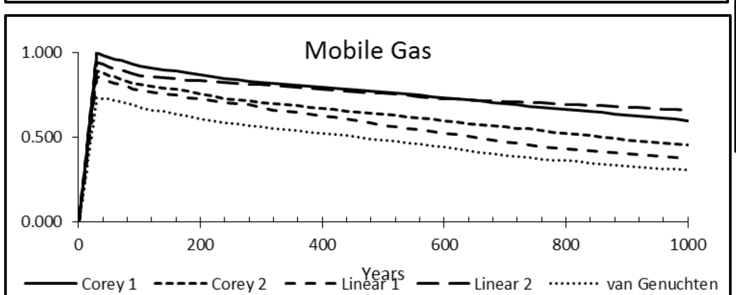
- Simulation contributes to the understanding of field observations via numerical simulation of reservoir processes.
- MVA records field observations for comparisons against numerical simulations and identifies data anomalies

Progress and Status of Simulation Tasks

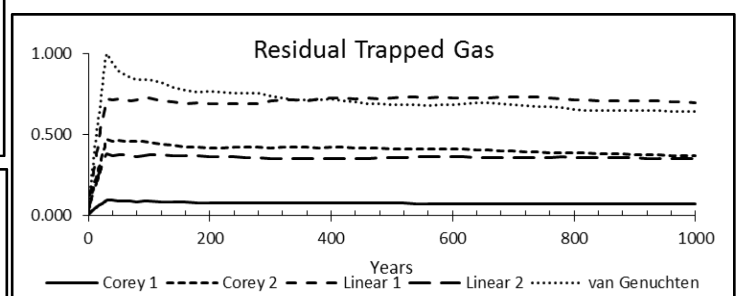
Relative Permeability and Mixed Wettability Models

- Exploration of the impact of relative permeability type models and parameters on the fate of CO_2 injected into deep saline reservoirs
- Exploration of the impact of three-phase relative permeability models and hysteresis models on the enhanced recovery of oil and long-term storage of CO_2 injected into a petroleum reservoir



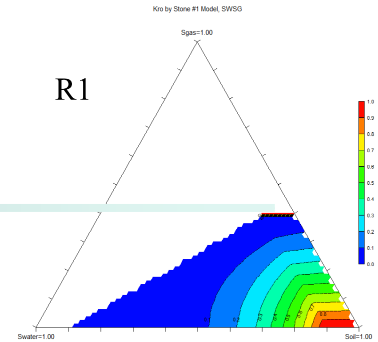


Four three-phase relative permeability models to calculate the impact of nonaqueous liquid relative permeability on the fate of injected CO_2

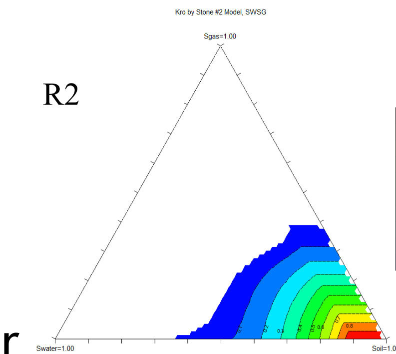


Normalized data of the total mass of CO_2 through time as trapped gas, dissolved gas, and mobile gas

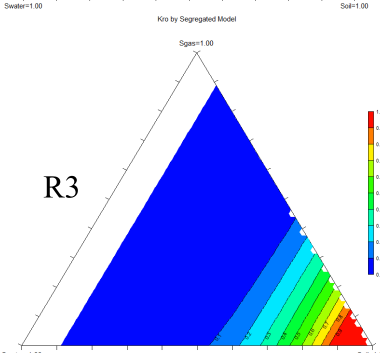
R1



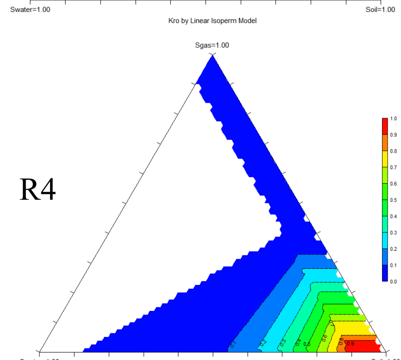
R2



R3



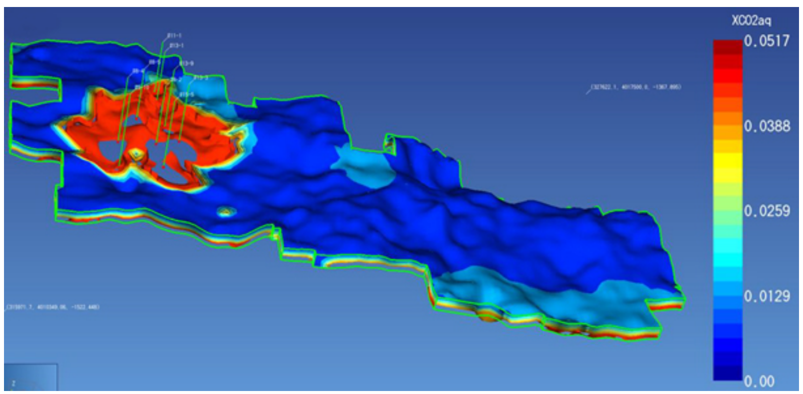
R4



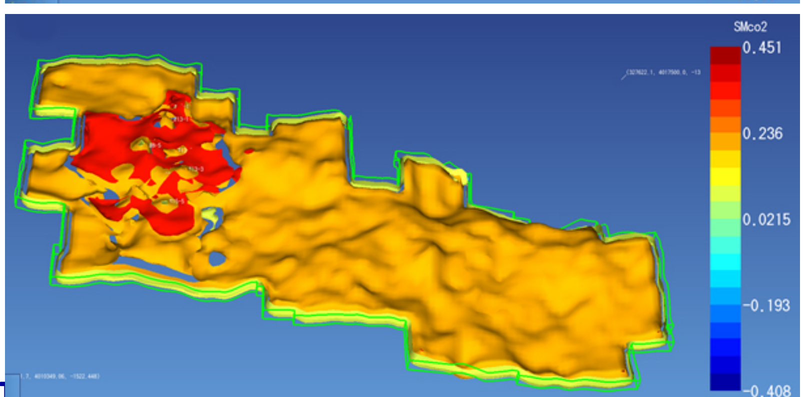
Progress and Status of Simulation Tasks

Carbon Dioxide Interactions

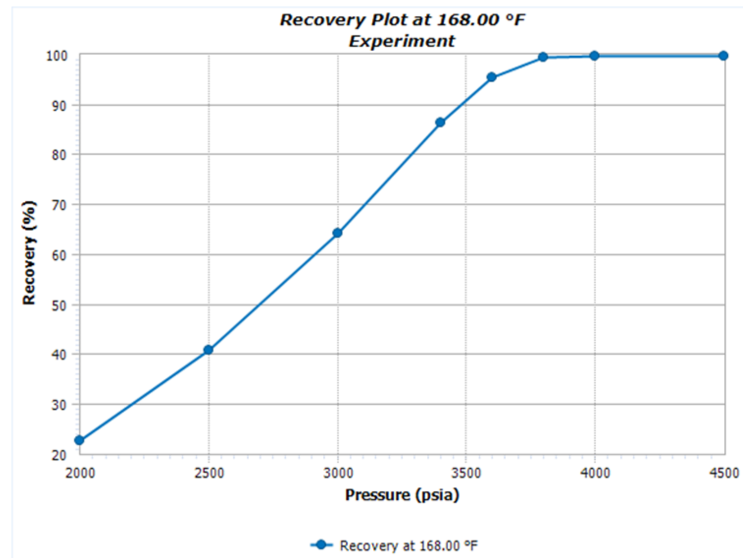
- Numerical reactive transport modeling of water-CO_2-mineral interactions.
- Compositional construction of Farnsworth oil sampled in 1956 from saturation pressure, constant mass expansion, differential liberation, and multi-stage separator experiments.
- Minimum miscibility pressure analysis of 1956 Farnsworth oil sample.



Mole fraction of aqueous CO_2 after 30 years, with CO_2 injected for first 10 years.



Mass (kg) of CO_2 precipitated as carbonate minerals per bulk volume (m^3) after 30 years, with CO_2 injected for first 10

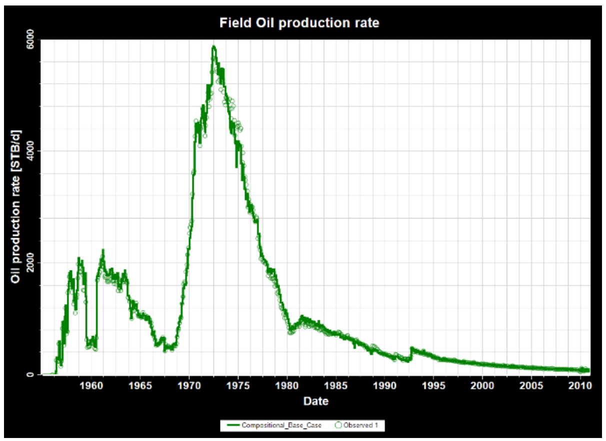


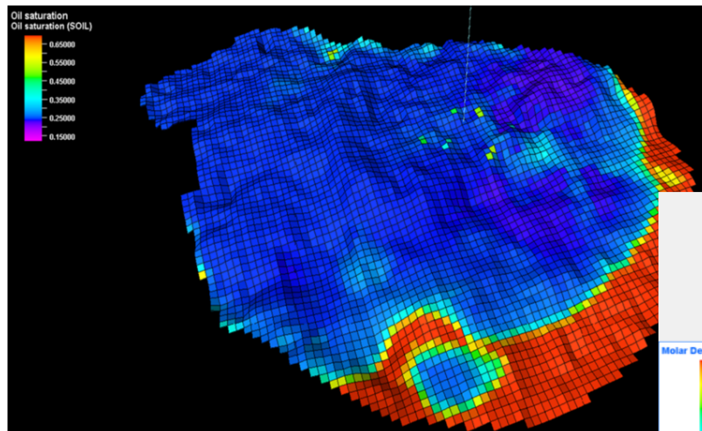
Minimum miscibility pressure determination for pure CO_2 and compositional construction of Farnsworth oil sampled in 1956.

Progress and Status of Simulation Tasks

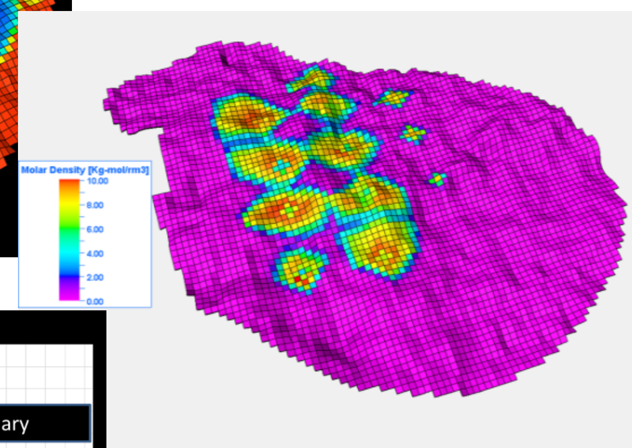
History Matching, Reservoir Performance, and CO_2 Storage

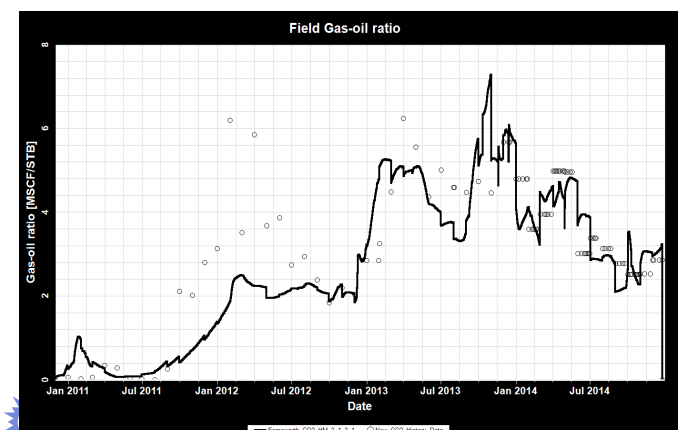
- Calibrated history match of Farnsworth unit over primary and secondary recovery.
- Predictions of CO_2 utilization and storage and tertiary oil recovery.

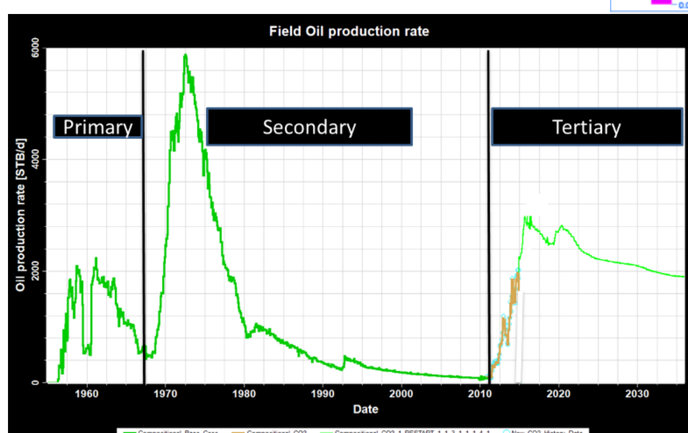




Primary and secondary recovery history matching





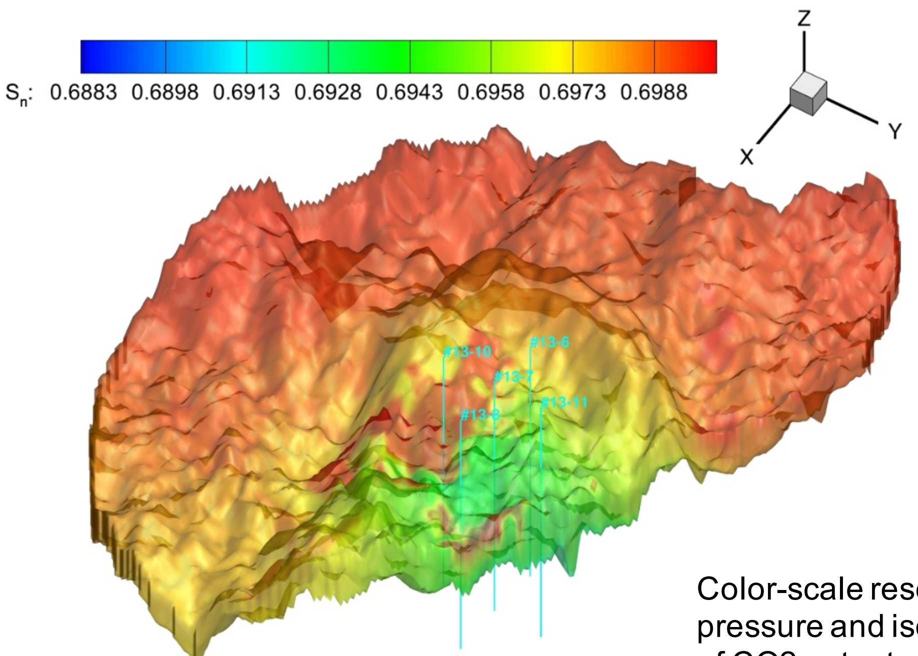


Tertiary recovery and CO_2 storage predictions

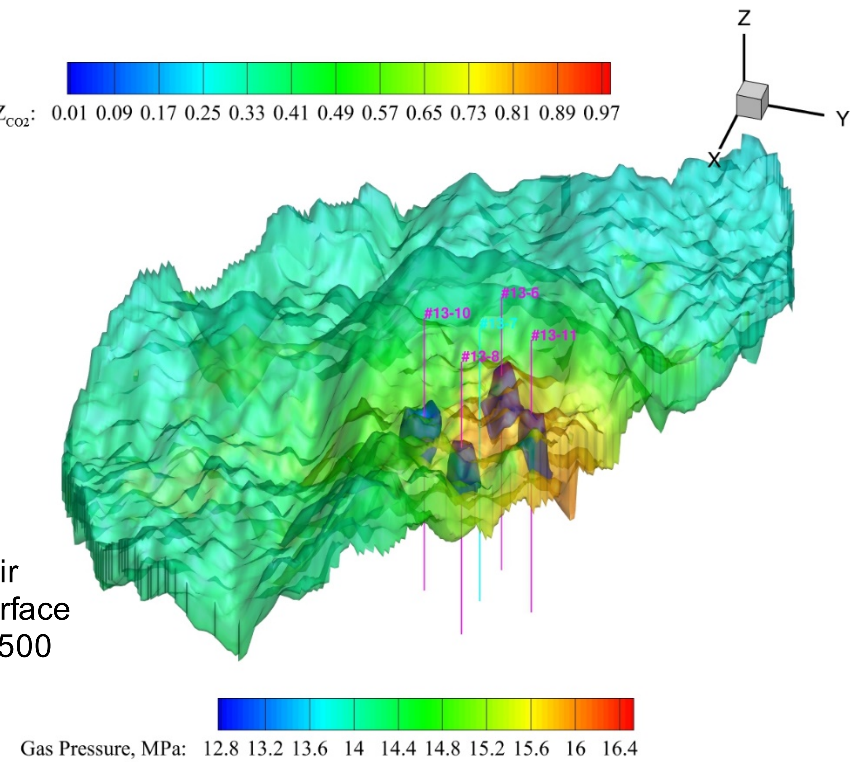
Progress and Status of Simulation Tasks

HPC Scientific Simulator

- Release STOMP-EOR to the SWP community with coupled geochemistry with sequential and threaded implementations
- Development of block refinement grid capabilities for isolation of five-spot well patterns
- Parallelization via Global Arrays and MPI; release to SWP planned for early 2016



Nonaqueous-liquid saturation around a five-spot pattern in the Farnsworth Unit after 2500 days of primary recovery.

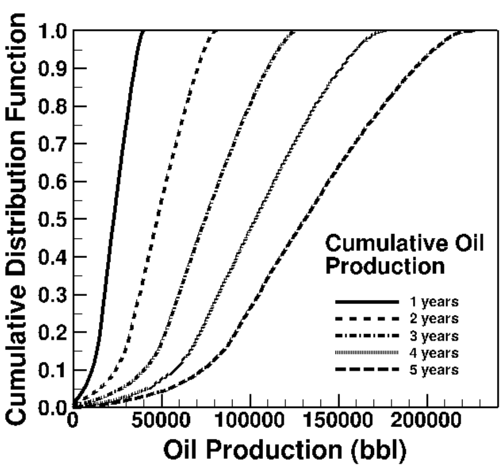


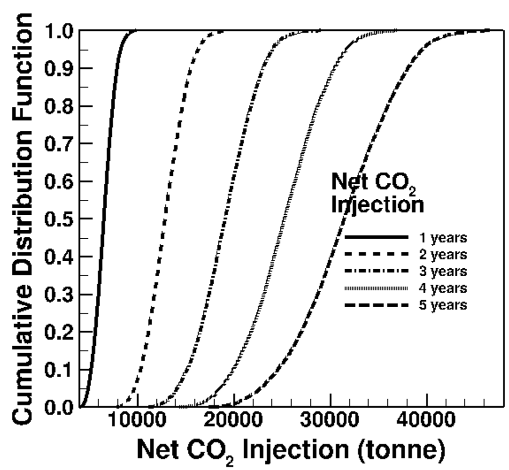
Color-scale reservoir pressure and iso-surface of CO2 extent after 500 days of the WAG schedule.

Progress and Status of Simulation Tasks

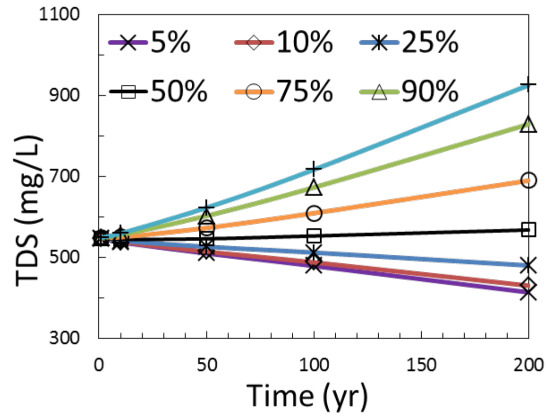
Reduced Order Modeling

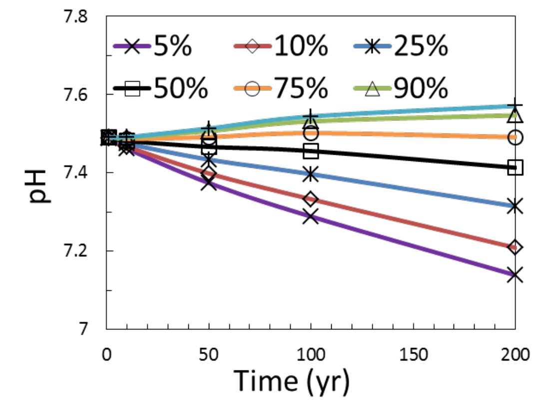
- Probabilistic risk analysis of CO_2 storage and EOR using a response surface methodology (RSM) for Farnsworth.
- Development of an integrated framework for optimizing CO_2 sequestration and EOR.
- Quantification of uncertainties in CO_2 trapping mechanisms with a generic model using a polynomial chaos expansion method.
- Quantification of risk analysis on the potential chemical impacts on groundwater in Ogallala aquifer due to CO_2 leakage using RSM approach





The CDFs of predicted oil production and net CO_2 injection.





The uncertainty bounds of predicted TDS and pH.

Presentation Outline

- Introduction, Goals and Major Accomplishments (Reid Grigg)
- **Technical Status:**
  - Characterization and MVA (Robert Balch)
  - **Simulation and Risk (Brian McPherson)**
- Summary, Questions and Answers

Presentation Outline

- Introduction, Goals and Major Accomplishments (Reid Grigg)
- **Technical Status:**
  - Characterization and MVA (Robert Balch)
  - **Risk Assessment and Results**
- Summary, Questions and Answers

Risk Assessment Workflow (6 Tasks)

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

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Risk Identification (Risk Source Assessment)

Online Risk Workshop

- Jan. 13 and 16, 2014
- Expert-Weighted Risk (= Likelihood x Severity) for ranking
- Total 405 FEPs identified
- 23 project experts evaluated 79 initial FEPs, and generated & evaluated 24 new FEPs.
- 10 FEP groups

Ongoing 2015 FEPs Re-evaluation/Ranking

- 1st email survey during May & June 2015
- 13 project experts evaluated top 50 FEPs of 2014
- Finished preliminary analysis
- 2nd survey for the identification of new FEPs is under preparation

Risk Assessment Workflow (6 Tasks)

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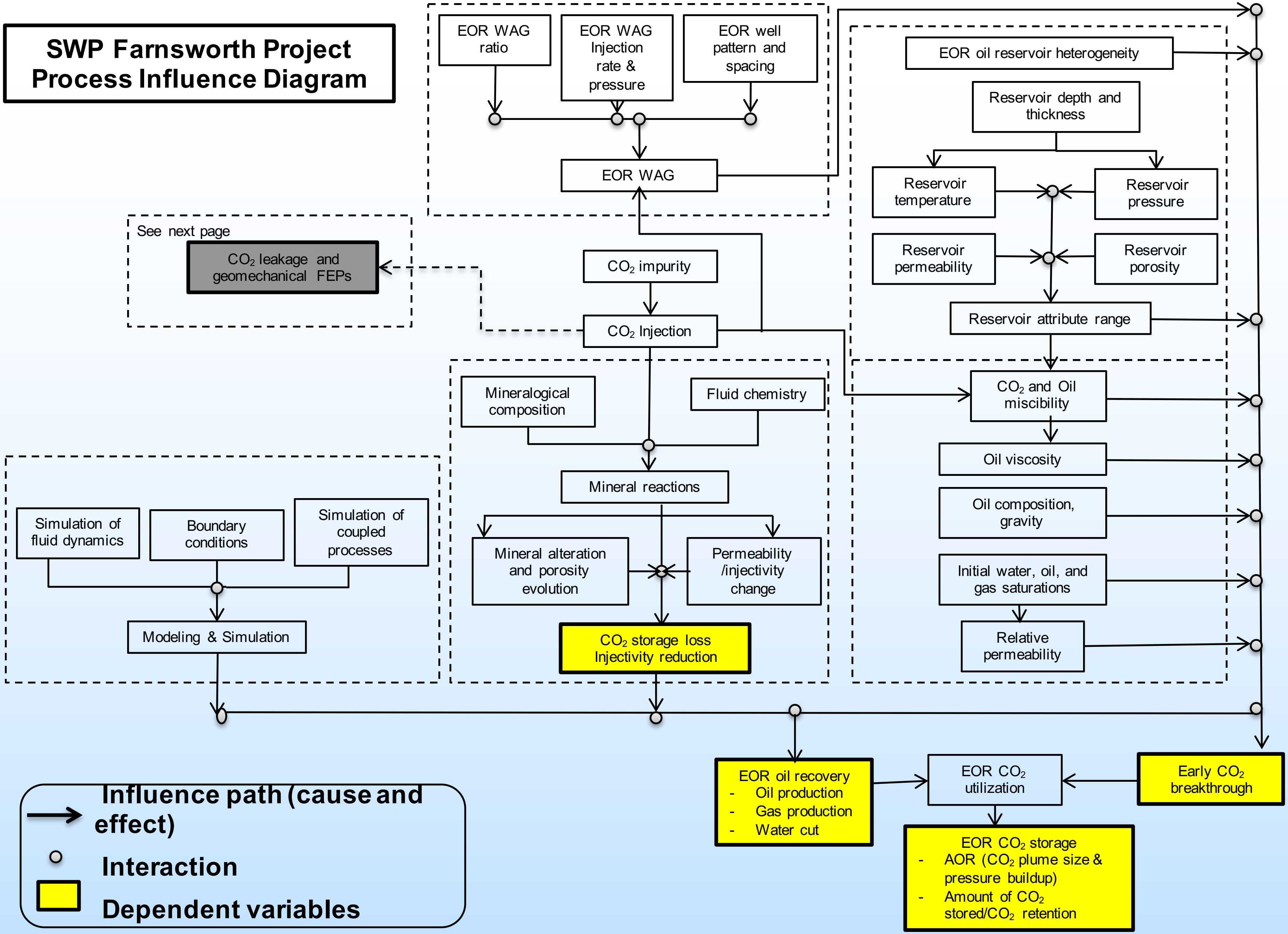
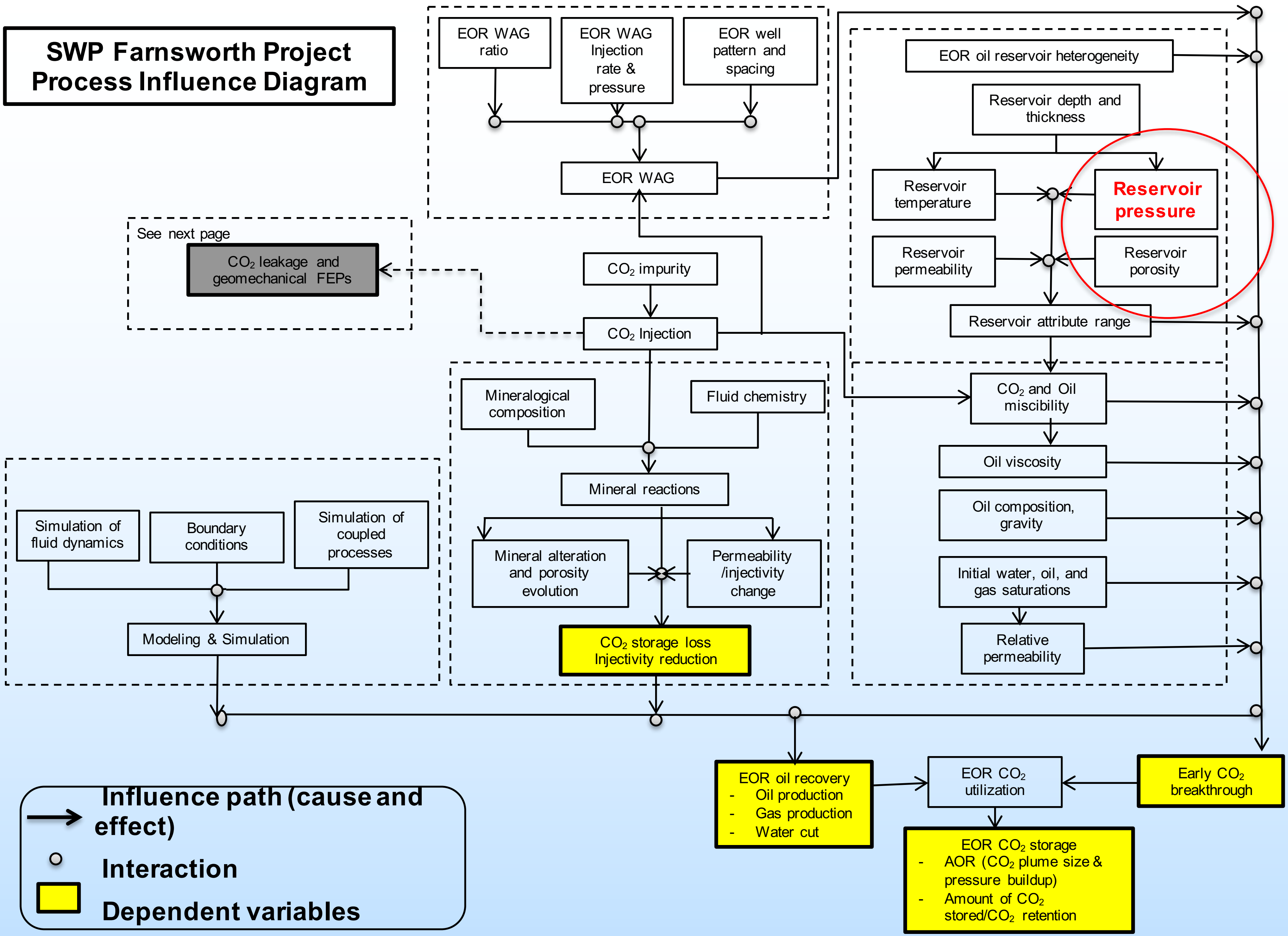
Qualitative Risk Analysis

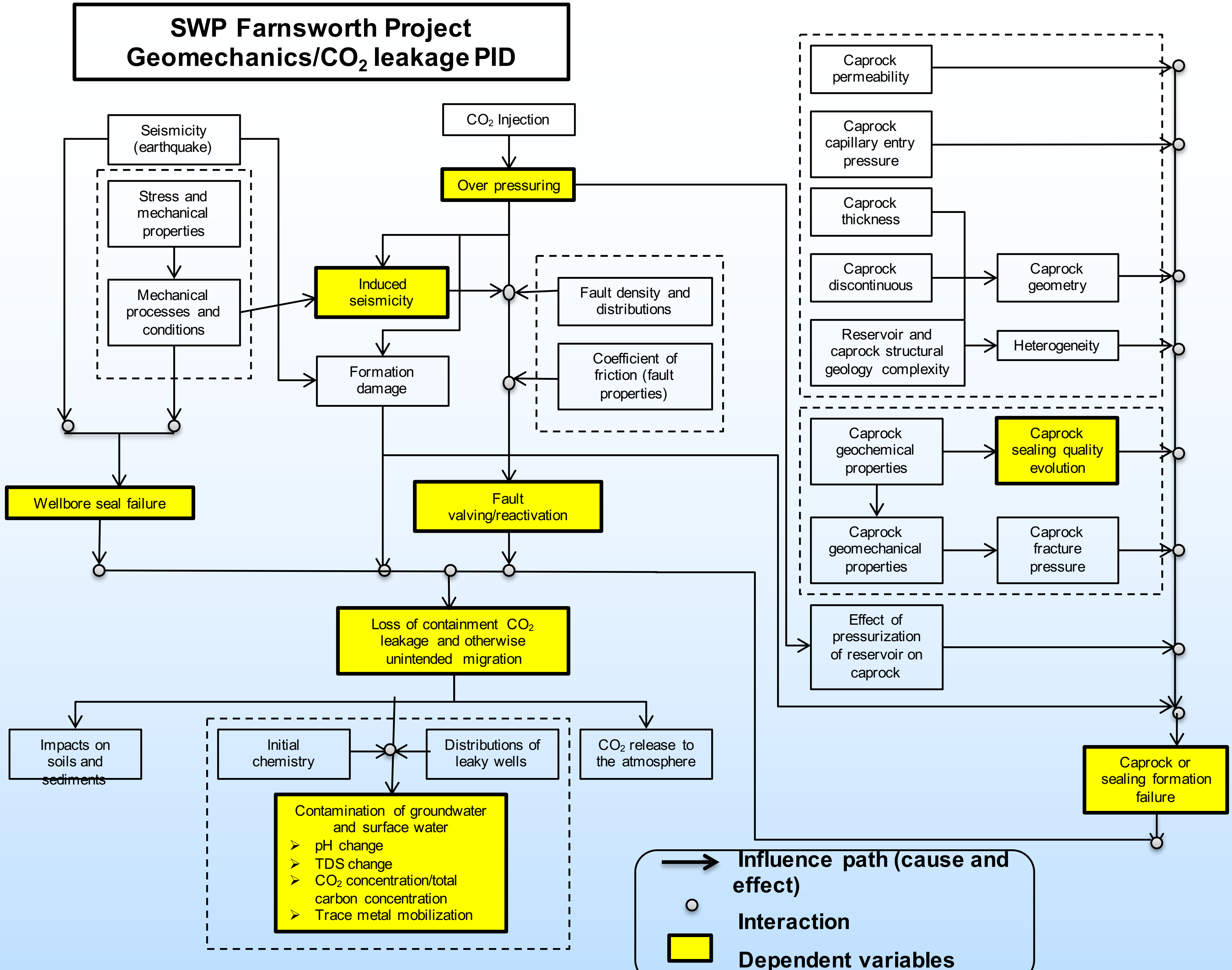
- **Updated the risk registry and identify interactions between FEPs**
- **Identified the risk factors for the quantitative risk analysis**
- **Constructed the process influence diagram (PID)**

  - PID identifies and represents all possible influences between all FEPs within a system.
  - Risk workgroup provided appropriate scenarios to the simulation workgroup throughout the PIDs for the qualitative risk analysis
  - Only direct impacts are included.
  - No loop or chain starts with Events.


SWP Farnsworth Project
Process Influence Diagram
EOR WAG ratio
EOR WAG Injection rate & pressure
EOR well pattern and spacing
EOR WAG
See next page
CO_2 leakage and geomechanical FEPs
CO_2 impurity
CO_2 Injection
Mineralogical composition
Fluid chemistry
Mineral reactions
Mineral alteration and porosity evolution
Permeability /injectivity change
CO_2 storage loss
Injectivity reduction
Simulation of fluid dynamics
Boundary conditions
Simulation of coupled processes
Modeling & Simulation
EOR oil reservoir heterogeneity
Reservoir depth and thickness
Reservoir temperature
Reservoir pressure
Reservoir permeability
Reservoir porosity
Reservoir attribute range
CO_2 and Oil miscibility
Oil viscosity
Oil composition, gravity
Initial water, oil, and gas saturations
Relative permeability
EOR oil recovery
- Oil production
- Gas production
- Water cut
EOR CO_2 utilization
Early CO_2 breakthrough
EOR CO_2 storage
- AOR (CO_2 plume size & pressure buildup)
- Amount of CO_2 stored/CO_2 retention
Influence path (cause and effect)
Interaction
Dependent variables

SWP Farnsworth Project Process Influence Diagram





SWP Farnsworth Project
Geomechanics/CO_2 leakage PID
Seismicity (earthquake)
Stress and mechanical properties
Mechanical processes and conditions
CO_2 Injection
Over pressuring
Induced seismicity
Formation damage
Fault density and distributions
Coefficient of friction (fault properties)
Wellbore seal failure
Fault valving/reactivation
Loss of containment CO_2 leakage and otherwise unintended migration
Impacts on soils and sediments
Initial chemistry
Distributions of leaky wells
CO_2 release to the atmosphere
Contamination of groundwater and surface water
pH change
TDS change
CO_2 concentration/total carbon concentration
Trace metal mobilization
Caprock permeability
Caprock capillary entry pressure
Caprock thickness
Caprock discontinuous
Caprock geometry
Reservoir and caprock structural geology complexity
Heterogeneity
Caprock geochemical properties
Caprock sealing quality evolution
Caprock geomechanical properties
Caprock fracture pressure
Effect of pressurization of reservoir on caprock
Caprock or sealing formation failure
Influence path (cause and effect)
Interaction
Dependent variables

Risk Assessment Workflow (6 Tasks)

- Risk Management Planning
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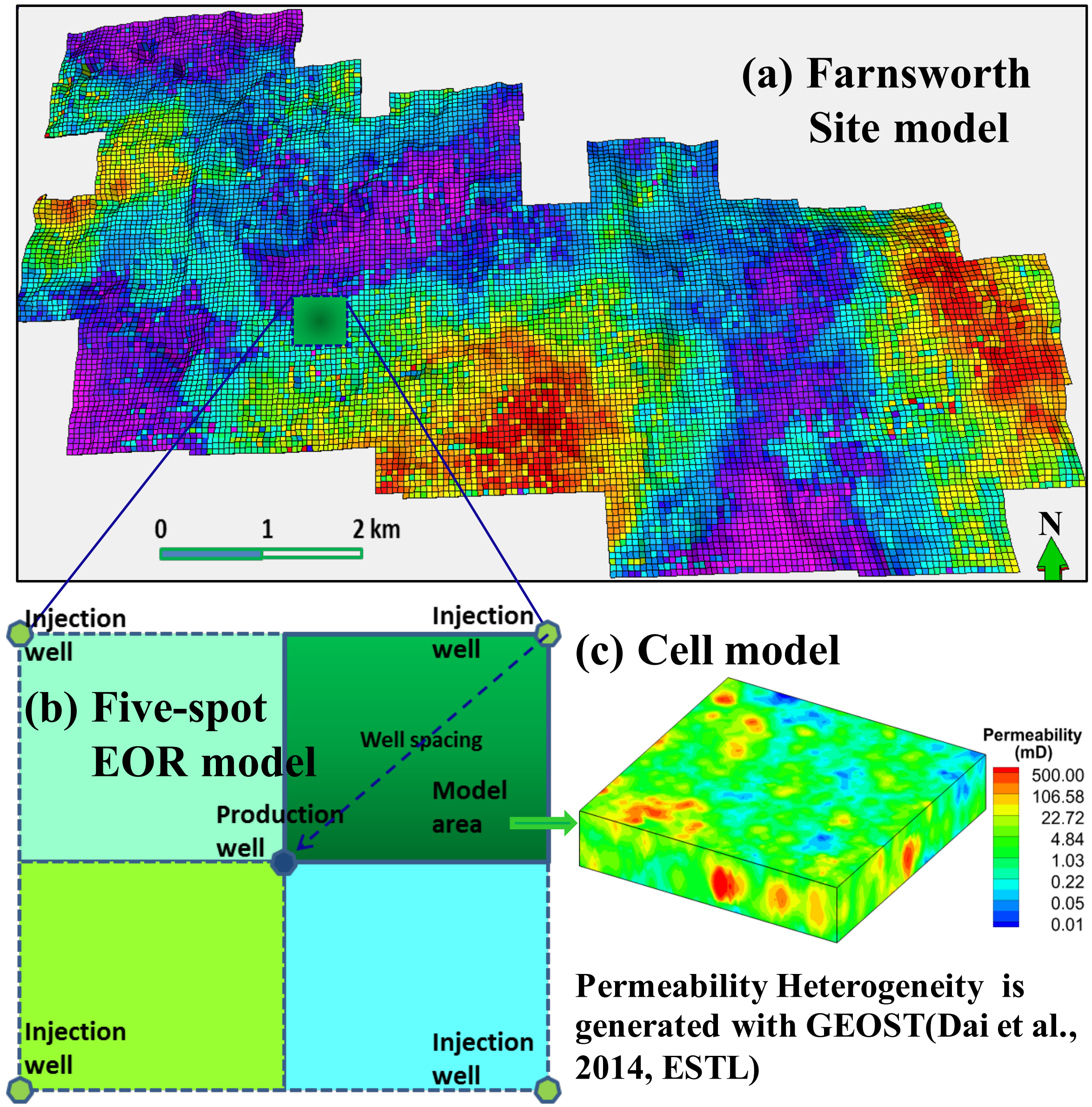
Quantitative Risk Analysis (Risk Characterization)

- Explicit treatment of uncertainties
- Quantitative information on the risk
- Probabilistic assessment due to uncertainty

  - Response Surface Method (RSM) combined with Monte Carlo samplings

  - Polynomial Chaos Expansion (PCE)

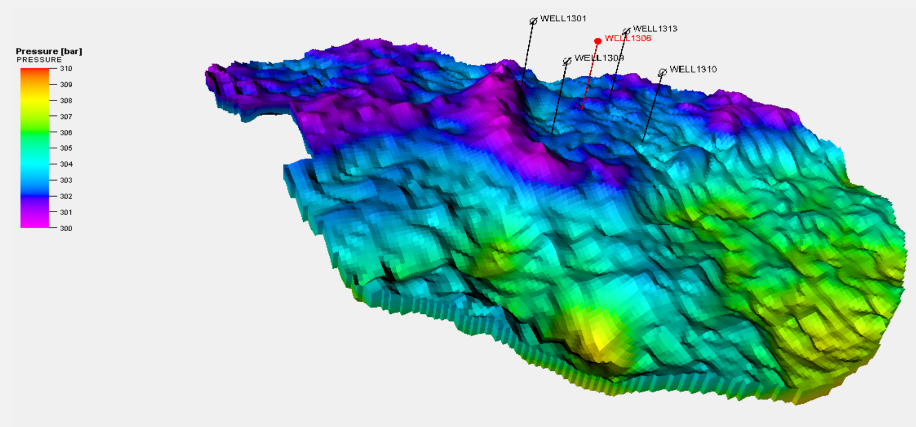
  - CO2PENS



Multi-scale simulations of CO_2-oil-water flow and transport in a heterogeneous reservoir based on a five-spot EOR pattern

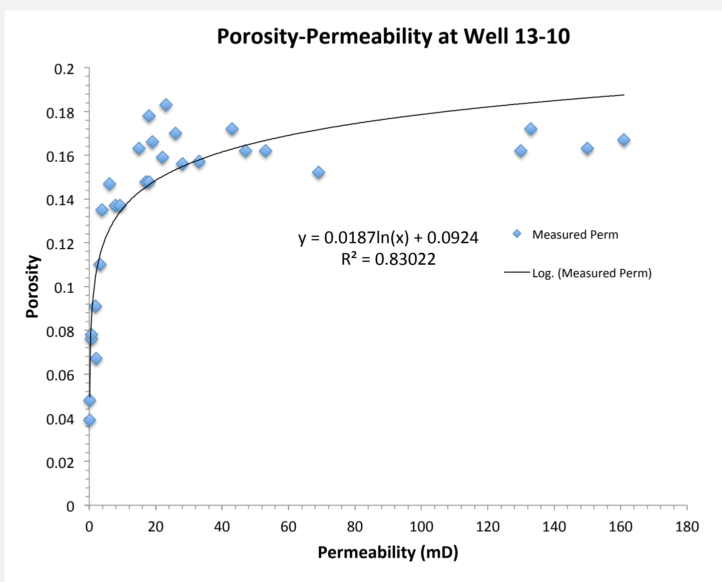
Probabilistic Risk Analysis

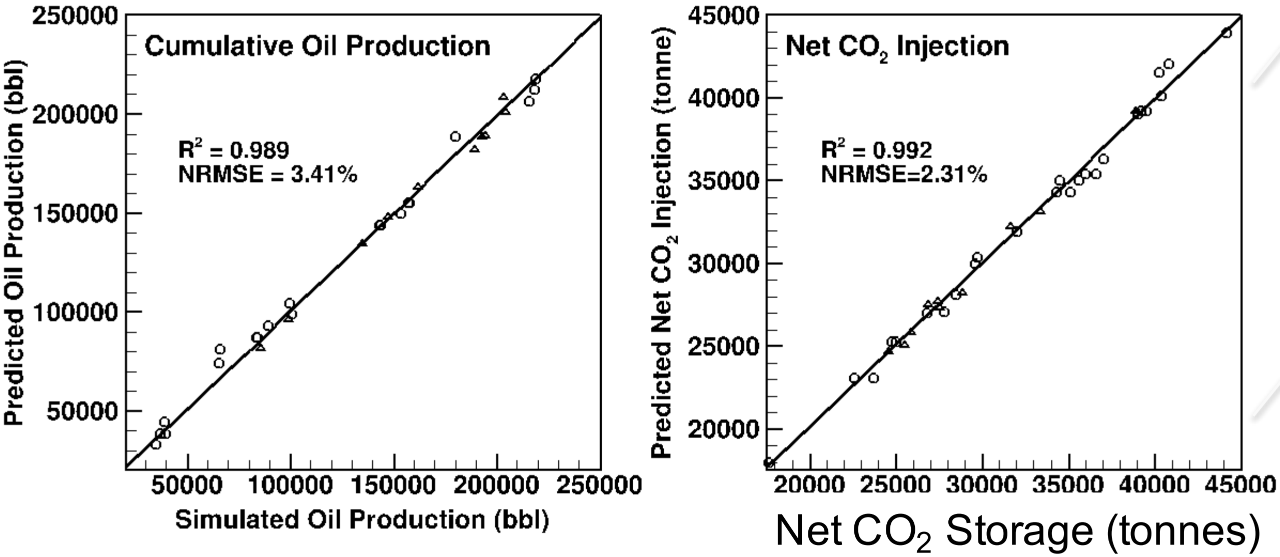
- Farnsworth 3-D reservoir model
  - Upscaled model with 202,120 cells (163*155*8) with cell size of 100*100 ft
  - One five-well pattern: 13-6 as production well, four injection wells (13-1, 13-13, 13-9, 13-10A)
  - 5-year water-alternation-CO_2 injection, and 1-year monitoring and recovery



- Response surface Methodology

Independent variables (Xi)		Low (-1)	Mid (0)	High (+1)	Statistical distribution
X1	Permeability (mD)	0.33	11.07	374.97	Log-normal
X2	Anisotropy ratio (K_v/K_h)	0.1	0.55	1.0	Uniform
X3	WAG time ratio (CO_2 injection time/water injecation time)	1.0	1.5	2.0	Uniform
X4	Initial oil saturation	0.19	0.28	0.37	Uniform

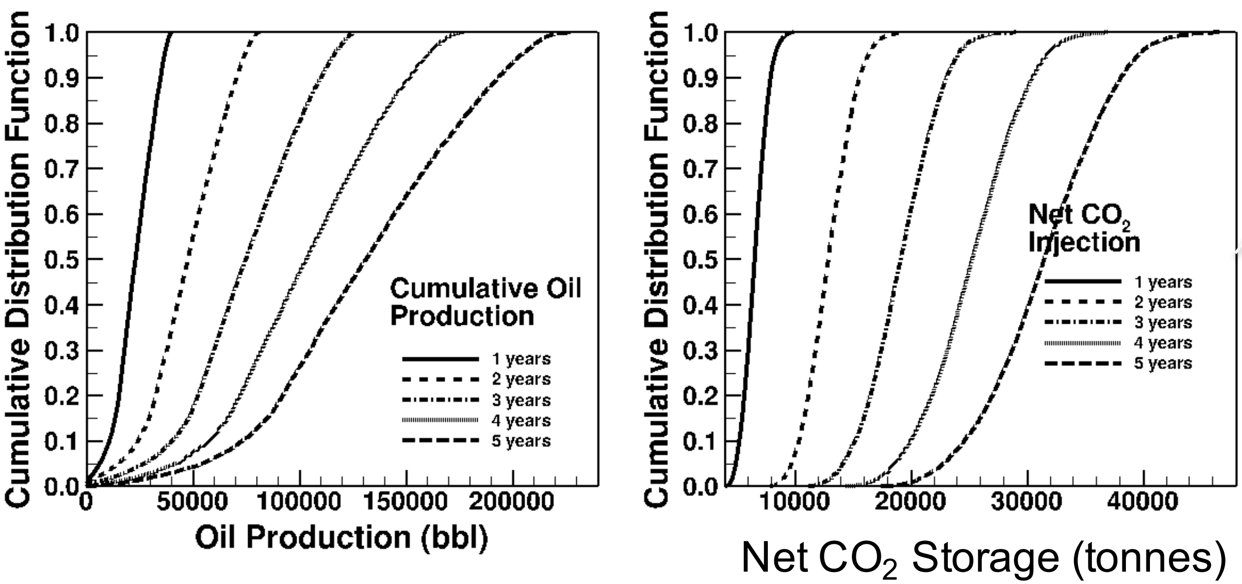




Simulated (circle dot), predicted (line), and verified (delta dot) output responses.

The results of goodness-of-fit measures indicates the high accuracy of the response surface models for predictions.

Reasonable match between trained ROMs and original full-scale reservoir models suggest that the ROMs are sufficiently robust for meaningful forecasts.



Cumulative distribution functions (CDFs) of output responses

The uncertainties of output variables increase over time and the significant uncertainties are propagated from parameter uncertainties.

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Risk Response Planning

- **Established risk prevention and mitigation treatments for top 40 FEPs and 10 black swans.**

FEP	Ranking	Risk Prevention	Risk Mitigation
Modeling and simulation - parameters	1	Understand the statistics (range, mean, variance, etc.) of parameters. Evaluate and select appropriate conceptual models. Select Equations of State (EOS) by using appropriate assumptions. Define model domain with appropriate initial and boundary conditions. Review simulation model results for accuracy and completeness using a cross-functional team of experts. Understand the solubility of CO_2 in the oil and gas of the Farnsworth Unit with tracking oil and gas compositions at the production wells. Using this information in the simulations will greatly reduce the potential of inaccurately modeling phase behavior. Reduce the parameter uncertainties by robust stochastic approaches	Periodic review of available data and simulation results . Understanding of the varibility across the five-spot patterns, including the isolation of perforation zones in the wells. Parameter calibration based on monitoring data Parameter uncertainty quantification Global sensitivity analysis of independent parameters.
CO_2 supply adequacy	2	Maintain multiple sources of CO_2 . Conduct CO_2 transportation uncertainty analysis. Perform CO_2 price variations analysis and trend prediction.	Monitor CO_2 quality. Cut back CO_2 injection on some patterns or compensate with increased water injection.
Release of compressed gases or liquids	3	Identify and protect/secure compressed gas/liquid lines, valve or tanks. Conduct HARC risk analysis on cased hole wireline operations for pressure testing lubricator for high pressure CO_2 operations. Use only materials that are fit for purpose; i.e. suited for CO_2 EOR service. Implement safety training and standard procedures for operators. Conduct regular safety audits during construction and operation. Implement emergency response plan and risk management plan.	Maintain safety training and standard procedures. Document response to safety incidents. Maintain emergency response planning and conduct regular drills. Maintain risk management plan. Maintain liability insurance.

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Risk Assessment Workflow (6 Tasks)

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- Risk Response Planning
- Risk Monitoring and Control – Yet to Begin

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- **Summary, Questions and Answers**

Summary

- Project is going great!
- Baselines completed: CO_2 flux, ground water, seismic, characterization, geomodel, reservoir performance, risk, etc.
- Ongoing updates of: CO_2 flux, ground water, seismic, characterization, geomodel, reservoir performance, risk, etc.
- Characterization Wells completed
- First repeat VSP and crosswells

Summary

- Other ongoing research: fluid rock interactions, caprock integrity, risk assessment, material balance.
- Outside influences: economics of oil, ethanol, fertilizer, production/injection & general national health; weather/nature (floods, hail, wind, heat, cold, snakes, weeds, mosquitos, etc.); national policies; public perception; personnel changes (transfers, graduations, layoffs, **retirements**).

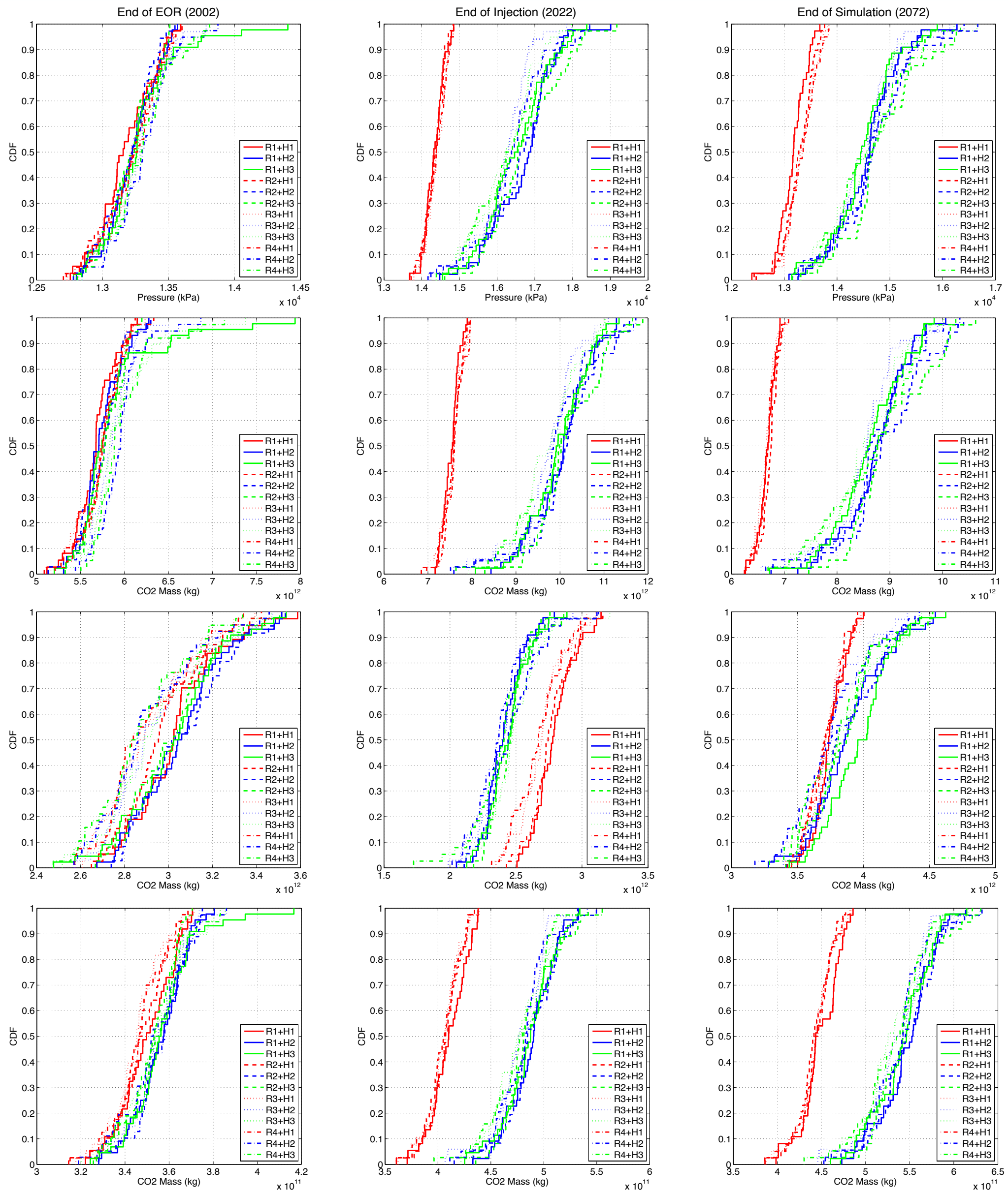
The End

Risk Assessment of Net CO_2 Storage and Reservoir Pressure

At the end of CO2-EOR (left), all R and H modes predict similar results

At the end of post-EOR (middle), H1 predicts **lower reservoir pressure, lower** CO2 storage in **oil** and **water** phases, **higher** in **gas** phase

At the end of simulation (right), H1 predicts slightly **lower** CO2 storage in **gas** phase



$P_{reservoir}$

CO_2 in Oil

CO_2 in Gas

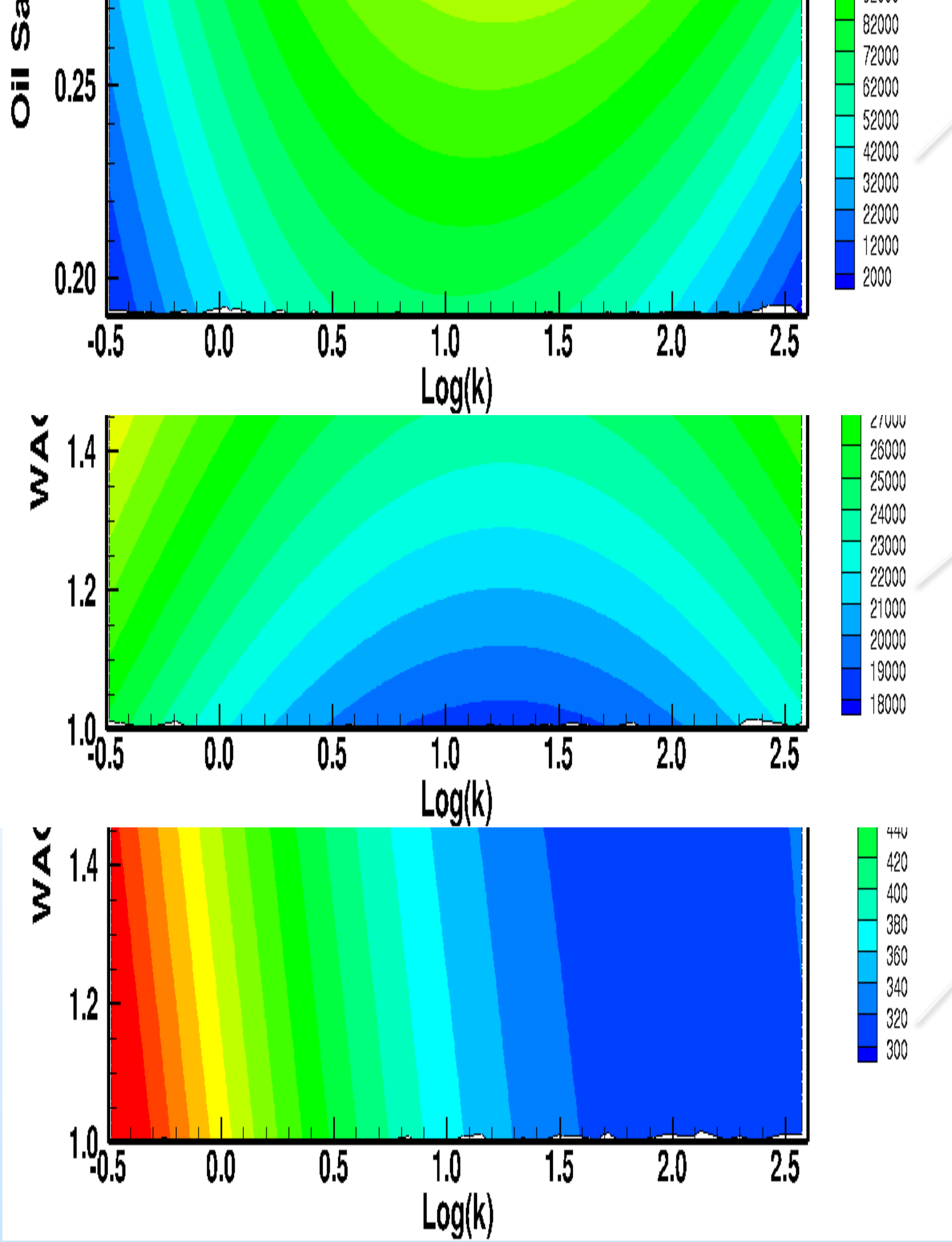
CO_2 in Water

Top 21 Risk- Ranked FEPs at Farnsworth (2014)

FEP	FEP ID	Orig/New	FEP Gp	T-P Technical vs Programmatic	Dtype	Expt-Weighted Risk Value
Modeling and simulation - parameters	H02	O	Monitor Model	T	4-RISK	8.50
CO2 supply adequacy	E10	O	CO2 supply system design, operation	P	4-RISK	7.86
Release of compressed gases or liquids	F07	O	Health Safety	P	4-RISK	7.80
Geomechanical characterization	Gp073	N	Geomech geochem	T	4-RISK	7.56
Simulation of coupled processes	Hp084	N	Monitor Model	T	4-RISK	7.46
Price of oil (or other related commodities)	J02	O	Proj & Prog Mgmt	P	4-RISK	7.12
Operating and maintenance costs	J03	O	Proj & Prog Mgmt	P	4-RISK	7.11
Blowouts	D06	O	Well drilling and completions	T/p	4-RISK	7.05
Simulation of geomechanics	Gp074	N	Geomech geochem	T	4-RISK	7.03
Over pressuring	G05	O	Geomech geochem	P/t	4-RISK	7.03
Caprock heterogeneity	Cp037	N	Reservoir and caprock geology and petrophysics	T	4-RISK	6.97
Seismic method	H07	O	Monitor Model	T	4-RISK	6.73
CO2 containing H2S	E06	O	CO2 supply system design, operation	T/p	4-RISK	6.68
Excavation/drilling	F02	O	Health Safety	P	4-RISK	6.67
Simulation of fluid dynamics	Hp087	N	Monitor Model	T	4-RISK	6.65
Reservoir heterogeneity	Cp081	N	Reservoir and caprock geology and petrophysics	T	4-RISK	6.59
Modeling and simulation - software	H01	O	Monitor Model	T/p	4-RISK	6.54
Accidents and unplanned events	F01	O	Health Safety	P	4-RISK	6.42
EOR oil reservoir heterogeneity	I01	O	EOR	T	4-RISK	6.35
Fluid chemistry	Hp088	N	Monitor Model	T	4-RISK	6.32
Execution strategy	J06	O	Proj & Prog Mgmt	P/t	4-RISK	6.22

Risk Factors

	Independent Variables (Uncertain Parameters)	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) 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 Initial water, oil and gas saturations Mineralogical composition	Amount of CO_2 stored (or CO_2 recovered or Net CO_2 stored) Early CO_2 Breakthrough time CO_2 Retention (or residence) CO_2 Injectivity reduction (Net CO_2 injection amount) 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	Oil production Water cut (or net water injection) Gas (CH4) production	
Geomechanics	Fault density and distributions Stress and mechanical properties Coefficient of friction (fault properties) Caprock geomechanical properties Mechanical processes and conditions	Pressure Buildup 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 CO_2 migration (point & non-pont source) Distributions of leaky wells	pH change in the overlying aquifer CO_2 concentration or total carbon concentration Heavy metal concentration TDS change in the overlying aquifer Trace metal mobilization CO_2 migration through caprock Caprock sealing quality evolution (porosity change)	

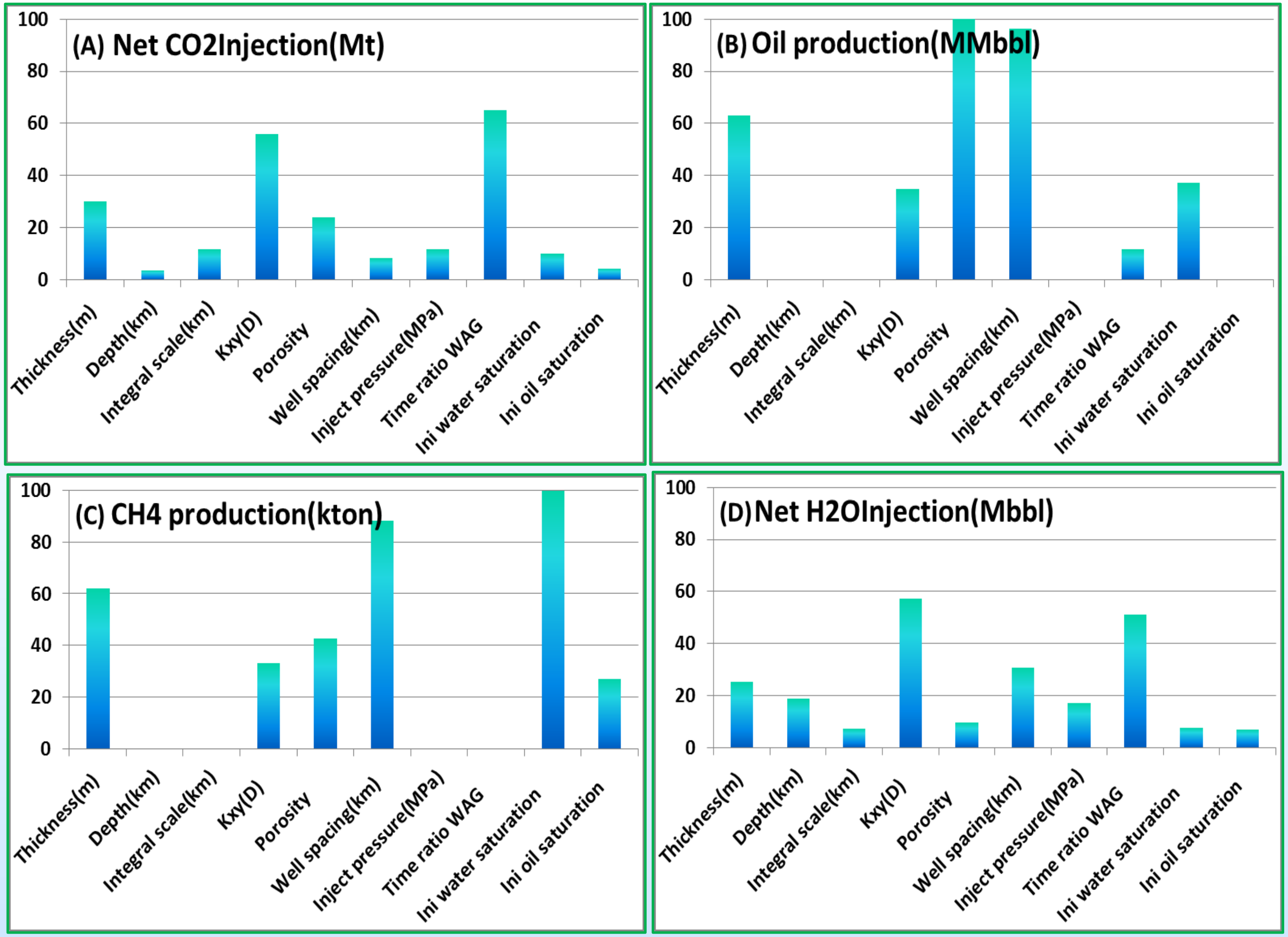


At the end of 5-year simulations, when permeability ranges from 10 to 32 mD (close to mean value), maximum oil production amount is achieved.

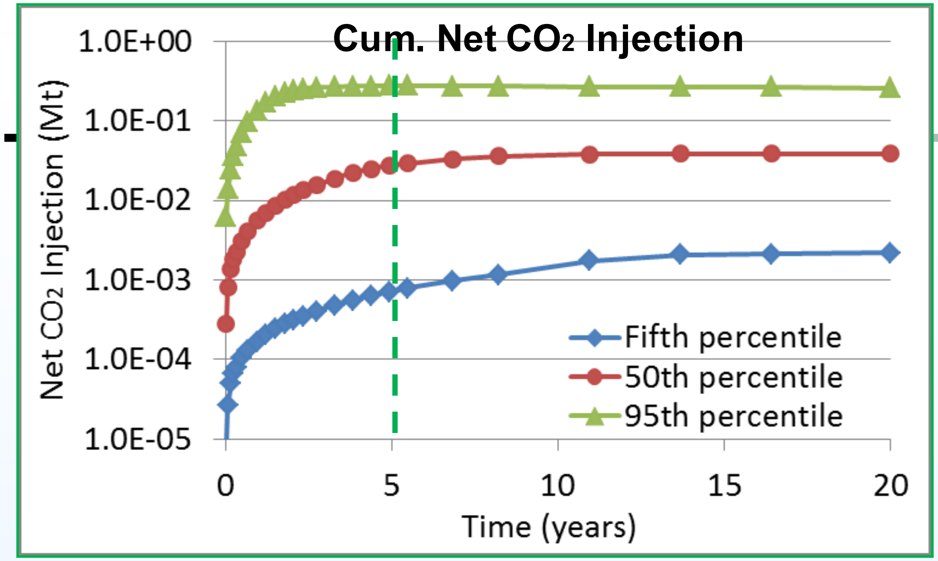
Effects of permeability on net CO_2 injection are similar in magnitude, but directly opposite to that for oil production.

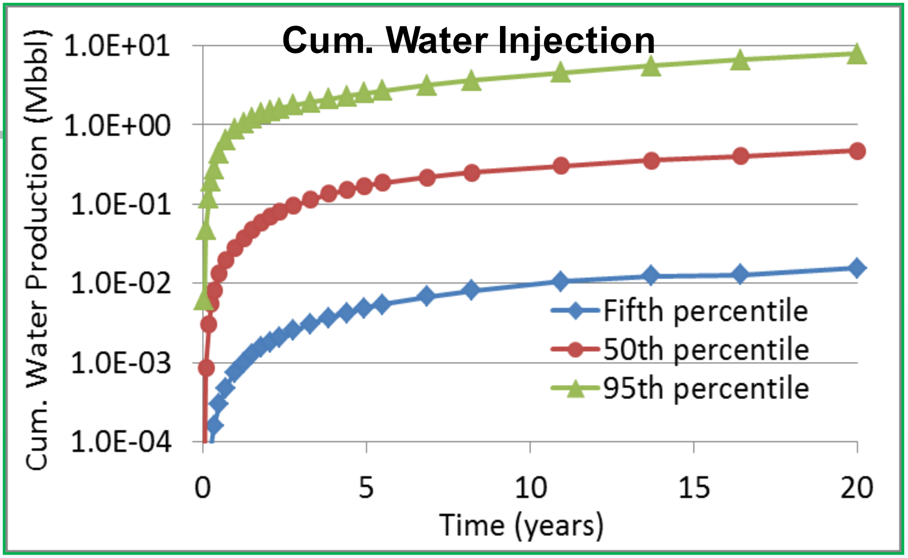
Pressure next to the injection well generally decreases with increases in permeability, illustrating that reduced (lower) permeability could cause significant pressure buildup around injection wells.

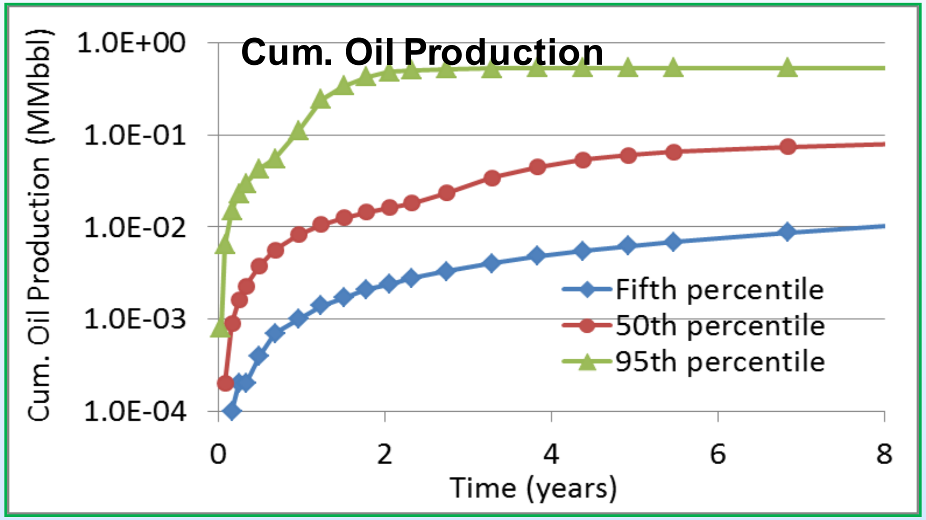
The response surface of output variables in relation to the uncertain input parameters after 5 years of injections.



Global sensitivity analysis with multivariate adaptive regression spline (MARS) method

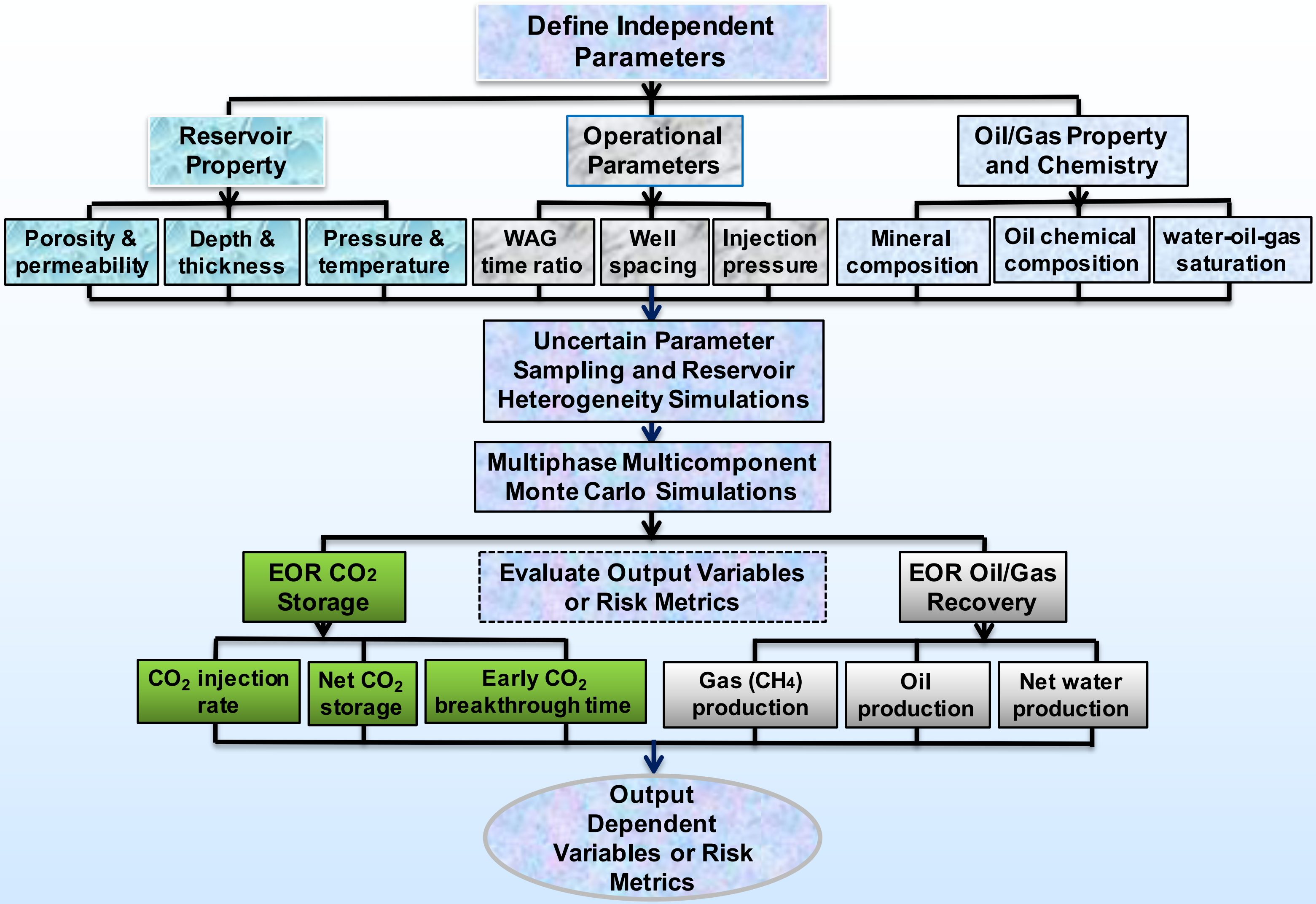






Statistical analysis of net CO_2/Water injection and Oil production

Combined Accounting and Risk Analysis



Flow chart for a statistical framework of CO_2 accounting and risk analysis for CO_2 enhanced oil recovery (EOR)